GW-3

Project report on

CCOP-GSJ/AIST-MONRE Groundwater Project Phase II Meeting

26-28 February 2013, Hanoi, Vietnam

COORDINATING COMMITTEE FOR GEOSCIENCE PROGRAMMES

IN EAST AND SOUTHEAST ASIA (CCOP)

In cooperation with

GEOLOGICAL SURVEY OF JAPAN (GSJ), AIST

Published by

CCOP Technical Secretariat

Bangkok, Thailand

Youhei Uchida (Chief Editor)

Authors (CCOP-GSJ/AIST Groundwater Project)
Mr. ChoupSokuntheara
Dr. Li Tiefeng
Mr. HaryadiTirtimihardjo
Dr. Youhei Uchida
Dr. Kyoochul Ha
Mr. QalamA'Zad Role
Mr. Win Myint
Mr. Simon Egara
Mr. Lutgardo S. Larano
Mr. AdisaiCharuratna
Mr. Francisco Xavier Pereira Sico
Dr. Nguyen Thi Ha

PREFACE

Since the establishment of the CCOP in 1966, geological and geophysical surveys have been carried out by the CCOP under the cooperative schemes in the East and Southeast Asia for offshore natural resources. These data have been distributedto member countries as printed maps and publications.As for the first groundwater project, “Groundwater database in East and Southeast Asia”had been compiled under the DCGM Phase IV project of CCOP from 2001 to 2004.

Groundwater is one of the limited natural resources of the world. Because of the lack a feeling of importance of groundwater, especially, in the late 20th century, groundwater has been significantly damaged by human activities, resulting in groundwater issues, such as land subsidence, seawater intrusion, and groundwater pollution by toxic substances, that have become remarkable problems in everywhere in the world. The countries in the East and Southeast Asia have been also faced the many groundwater problems which are needed international cooperation to be solved.

The GW meeting has country reports of each member country and edit for CCOP Project Report. Title of the first country report was “Introduction of groundwater issues in each country”, and the second was “Ground water Pollution and Risk Management”.The third meeting of Phase II for the CCOP-GSJ/AIST-CWRP Groundwater project was held on 26-28 February 2013, Hanoi, Vietnam.Title of country report on the 3rd GW meeting had been set in each member country and we had deep discussion and confirmed that these reports showed individualproblems of pollution and method of risk management for groundwater in each country. I believe that CCOP member countries will be able to have some solutions about groundwater management from the country reports.

I am very grateful to the authors for their invaluable contributions and to the organizations to which the authors belong for their permission to publish those important reports. I am indebted to Dr. Yusaku Taguchi, Ms. Kyoko Nakayama, Dr. Nguyen Thi Minh Ngoc, andCCOP Technical Secretariat for constructive suggestions and editing.

Youhei UCHIDA
Chief Editor

CONTENTS

Land Subsidence in Angkor Wat Area

Choup Sokuntheara
Deputy Director of Department of Geology, GDMR
Ministry of Industry Mines and Energy

1. Geological Setting

Cambodia is geologically composed of three different regions:

The Triassic and Liassic covering a large area in the east, the Jurassic-Cretaceous continental sandstone forming important highlands in the southwest and west and, between them, the Quaternary basin which occupies the whole central plain of the country.

Geological studies show series of sedimentary formation extending from Precambrian at the bottom through to Cretaceous at the top; the whole are affected by successive tectonic and volcanic activities.

The Tertiary formation of which outcrops are very limited on land, forms a thick layer in the sea bottom and seems to be an important target for the oil and gas exploration.

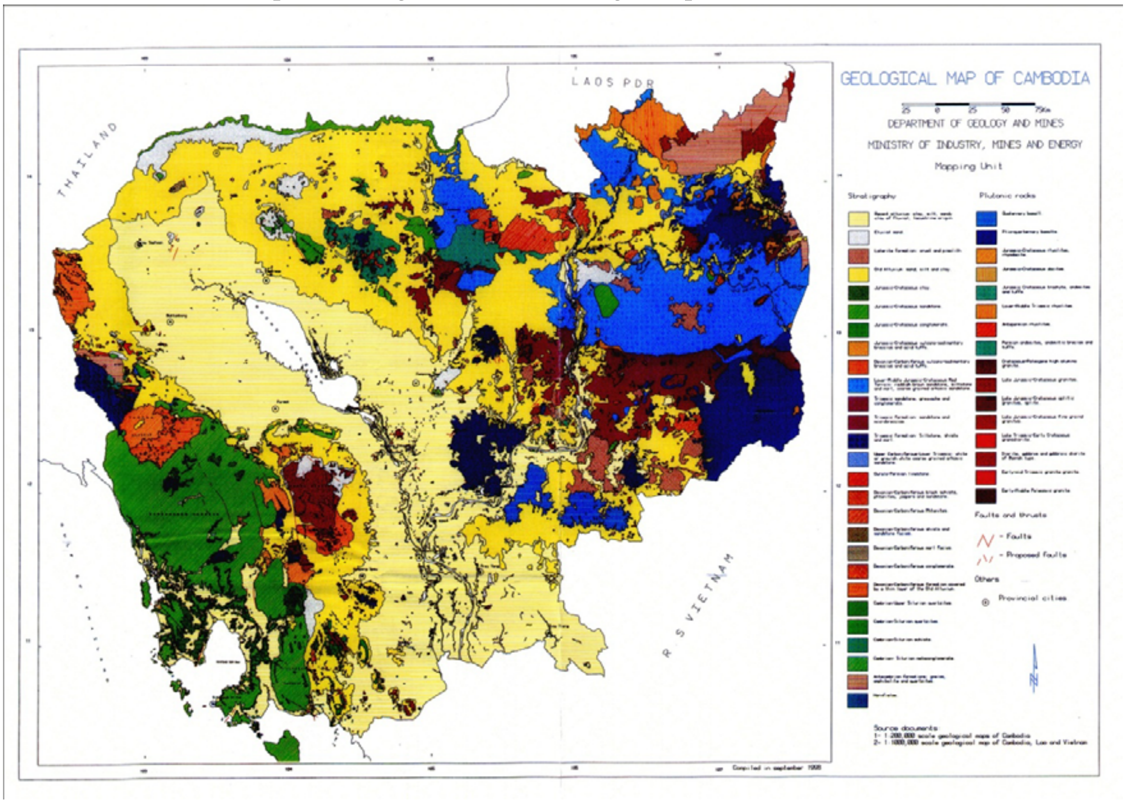


Fig.1 Geological map of Cambodia

2. History of Groundwater in Cambodia

In Cambodia, groundwater has been investigated and exploited. In year 1958, on behalf of the United States Operation Mission (USOM) in Cambodia, it has been investigated by U.S.

Geological Survey (USGS), R.V. Cushman. The main purpose could be for agriculture economic for irrigation was available during dry season from December to May. The result of this program had been collected for all the data needed and carried out for the groundwater used in the future. During 1960-63, 1,103 holes were drilled of which 795 of approximately 72 percent productive wells at rates were ranging from 1.1 to 2,967 l/min. The productive wells ranged in depth from 2 to 209.4 m and were 23.2 m deep on the average.

Mr. Rasmussen studied the subsurface geology of Cambodia in considerable detail by examining drillings logs and constructing nine geologic cross sections.

The principal aquifer tapped by drilled wells in Cambodia is the old Alluvium. In many places, however, dug wells and a few shallow drilled wells obtain water from the young Alluvium. Sandstone of the Jurassic - Cretaceuos formation yields is moderate to small quantities of water to wells in a number of places.

Also, numbers of wells tapping water bearing basalt have a small to moderate yield.

The quality of water is recorded in only a few analyses. The dissolved-solids concentrations appear to be generally low so that the water is usable for most purposes without treatment. Some well waters are high in iron and would have to be filtered before use. From May 2009 to August 2011, MIME and SRWSA and JICA, had undertaken a preparatory study on the Siem Reap Water Supply Expansion Project.

3. The Study Area

3.1 Location of the Study Area in Siem Reap City

The study area covers all the communes of the newly established Siem Reap City and one adjacent commune of the City, for a total of 14 communes (see Fig.2).

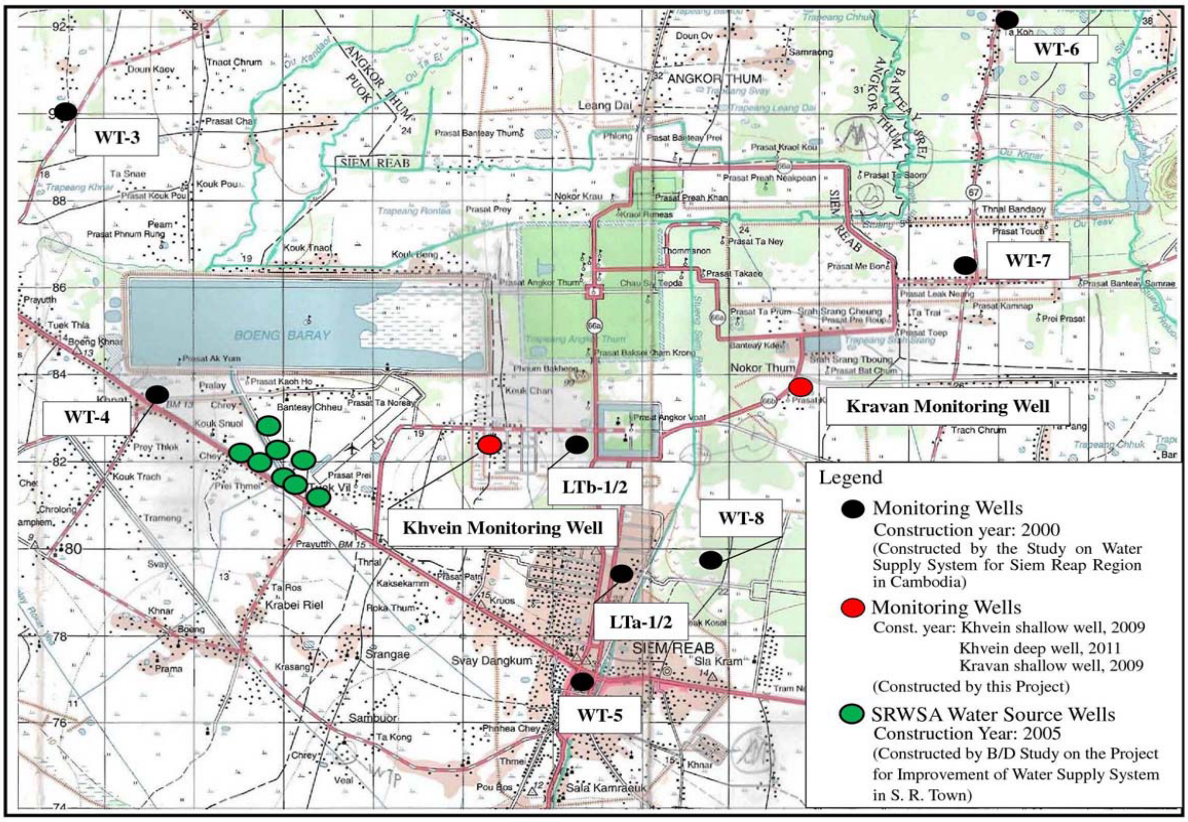


Fig.2 A location map of monitoring wells

Photo 1: SRWSA production well (PW-4)
located along canal

Photo 2: SRWSA Production well (PW-4)
and a control box

Photo 3: LTb-1 monitoring well
(Location: In front of Angkor Wat)

Photo 4: Monitoring facility of land subsidence
and groundwater level

Photo 5: WT-4 monitoring well

Photo 6：Monitoring equipment & well (WT-4)

Photo 7: Kravan monitoring well
(Completion date: October 2009)

Photo 8: Monitoring equipment & well
(Kravan monitoring well)

3.2 Groundwater Sources

3.2.1 Background and Outline

The use of groundwater in the plain area along the shore of Tonle Sap Lake was proposed by the team of JICA preliminary study (conducted in 2009) for this preparatory study as a possible alternative source for water supply to the city of Siem Reap. The Study on Water Supply System for Siem Reap Region in Cambodia (2000) had already been conducted and had clarified the underground geology of the urban and suburban areas of Siem Reap City. However, there has been little geological information available on the zone along the shore of Tonle Sap Lake. For this reason, the entire survey area extended about 30 km on both western and eastern sides of Phnom Kraom hill along the shore of Tonle Sap Lake. In the study on Water Supply System for Siem Reap Region in Cambodia (2000), a four-layer subsurface structure was established as a result of the analysis. By reference to the above study result, the geophysical survey data of this study were analyzed and the analyzed geological structures are shown in Table 1.

Table 1 Geological and Hydrogeological Characteristics of the Layers in the Study Area

Layer Sign	Age	Thickness (m)	Description	Hydrogeological Characteristics
1. Qal	Quaternary (Holocene)	10-20	Alluvial deposits Silty sand with coarse particles. Very loose sand in the middle part.	Static water level: 0.855 m (1997 May) Permeability: 1.87-1.67x 10-2 (cm/sec) Discharge:444 liters/min With 0.73 m drawdown.
2. Qsd	Quaternary (Pleistocene)	10-30	Diluvium deposits Containing silt (stone) from the lower formation. Clayey sand (stone) with coarse matrix. At the bottom, gravelly sand and core lost by loose matrix.	
3. Tcy	Tertiary (Pliocene)	20-50	Pliocene formation Sandy clay stone. Cylindrical core.	Aquiclude – Aquifer*
4. Mbr	Mesozoic	-	Bedrock: Weathered tuff of Mesozoic rock.	Unknown

Note: Table was compiled and modified from the data in the Study on Water Supply System for Siem Reap Region in Cambodia (2000). The Study on Water Supply System for Siem Reap Region in Cambodia (2000) revealed that geological structures in Siem Reap area were formed by 4 ones and the layer 1 and 2 above were the major aquifers. The geophysical survey data of this study were analyzed by reference to the survey results of the above study (2000).

3.2.2 Well Inventory Survey

Well inventory survey was conducted mainly to obtain basic data for Groundwater use and demand estimation. The survey targets are large consumers of Groundwater consisting of 280 establishments.

All the surveyed establishments use wells deeper than 20 m and 15 % of hotels and guesthouses use more than 2 wells. On the other hand, 35 % of the hotels, guesthouses, and restaurants use public water supply system as well.

Table 2 Average Number of Wells and Depth of Wells (m³/ day / establishment)

Category	Hotel	Guest House	Restaurant	Factory	Other
Number of wells	1.37	1.06	1.40	1.60	1.03
Depth *(GL-m)	45.5	30.9	31.0	43.6	32.1

*In each establishment with more than 2 wells, depth of frequently-used well was adopted. Above table shows average depth of the wells.

The data for water use amount had to be estimated due to the lack of measurement record. Thus, it was estimated based on pump capacity, tank volume, and operational hours of pumps. The results are summarized in the following table.

Table 3 Estimated Daily Average Water Use Amount by Category (m³/day/establishment)

Category	Hotel	Guest house	Restaurant	Factory	Other
Rainy Season	30.35	4.62	8.89	39.00	8.89
Dry Season	47.27	5.65	9.91	85.4	8.51

Due to the increased number of tourists, the water use during the dry season is much larger except under category “Other” where majority of the establishments are car wash places. Majority of respondents under tourism related categories (hotel, guesthouse, and restaurants) are aware of the possible negative effect (lowering of groundwater level and occurrence risk of land subsidence) of groundwater pumping to the surrounding environment as can be seen in the table below.

Table 4 Ratio of Awareness on Possibility of Occurrence of the Groundwater Issues

Category	Hotel	Guest house	Restaurant	Factory	Other
Ratio of Awareness (%)	64	53	65	10	17.5

Many of the surveyed establishments are willing to connect to the public supply system when it becomes available. The main reason is to cut down the operational cost of current groundwater pumping system.

3.2.3 Important Findings from the Inventory Data

The total amount of daily groundwater use in Siem Reap at present (year 2009) was estimated using the data obtained in the well inventory survey. The following set of data and conditions were adopted to estimate the daily groundwater use amount for both dry and wet seasons.

Table 5 Estimated daily groundwater use amount for both dry and wet seasons

Category	Use amount (m^3/day)		Conditions of estimation
	Wet season	Dry season	
Large establishments with own Groundwater pumping facilities	3,908	5,786	-Total from 280 establishments Based on the inventory. Separately calculated for dry and wet seasons.
Large establishments connected to public water supply of SRWSA except the above establishments	3,739	5,009	-Number of : hotels = 61, Guesthouses = 43,Restaurants = 190 (source: SRWSA list of registered customers), - Average pumping amount data for the above category was taken from the inventory data. -Some part of water is supplied by their own groundwater pumping facilities
Small establishments and ordinary houses	21,569	24,418	-Population of Siem Reap in 2009 = 203,483 (source: department of planning Siem Reap province) -Part of the water is supplied by SRWSA 's public supply system -Unit water use amount =0.106 m^3/day/capita for wet season , 0.120m^3/day/capita for dry season
Total	29,216	35,213	

3.2.4 Field Water Quality Tests

The quality of groundwater in the areas of possible groundwater sources for the water supply was tested in the field. The water samples were taken mainly from tube wells with a hand pump and tested for the following indicators. The results were compiled, for the three areas of west of Siem Reap, East of Siem Reap and Phnom Kraom as shown in the table 6.

Similar to the water quality test results of the Well Inventory Survey, the water quality of the samples were characterized by low pH and sporadic high iron concentration. In every area, average values of pH and iron concentration exceed drinking water quality standards and it may need water treatment for drinking.

Table 6 Average Value of Water Quality by Area (Unit: mg/L)

Item	pH	EC (μS/cm)	Fe	Mn	NH_3-N
DWS*	6.5 - 8.5	1,600	0.3	0.1	1.5
East	5.43	48	1.21	0	0.18
West	5.60	83	2.08	0	0.15
Phnom Kraom	4.90	518	0.45	0.17	0.15

(Note) DWS*: Drinking Water Quality Standards, January 2004, Ministry of Industry, Mines, and Energy

4. Hydrological Conditions in Siem Reap

4.1 Available Meteorological and Groundwater Monitoring Data

Data from five (5) meteorological stations and eight (8) groundwater monitoring wells have been collected to be used for groundwater recharge analysis. A strict inspection has conducted for data availability checking to avoid using wrong data in analysis.

4.2 Groundwater Recharge Analysis

Of the many methods of groundwater recharge analysis, the tank model was selected because it is excellent for obtaining relatively high precision results by directly linking the precipita- tion, evaporation and groundwater level fluctuation. The annual groundwater recharge is calculated as 341 mm/year, corresponding to an annual groundwater recharge amount of 435,517,000 m^3 in the whole recharge area. Considering the groundwater basin structure, the recharge amount in upstream area near the Kulen mountain range has little effect on the water supply area in Siem Reap. Then, groundwater recharge amount in the Siem Reap area can be calculated as 188,320,000 m^3/year, corresponding to a daily amount of 516,000 m^3.This value is far more than the maximum daily water demand of 86,300 m^3/day. However, the water supply area is a sensible area on land subsidence by groundwater level drawdown because of the existence of many world famous heritages. And groundwater drawdown is unavoidable when groundwater is withdrawn. Hence, the magnitudes of groundwater drawdown in different groundwater use plans should be taken as the main issue for groundwater evaluation.

4.3 Simultaneous Groundwater Observation

To make clear the groundwater level distribution and fluctuation in different seasons in Siem Reap, simultaneous groundwater observations were conducted twice, in the rainy and dry seasons. The observation for the rainy season was conducted at the end of September 2009, and the observation for the dry season at the end of April, 2010.

As a survey result, a relative large groundwater level drawdown in the dry season can be found in town area, when comparing the water level in the rainy season. This large drawdown in town area can be considered as the result of large amount of groundwater use by many private wells in town area of Siem Reap.

4.4 Comparison of Groundwater Level Observation Result

In the Study on Water Supply System for Siem Reap Region in Cambodia (2000), 79 wells have been used for monthly groundwater level observation from February 1998 to November 1999. More than 25 wells were extracted from the each of two studies for comparison.

The following 2 tables show the water level in rainy season and dry season in different months and years. The values in the tables give the water level (m) below the ground surface.

Table 7 Comparison of Water Level in Rainy Season in Town Area

Time	Sep.'09	Sep.'98	Oct.'98	Nov.'98	Sep.'99	Oct.'99	Nov.'99
Average (m)	1.63	1.41	1.2	1.32	1.24	0.85	0.6
Maximum	5.12	3.51	3.1	3	3.26	2.9	2.32
Minimum	0.2	0.1	0	0.3	0.23	-0.28	-0.41

Table 8 Comparison of Water Level in Dry Season in Town Area

Time	Apr.'10	Apr.'98	May.'98	Apr.'99	May.'99
Average (m)	4.19	3.5	3.5	2.5	2
Maximum	7.4	5	5.1	4.6	4.81
Minimum	2.6	2.35	2.25	1.46	0.82

Compared to the average of observation result in 1998 and 1999, the groundwater level in 2009 got down in a range from 0.22 m* to 1.03 m* in rainy season and 0.69 m* to 2.19 m* in dry season. That is obviously the groundwater drawdown has happened in the town are in Siem Reap.

(Note: 0.22 m* = {1.63 m (2009/9) – 1.41 m (1998/9)}, 1.03 m* = {1.63 m (2009/9) – 0.6 m (1999/11)}, 0.69 m* = {4.19 m (2010/4) – 3.5 m (1998/4)}, 2.19 m*= {4.19 m (2010/4) – 2 m (1999/5)}

5. Groundwater Simulation

Daily water demand in Siem Reap has been estimated at a maximum of 86,300m³/day in 2030, about one sixth of the groundwater recharge amount of 516, 000 m³/day.

However, for groundwater simulation, not only the balance between groundwater recharge and withdrawal, but also the effect of groundwater development has to be taken into consideration. In Siem Reap the most important effect from groundwater development is the groundwater level drawdown, because the groundwater drawdown can cause land subsidence.

In this study, several scenarios which combined surface water and groundwater as water supply sources were supposed. The effect of these scenarios was evaluated by a groundwater simulation model created on the basis of hydrogeological survey results and other relative surveys.

5.1 Groundwater Simulation Model Structure

The domain of the groundwater simulation model covers whole water supply service area and surrounding area, with a extent of 39 km in the west-east direction and 46.5 km in the north-south direction.

5.2 Layer Specification

5 layers area is specified in the model: Layer 1 and Layer 2: shallow aquifer / Layer 3: aquiclude /Layer 4: deep aquifer /Layer 5: basement rock. (Note: as shown in "Table 1 Geological and hydrological characteristics of Geophysical survey", a part of Tertiary formation forms aquifer. Thus, Tertiary formation in this simulation model is supposed to divide into an aquiclude of 3rd layer and a deep aquifer of 4th layer. As a result, the model including basement rocks (5th layer) assumed 5 layers as groundwater basin structures).

5.3 Boundary Condition Specification

Therefore the following features were specified into the model as constant water boundaries. Siem Reap River/Angkor Wat Moat/West Baray (Reservoir) and its channels for water conveyance in its upstream and downstream sides/Tonle Sap Lake.

5.4 Parameter Specification

Hydraulic conductivities are specified for each layer based on the pumping test results of the Study on Water Supply System for Siem Reap Region in Cambodia (2000). Other parameters are specified for Storage Coefficient, Effective Porosity, and Specific Yield based on empirical values.

5.5 Model Calibration

1) Steady Flow Simulation: Steady flow simulation is conducted for model convergence and general parameter's specification confirmation.
2) Transient Flow Simulation: Transient flow simulation is conducted for parameter calibration by using the last 3 years (2006-2008) relative data of precipitation, evaporation, groundwater withdrawal amount.

5.6 Model Specification for Groundwater Prediction

1) Specification of External Factors

Precipitation and Evaporation: The last 20 years of observation results from 1989 to 2008 in meteorological station Siem Reap City were taken for precipitation specification. Water Head for Constant Head Boundary: The result of hydrological observation and the last 10 years water level observation results of Tonle Sap Lake were used for constant head boundary specifications.

2) Specification of Scenarios

Scenario 1: Natural condition without any groundwater use.

Scenario 2: Continue groundwater use by the present amount.
{Total withdrawal volume = average 22,176 m³/day: (SRWSA wells' extraction volume = 9,000 m³/day) + (private wells' extraction volume)}

Scenario 3: Expending groundwater supply capability by an amount of 77, 000 m³/day. {Total withdrawal volume = 86,000 m³/day: (SRWSA wells' extraction volume = 9,000 m³/day) + (Groundwater development volume by new wells 77,000 m³/day)}

Scenario 4: Taken KTC project into consideration and then expending groundwater supply capability by an amount of 43,000 m³/day.
{Total withdrawal volume = 52,000 m³/day: (SRWSA wells' extraction volume =9,000m³/day) + (Groundwater development volume by new wells 4,300 m³/day)}

Scenario 5: Also taken KTC project into consideration, but the expanding amount is set following maximum water demand to be 60,000 m³/day.
{Total withdrawal volume = 69,000 m³/day: (SRWSA wells' extraction volume =9,000 m³/day) + (Groundwater development volume by new wells 60,000 m³/day)}

Scenario 6: Don't build new wells on the east side of Siem Reap River, and then set the expanding amount as 30,000 m³/day.
{Total withdrawal volume = 39,000 m³/day: (SRWSA wells' extraction volume =9,000 m³/day) + (Groundwater development volume by new wells 30,000 m³/day)}

Scenario 7: Stop all deep wells withdrawal except SRWSA production wells, using surface water as water supply source.
(Total withdrawal volume = SRWSA wells' extraction volume = 9,000 m³/day).

5.7 Simulation Results

1) Groundwater Level

Five (5) provisional observation wells (deep wells) are specified in deep aquifer under and near main heritages. The maximum groundwater level drawdown in these wells are calculated and summarized in the table below.

Table 9 Summary of Water Level Drawdown (Unit: m)

Scenario	Near_ANW*	ANW*	ANT*	Near_WB*	WB*
Scenario 2	0.73	0.59	0.57	1.34	1.17
Scenario 3	0.7	0.65	0.74	3.31	2.12
Scenario 4	0.41	0.38	0.49	2.31	1.62
Scenario 5	0.51	0.47	0.6	2.83	1.9
Scenario 6	0.45	0.38	0.49	1.71	1.34
Scenario 7	0.13	0.12	0.23	1.16	0.96

Note: (Column heading＊) is the code of each provisional observation well and the locations of each provisional observation well are shown in Figure 5.18.
Each location which is indicated by each well number is as follows:

ANW: under Angkor Wat

Near ANW: near Angkor Wat
ANT: under Angkor Thom
WB: under West Baray
Near West Baray: near West Baray

2) Land Subsidence

The potential land subsidence amount are calculated and shown in the tables below:

Table 10 Potential Land Subsidence Amount Prediction (Unit: mm)

Location	Near ANW*	ANW*	ANT*	Near WB*	WB*
Scenario 2	7.02	5.67	5.48	5.84	5.1
Scenario 3	6.73	6.25	7.12	14.43	9.24
Scenario 4	3.94	3.65	4.71	10.07	7.06
Scenario 5	4.9	4.52	5.77	12.34	8.28
Scenario 6	4.33	3.65	4.71	7.46	5.84
Scenario 7	1.25	1.15	2.21	5.06	4.19

(Note): (Column heading＊) is the code of each provisional observation well and the locations of each provisional observation well are shown in Figure 5.18.
Each location which is indicated by each well number as follows:
ANW: under Angkor Wat
Near ANW: near Angkor Wat
ANT: under Angkor Thom
WB: under West Baray
Near West Baray: near West Baray

Table 11 Potential Land Subsidence Amount Prediction for Heritage Site of Bakong
(Unit: mm)

Scenario	S 2	S 3	S 4	S 5	S 6	S 7
Shallow A	1.59	48.73	20.45	29.93	1.9	0.34
Deep A	0.71	24.23	11.19	16.51	0.92	0.11
Total	2.3	72.96	31.64	46.44	2.28	0.45

(Note) Shallow A: potential land subsidence amount in the shallow aquifer.
Deep A: potential land subsidence amount in the deep aquifer.
S: Scenario
Total: Sum of potential land subsidence amount of both shallow and deep aquifers

6. Conclusion

The purposes for the study are to evaluate groundwater use at present and in the future and to assess the influence to world heritage-Angkor Wat ruins by pumping of much groundwater due to rapid increase of tourists and tourist facilities such as hotels and restaurants in recent years in the Siem Reap City, and to review the reinforcement of groundwater monitoring system.

Evaluation of Groundwater use at Present and in the Future

In Siem Reap City area, current status of groundwater use of large establishments was surveyed by well inventory survey. As a result, the survey revealed that there were 280 establishments of tourist facilities such as hotels and public facilities including schools and factories in the city area and they withdraw of a groundwater bout 5,786 m^3/day in the dry season. In addition, SRWSA pumps up of a groundwater bout 9,000 m^3/day for water supply and ordinary houses use of groundwater about 24,000m^3/day by shallow wells. Thus, it is estimated that groundwater of 38,000 m^3/day is presently at least extracted in the city area.

On the other hand, a part of world heritage ruins are located near the city center area and many tourist facilities such as hotels are also concentrated in the area. If in the future, a large number of tourist facilities are continuously constructed in the city center area and withdrawal volume of groundwater increases, it is supposed that groundwater level (hydraulic head) in the area is lowered and land subsidence by consolidation may be caused and they may have an impact to world heritage.

To identify this phenomenon, monitoring data of groundwater level of existing observation wells were analyzed. As a result, in monitoring data, small fluctuation of groundwater level influenced by pumping wells near monitoring wells was identified but constant and large drawdown of groundwater level was not observed. In addition, lowering of groundwater level by pumping of SRWSA production wells in WT-4 monitoring well was not observed.

WT-4 well is located along National Road No.6 and apart about 2.6 km from SRWSA wells. As a result, the influence of groundwater withdrawal was not identified under existing conditions. To review the influence to world heritage in future water demand, groundwater simulation was conducted. In this simulation, the following 6 scenarios to deal with future water demand (86,000 m^3/day) or water supply planning year 2030 were prepared and reviewed.

Table 12 Future water demand simulated by 6 scenarios

Scenario	Scenario Condition
Scenario 2	To continue groundwater use by the present amount.
Scenario 3	To use groundwater as the only source for water supply.
Scenario 4	To use irrigation canal water from West Baray reservoir for water supply and diminish a part of groundwater develop ment volume (Withdrawal volume including SRWSA production wells: 52,000 m^3/day – 69,000 m^3/day).
Scenario 5	
Scenario 6	To lessen the impact to Bakong ruins, new production wells are not planned in eastern bank area of the Siem Reap River.
Scenario 7	As water sources for water supply, pumping by existing wells excluding SRWSA production wells are halted. Only lake water of Tonle Sap is used.

(Note) Scenario 1 is natural condition without groundwater use and a case for comparison for other scenario and for calculation. Thus, it was omitted.

The report has briefly elaborated the importance of groundwater monitoring. Integrated monitoring networks, which include meteorology, surface water, and groundwater integrated databases, should be introduced as one of the strategies for better and sustainable long term water resources planning and management.

Referrences

1. Geographic map of Cambodia.
2. Atlas of Mineral Resources of the ESCAP Region, volume 10.
3. A Report on a Program of Groundwater Investigations for Cambodia by R. V. USHMAN, U. S. Geological Survey, June 1958.
4. Groundwater Resources of Cambodia by W. C. RASMUSSEN and G. M.BRANDFORD, Geological Survey Water-Supply paper 1608-P, Government of Cambodia under the auspices of the United States Agency for International Development, USGS-1977.
5. Final Report of: The Study on Groundwater Development in Southern Cambodia by JICA with the Ministry of Rural Development of the Kingdom of Cambodia, January 2002.

Investigation and Monitoring of Land Subsidence in Yangtze River Delta Area of China

Li Tiefeng[1] and Shi Yujin[2]

1, China Geological Survey, Beijing 100037 P.R.China;

2, Shanghai Institute of Geological Survey, Shanghai 200072 P.R.China

Abstract: Land subsidence is one of the main geological disasters in China, which makes great effect on city planning, flooding prevention, and municipal infrastructure. This paper is intended to present a brief review on the current situation of land subsidence and its investigation， monitoring and remedial works made in Yangtze River Delta area. Investigation has shown that land subsidence has been caused primarily by extensive pumping of groundwater. With the restriction of groundwater mining, prevention and cure of land subsidence has been acquired a favorable effect since 1960s. However, with the developing of massive construction and increasing of shallow groundwater mining during excavation, land subsidence had presented some new peculiarities in recent years. In order to strengthen the work in guarding against land subsidence, China government adopted various integrative methods about groundwater resources utilization, city planning, engineering measures and municipal infrastructure, and also established multi-provinces land subsidence management information system. A control for land subsidence control gets primary effect, which provides a safeguard for the sustaining development of the city.

Key Words: land subsidence, present situation, groundwater, monitoring network, cause, prevention

1. **Introduction**

In China, land subsidence is mainly distributed in the coastal cities. In Yangtze River Delta area, Shanghai was one city which of land subsidence the first discovered in the 1920s and impaction was most prominent. Land subsidence has long-term and variously impact on the development of city. From the 1970s, land subsidence also occurred in major cities along the Yangtze River Delta Plain such as Suzhou, Wuxi, Hangzhou, and Huzhou. Since the 1980s, the range of land affected by subsidence extended from cities to rural areas, accompanied with ground fissures, which showed that the disaster of land subsidence had become more serious.

At present, the land subsidence area of the Yangtze River Delta Plain where the cumulative amount of subsidence exceeds 200mm is approximately 10,000km^2, where, in the subsidence centers such as the downtown of Shanghai and Wuxi of Jiangsu Province, the maximum cumulative amount of subsidence exceeds 2,500mm. Ground fissures have occurred in this area due to differential subsidence.

China government has paid much attention to the prevention and control of land subsidence. In recent years, investigation, monitoring and prevention on land subsidence have achieved great progress. As a result of these efforts, the control of land subsidence has achieved initial success. However, the gradual worsening of land subsidence has not been effectively controlled. There are still severe problems to be solved and hard prevention tasks to be accomplished.

2. Present Situation and Cause of Land Subsidence

2.1 Present Situation of Land Subsidence in Yangtze River Delta Area

1.1.1 Present Situation of Land Subsidence in Shanghai City

Through repetitive leveling survey, the landmark which lies to Shanghai Ningbo road has reflected the land subsidence at that time between 1910 and 1919, the change in height is 3.9mm. But from 1921 to 1948, land subsidence is more visible than before. The character of land subsidence can be divided into two historical periods and nine different phases (Table.1).

Table.1 Characters and phase of land subsidence in Shanghai

period	phase	Annual setting velocity(mm/a)		Cumulative setting velocity (mm/a)	
		average	maximum	average	maximum
Developing period of land subsidence (1921～1965)	Original(1921-1948)	22.8	42.0	639	1,136
	Accelerative(1949-1956)	40.3	96.0	322	671
	Serious(1957-1961)	98.6	287.0	493	1,149
	Demulcent(1962-1965)	59.3	164.0	237	493
Controlling period of land subsidence (1966-now)	Recoil in minute quantity(1966-1971)	+3.0	+17.0	+18	+53
	Dram setting (1972-1989)	3.5	+3.9	62	
	Increscent(1990-2001)	15.6		172	
	Demulcent(2002-2005)	9.7		39	
	Dram setting (2006-now)	6.1		36	

(+ stand for recoiling of land subsidence)

In the past 10 years, between 2002 and 2006, land subsidence in the whole city of Shanghai was controlled to a certain extent. Land subsidence in the city area was basically controlled and the average sinking rate for the city area was 12.7mm/a. Then between 2006 and 2010, the cumulative subsidence amount of most areas, except some local areas where there were subsidence cones, was relatively small, between 0 and 25mm.

However, land subsidence in Shanghai presents asymmetric features. Statistical data present the index of land subsidence in every district at different periods. Take standard deviation as an example, the more the standard deviated, the more the data dispersed. The data of subsidence separated from each other seriously, what indicated the difference for sedimentation. The standard deviation of maximum cumulative sedimentation is 20.4mm from 1986 to 1990, which is 49.9mm from 1991 to 1995, and which is 64.3mm from 1996 to 2000, those indicated that maximum sedimentation separated from each other seriously in every district as the time pass by. The minimum and average sedimentation deviation increased more along with the time going. From 1996 to 2000, the maximum of falling velocity in space reach to 112mm/km.

1.1.2 Present Situation of Land Subsidence in Suzhou, Wuxi and Changzhou City

On August 26, 2000, the Decision to Prohibit Extraction of Groundwater in Suzhou, Wuxi and Changzhou was reviewed and accepted at the 18th meeting of the 9th NPC Standing Committee of Jiangsu. It regulated that the prohibition on groundwater extraction should be fully achieved within 5 years. Within the 10 following years, the regional geological environment changed a lot. Due to the prohibition on groundwater extraction, the conditions of land subsidence in Suzhou, Wuxi and Changzhou improved significantly and the situation of the whole area was relieved to various degrees.

1.1.3 Present Situation of Land Subsidence in Hangzhou, Jiaxing and Huzhou City

Since 2006, with the promotion of the prohibition and restraint of groundwater mining, the rate of land subsidence was reduced to a certain extent and thus the advancement of subsidence was effectively contained. By 2010, areas of subsiding rate larger than 30mm/a had disappeared. Those areas of subsiding rate larger than 10mm/a were 195km2, reduced by 92% as compared with 2005. Also, the land slightly rose in many areas.

2.2 Analysis on Causes of Land Subsidence

Groundwater mining remains the primary factor of land subsidence. The exploitation and utilization of groundwater cause the decreasing of groundwater levels and the deformation of soil layer, which finally lead to land subsidence (Fig.1). Before the 1960s, the exploitation of groundwater in Shanghai was mainly conducted in superficial artesian aquifers. After the alteration of exploitation layers, the deep artesian aquifers became main exploitation layers. In other place of Yangtze River Delta area, the frequently exploited part is the deep artesian water. To control land subsidence, Shanghai municipality had restricted the mining since 1964. The total mining has compressed, at the same time, mining place convert from midtown to suburb, mining layers transferred from shallow aquifers to deep aquifers.

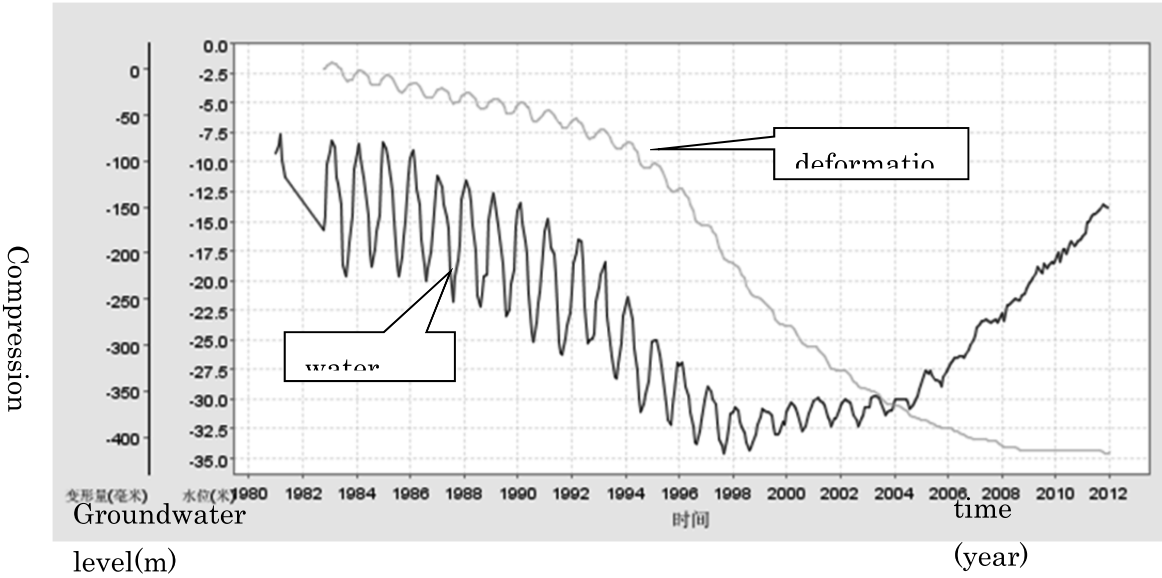


Fig.1 Historical water level and deformation of the confined aquifers system

Massive construction and increasing architectural loading have been the new factors which influence land subsidence in downtown area. An impressive increasing about loading on urban architectural has impact on land subsidence, what has been noticed in 1970s and sedimentation effect partly high buildings which has been inspected in a short-term. In Shanghai, through three year's inspecting around some typical high buildings, the volume of sedimentation respectively up to 101.5mm, 65.0mm and 60.6mm, the average of subsidence is 45.8mm, which is 1.3 to 2.2 times higher than background value, what reflects that load on architecture made great effect on the value of sedimentation. In addition, increasing of foundation ditch, well point method made the scare consolidated soil present the compressed and rheological behavior.

2.3 Land Subsidence Investigation and Monitoring

The Yangtze River Delta was the first area in which land subsidence investigation, monitoring and research was conducted. As of today, the dynamic monitoring network for groundwater has already covered the whole area of the Yangtze River Delta. A 3D monitoring system has been formed in key cities including precise surface level monitoring network, many underground bedrock bench marks, and borehole extensometers. Since the 1990s, with the development of new technologies and methods, GPS, automatic monitoring, InSAR and information technology have been used in the monitoring of the land subsidence in this area. Through ten years of monitoring, the time and space variation law of the whole area has been mastered, and by that, a lot of data has been collected for the research and control of land subsidence.

3.1 Groundwater Monitoring Network

The groundwater monitoring network of the Yangtze River Delta covers shallow aquifers and deep artesian aquifers. As for space distribution, the network is concentrated on the south area of the Yangtze River and scattered in the north area. Until 2010, there had been 625 groundwater monitoring wells and 285 groundwater quality monitoring wells. Manual and automatic methods were combined to perform the groundwater monitoring. There had been a total number of 72 automatic monitoring points by 2010.

3.2 Local Land Subsidence Monitoring Network

The land subsidence monitoring network is mainly composed of GPS monitoring points, underground bedrock bench marks and borehole extensometers (groups). The distribution of Grade I and II GPS monitoring points is balanced, but in the south area of the Yangtze River, Grade II points are more concentrated. The distribution of the bedrock bench marks and borehole extensometers in Shanghai, Wuxi and Changzhou is concentrated, and in other areas, distributed. By 2010, there were 72 bedrock bench marks, 83 borehole extensometers, 8 ground fissure monitoring points, 554 Grade I and II GPS monitoring points, 12 permanent tracking stations and 72 automatic monitoring points (including monitoring stations).

Through the InSAR land subsidence monitoring since 2007 in the Yangtze River Delta, the land subsidence information of about 66.9 thousand km2 has been obtained, including about 44.8 thousand km2 of fluvial plains (accounting for 94.36% of the actual area) and central Jiangsu (north of Yangtze River) and coastal areas where there are not enough investigation on land subsidence.

3.3 Engineering Land Subsidence Monitoring Network in Urban Areas

To obtain the information of the land subsidence along railways and overhead roads and provide it for the prevention of engineering land subsidence, Shanghai deployed facilities like leveling nodes, borehole extensometers and bedrock bench marks in different geological formation areas along project lines. In key engineering areas during the 11th Five Year Plan, a land subsidence backbone network was formed, which is independent but still tightly associated with the leveling network of the central city.

4. Prevention and Control of Land Subsidence

China government has paid much attention to the prevention and control of the land subsidence in coastal cities. In recent years, important accomplishments have been achieved in land subsidence investigation, monitoring and groundwater control. The prevention has begun to take effect.

A coordination system for local land subsidence prevention has been basically established. In May 2004, Shanghai, Jiangsu and Zhejiang jointly established a joint conference system for local cooperation in land subsidence areas of the Yangtze River, by which the overall coordination for land subsidence monitoring in the Yangtze River Delta was achieved. This laid a good foundation for the monitoring network construction and comprehensive prevention of land subsidence across the areas.

Significant results have been gained in groundwater exploitation control and over-exploitation governance. To solve the problems caused by the over-exploitation of groundwater and the land subsidence thereby, provinces (districts and cities involved) focused on the exploitation control and over-exploitation governance, strengthened the management of groundwater resources, controlled the overall amount of groundwater exploitation, set the groundwater over-exploitation areas, regulated the range of exploitation prohibition and limitation, and implemented prohibition and limitation of groundwater extraction. The exploitation amount of groundwater in Shanghai was decreased from 94.59 million km^3 in 2000 to 30 million km^3 in 2009. As a result of Jiangsu's NPC issued the *Decision to Prohibit Exploitation of Groundwater in a Limited Period in Suzhou, Wuxi and Changzhou*, the exploitation of groundwater was generally prohibited in these three cities. In Hangzhou, Jiaxing and Huzhou of Zhejiang as well as the coastal plains, efforts to prohibit and limit groundwater exploitation were also carried out.

Significant results have been gained from the comprehensive prevention of land subsidence. By the exploitation limitation and artificial recharge to groundwater, Shanghai has controlled the yearly subsidence to below 10mm/a. After the 2000's groundwater exploitation prohibition, in Suzhou, Wuxi and Changzhou of Jiangsu, the land subsidence in downtowns has been controlled. The decreasing amplitude exceeds 20mm, compared with the figures before the prohibition. After the prohibition, in Hangzhou, Jiaxing and Huzhou of Zhejiang, the yearly land subsidence in some downtown area has been decreased to 10mm.

5. Land Subsidence Information Management System

China adapted GIS into its land subsidence research later than others, but it developed fast. Land subsidence workers have made many effective efforts in exploration. For example, in Suzhou, Wuxi and Changzhou, a land subsidence management information system based on the ArcGIS platform was established, relevant data of basic geology, hydrogeology and environmental geology have been sorted, summarized and summed up. A multi-source geological information spatial database has been built, and a 3D visual model of bedrock structure, Quaternary deposits and underground aquifer systems have been set up by using ArcGIS platform and GMS. Based on that, scientific forecasting and management for the land subsidence have been developed through the use of the ArcGIS system. Many statistic methods are also used to forecast the land subsidence. The spatial analysis method and the Analsis Hierarchy Process (AHP) method have been used to build the warning and evaluation system, sub-system of land subsidence database and sub-system of the land subsidence model method.

Shanghai established databases of basic geology, hydrogeology and engineering geological structure and spatial data, as well as the geological environment monitoring and land subsidence remedial database.

7,588 pieces of geological data, including 438 thousand drills, 123 thousand geological drill databases, 500 geological drawings and 1,500 thousand pieces of land subsidence monitoring data have been achieved. The overall data amount has reached 800G. Through deep studying using 3D geological models, 3D geological models of different specialties and details have been established. With these models, the analysis and evaluation of land subsidence can be conducted in a more comprehensive and deep way, and so the level of forecasting and scientific management of land subsidence in Shanghai has been improved.

The establishment of Shanghai's geological information platform has helped the deep analysis and comprehensive research on the past land subsidence data and research results and can also help the adjustment of the exploitation layout of groundwater and the research and control of the development of land subsidence. In this way, they may promote the positive development of geological environment, which can be used to make auxiliary decisions and used for reference of urban construction and development planning. In addition, by fast query and search methods, data collecting and sorting can be done for the future researches on land subsidence and other subjects, so as to reduce the working load of researches, shorten the period of research and save on costs. Meanwhile, when the system is successfully established, the current data and results may be fully used to provide consulting services for the society.

Conclusion

The land subsidence in Yangtze River Delta area has experienced several phrases since 1960, and now land subsidence value gradually comes down. However, land subsidence presents asymmetric features, and the influenced factors vary in a different period. In recent years, massive construction, especially groundwater pumping during excavation construction, has been the new factor inducing the land subsidence. The uneven land subsidence has a big impact on municipal infrastructure, such as subway, flood prevention wall, highway road, underground pipeline, and so on. China government has carried out a series of measures to prevent and cure land subsidence, and get highly effective achievement. But land subsidence is very complicated in mechanics, monitoring and control, we still need to look for the new method and technique to deeply study land subsidence, and provide the suggestions on the municipal safety.

References:

Zhang, Agen, Wei Zinxin, et al. (2005): Land subsidence in China. Shanghai Scientific and Technical Publishers. (in Chinese)

Wei Zixin (2005): Stress-strain characteristics of the confined aquifer system and land subsidence controlling countermeasures in Shanghai. The Chinese Journal of Geological Hazard and Control. no.1

Zhu Xing-Xian and Zhu Jin-Qi (1997): Subsidence hazard in Suzhou-Wuxi-Changzhou area and economic analysis of its damnification expense. Hydrogeology and Engineering Geology. 24(3) .

Gong Shi-Liang (1999): The environmental geological problems and its effects to flood control engineering in the middle and lower reaches of the Yangtze River. The Chinese Journal of Geological Hazard and Control.

Hou Yan-sheng, Zheng Xian-Xin, and Ying Yu-Fei (2000): Sustainable development strategy and systematic control on land subsidence in coastal regions of China. Chinese Journal of Geological Hazard and Control (in Chinese), 11(2).

Zhang Wei-Ran, Duan Zheng-Liang, Zeng Zheng-Qiang (2003): Methods to control or arrest land subsidence and their economic benefit in Shanghai. Journal of Tongji University.

Ye Weimin, Zhu Hehua and Tang Yiqun (1999): Foundation pits and geological environmental problems related to excavation in soft clay. Sino-Japan Geotechnical Development, Hongkong.

Wei Zixin (2002): The analysis of stress-strain about 4th confined aquifer in Shanghai.

Wei Zixin and Zeng Zhengqiang (2003): Shanghai flooding and water-logging hazards caused by land subsidence factor and its long-term impact.

Zhang Agen and Wei Zixin (2002): Past, present and future research on land subsidence in Shanghai City. Hydrogeology and Engineering Geology.

Saltwater Intrusion Issues for Groundwater in the Jakarta Plain

Haryadi Tirtomihardjo
Center of Groundwater Resource and Environmental Geology,
Geological Agency, Ministry of Energy and Mineral Resources

Abstract: Since the last three decades, intensive groundwater abstraction due to an explosive economic and population growth in Jakarta area had led to negative impacts, particularly on degradation of groundwater conditions, both quantity and quality. Degradation of groundwater quantity as shown by lowering of groundwater heads as affected by large quantity of water pumped from deep aquifer system is the main cause of the contamination problems, mainly due to increasing of groundwater salinity at the aquifer system that may related to saltwater intrusion phenomenon. Laboratory analysis of groundwater samples taken in December 2011 at 18 wells represented for shallow aquifer system and 8 wells represented for deep aquifer system. Hydrochemical analysis results showed that saltwater intrusion for free groundwater might occur at some places in North Jakarta area (Ancol, Penjaringan, and Cilincing) and West Jakarta area (Kapuk-Cengkareng). Meanwhile, saltwater intrusion for artesian groundwater might occur at some places in North Jakarta area (Pademangan and Penjaringan) and West Jakarta area (Kapuk and surrounding). In future, comprehensive research is urgently required which is comprising of set-up monitoring system for monitoring fresh-saline interface movements (monitoring well density, frequences of monitoring, components, and tools), and also applying transport model for saltwater intrusion in order to decide strategies for controlling saltwater intrusion.

Keywords: Groundwater abstraction, groundwater quantity, groundwater quality, shallow aquifer system, deep aquifer system, saltwater intrusion

1. Introduction

Jakarta Plain is a part of groundwater basin which is so called Jakarta Groundwater Basin. The basin is trans-provincial boundary basin covering Jakarta Metropolitan Province, West Java Province, and Banten Province. Geographically, the basin covers all areas of Jakarta Metropolitan Province; part of Bekasi Regency/City, Depok City, and Bogor Regency/City (West Java Province); part of Tangerang Regency/City and South Tangerang City (Banten Province). The lateral extend of the Jakarta GB is about 1,439 km^2 (Fig.1)

Jakarta, the capital of the Republic of Indonesia, is one of the economic and industrial development centres in Indonesia. Inhabitant of the Jakarta Metropolitan Province tends to increase since 1950 and reaching 11.5 million peoples in the year of 2010 (Fig.2). The population density is about 14,469 peoples/Km^2, and population growth is about 1.4%/year during 2000-2010 (Haryadi *et al.* , 2012).

The tropical monsoon climate of the region is characterized by a rainy season extending from October to May, with a maximum monthly rainfall occurs in January and February of about 300 mm, and a relatively dry season between June and September with a minimum monthly rainfall occurs in August of lower than 50 mm. The mean annual rainfall is in the order of 1,750 mm.

Fig.1. Location map of Jakarta Groundwater Basin.

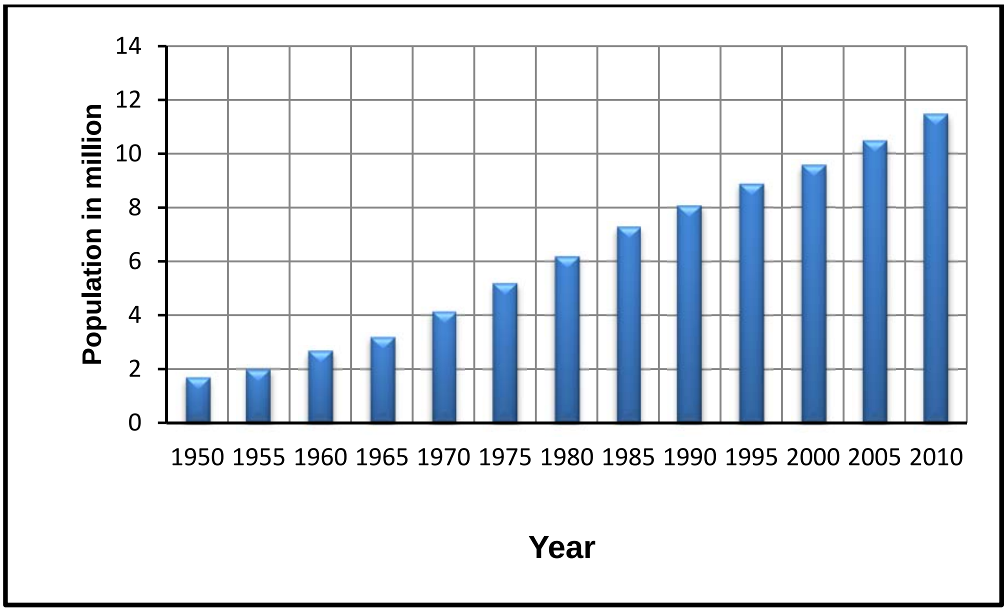


Fig.2. Population growth in Jakarta Metropolitan area.

In the mid 1990s the capacity of the water treatment plants was about 12.5 m^3/s and the actual production in the order of 11 m^3/s (394 MCM/a and 347 MCM/a) respectively. Losses in the pipeline distribution system varied between 24% and 40%. It is estimated that the pipeline distribution system serves only 25% to 30% of the population and 45% of the industry and commercial needs. Therefore, there is a heavy demand for groundwater as a source of water supply. Industry and commerce mainly derive their water from deep wells. Recorded abstraction from registered deep wells was about 1 m^3/s (31.5 MCM) in 1994, but actual withdrawals are estimated to be in the range 2 to 4 m^3/s (63 to 126 MCM/a) (Maathuis *et al*., 2000).

As shown in Fig. 3, the development of intensive groundwater abstraction in Jakarta area had been occurred since 1968 where the volume of groundwater of about 10.3 million m^3 (MCM) were abstracted from productive aquifer by 325 registered production wells, and the maximum abstraction of about 33.8 MCM occurred in 1994 which were abstracted by 3018 registered production wells. Significant drop of groundwater abstraction occurred during the period of 1997 (22.6 MCM) and 1999 (16.4 MCM) due to economic crisis. The period after, groundwater abstraction tends to increase yearly up to 23.6 MCM in 2008. During the last three years, groundwater abstraction tends to be decreasing with the lowest abstracted volume of about 7.5 MCM in 2011 (Haryadi and Taat Setiawan, 2012).

Like other groundwater dependent areas, Jakarta area is already affected by groundwater related problems mainly related to over-pumping and pollution of aquifers. More specifically, four major problems i.e. lowering of groundwater level, saltwater intrusion, land subsidence, and groundwater pollution, were identified that required immediate attention.

This paper intends to discuss briefly the general hydrogeological setting, change of groundwater level, distribution of groundwater salinity, origin of brackish-saline groundwater, and (proposed) activity plan related to saltwater intrusion in Jakarta Plain as a concluding remarks.

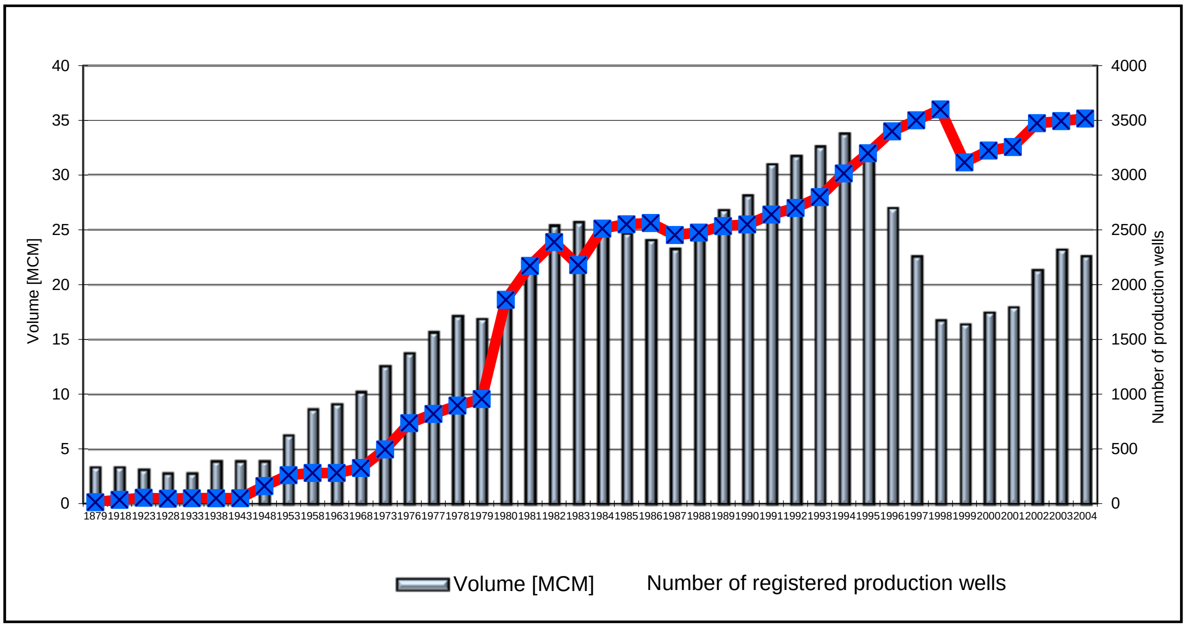


Fig.3 Volume of groundwater abstraction and the number of production wells in Jakarta area (1879-2004). Source: Haryadi and Taat Setiawan (2012)

2. Hydrogeology

The areal distribution of the lithological units of the Jakarta basin and their hydrogeological significance regarding their relative hydraulic conductivity and groundwater productivity, as well as the extent of the zone under artesian pressure and zone of heavy groundwater exploitation in the early 1980s are shown on the Hydrogeological Map of Indonesia, scale 1:250,000, Jakarta Quadrangle (DEG 1986).

In terms of hydrogeological units, the aquitard formed by the Holocene deposits and the aquifer formed by the Upper Pleistocene Volcanic Fan deposits are perhaps the only units which can be identified with some measure of confidence. It is not possible to identify individual aquifer and aquitard units within the underlying sequence of marine and non-marine Quaternary sediments. Consequently, this sequence forms an undifferentiated, very complex aquifer-aquitard system. Despite the fact that a classical differentiation between aquifers and aquitards is not possible, for practical reasons, it has become standard practice to subdivide the Quaternary sequence into hydrogeological horizons. The hydrogeological horizons that commonly used are 0-40, 40-140, and 140-250 m below ground level as shown in Fig. 4 (Soekardi, 1987).

The bottom of the aquifer-aquitard system is formed by Miocene sediments which crop out at its southern boundary. The basin fill consists of Quartenary sediments up to 300 m in thickness. The thickness of the individual mainly fine-sandy aquifer layers intercalated within a predominantly silty to clayey sequence ranges from only 1 to 5 m, totalling only some 20% of the entire sequence. The transmissivity of the entire Quaternary sequence of 250 m thickness is thought to decrease northward from 500 m2/day near the hinge line to 250 m^2/day near the coast. Based on modelling, JWRMS (1994) suggested that the transmissivity might be less than this by a factor of 2. The mean transmissivity of the Pliocene sequence cropping out in the western part of the model area is lower than that of the Quaternary sequence. The horizontal hydraulic conductivity (KH) has a mean value of 1.3 m/day (1.5×10^{-5} m/s) ranging from 0.4 to 2.1 m/day (5×10^{-6} to 2.5×10^{-5} m/s). The vertical hydraulic conductivity (KV) has a mean value of 2×10^{-4} m/day (2×10^{-9} m/s). Thus, the an-isotropy factor (KH/KV ratio) is in the order of 5000 for large parts of the aquifer system near the coast. The KH/KV ratio may amount to 500 or 100 in the uppermost part of the aquifer or in the southern part of the model area, respectively. The storativity of the deep aquifer system is between 10^{-4} and 10^{-6}, typical for a confined aquifer (Soefner *et al.* 1986, Schmidt & Soehner, 1988).

Under natural flow conditions, the recharge area of the deep aquifer system was situated in the southern hilly area at altitudes of between 25 to 200 masl. Discharge from the confined aquifer system to the natural base level of the flat coastal area occurred predominantly by upward leakage, evapotranspiration and outflow into the surface water system. During the last few decades, recharge into the deep aquifer system, apart from horizontal inflow, may originate from downward leakage throughout the city, as piezometric heads of the confined system dropped regionally below that of the water table of the unconfined shallow aquifer. The shallow aquifer was fully replenished during normal rainfall years at least until 1985. Discharge from the deep aquifer system in 1985 was almost exclusively maintained by groundwater abstraction by deep wells. The 1985 groundwater abstraction of 47 MCM/a from the deep aquifer system was not counterbalanced by the horizontal inflow across the hinge line of an estimated volume of 15 MCM/a and by vertical leakage from the shallow aquifer. In response to over-exploitation, water levels in the confined deep aquifer system declined by 1 to 7 m/a from 1983 to 1985 and were at -20 to -30 m asl during that period of time (Soefner *et al*., 1986, Djaeni *et al.*, 1986).

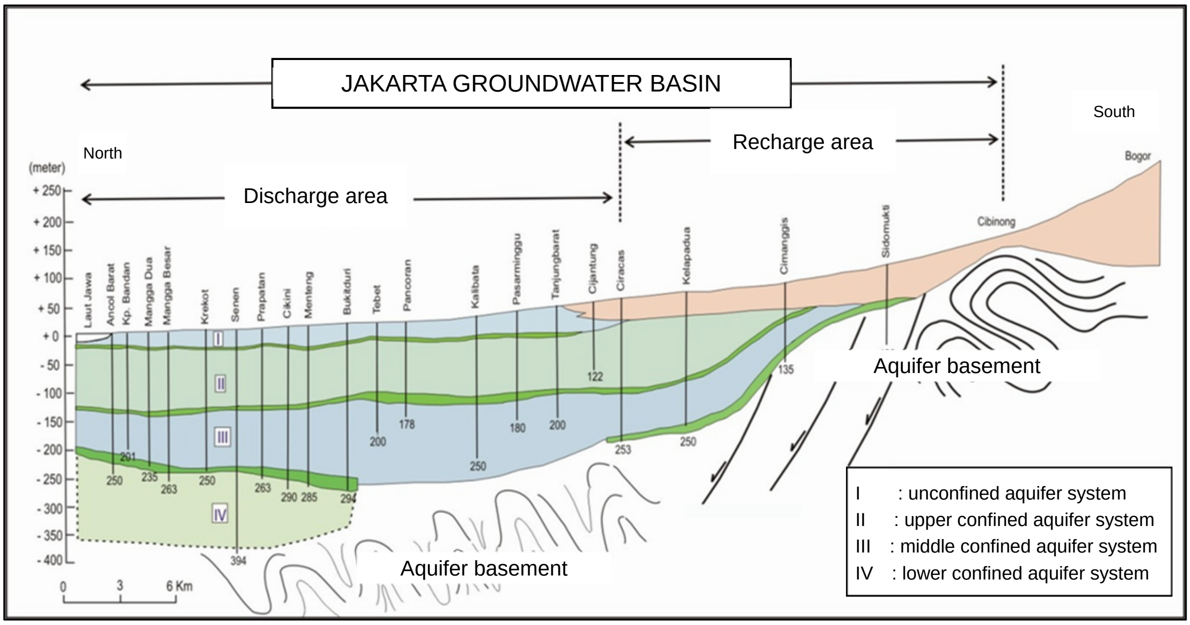


Fig. 4. Hydrogeological section of Jakarta Groundwater Basin.

3 Change of groundwater levels

According to Soetrisno, *et al.* (1997), the piezometric level in North Jakarta has changed from 12.5 m above sea level in 1910 to about sea level in 1970, and then deepened significantly to 30-50 m below sea level in 1990.

Arismunandar, *et al.* (2009) has been measured the groundwater depletion during the period of 2005-2009 as follows:

- Groundwater depletion of unconfined aquifer (depth < 40 mbls) in the Central Jakarta has an average value of 3.44 m.
- Groundwater depletion of upper confined aquifer (depth of 40-140 mbls) in the North Jakarta was in order of 0.15 and 1.11 m.
- Groundwater depletion of middle to lower confined aquifer (depth of > 140 mbls) which occured in the North Jakarta was in order of 0.11 and 2.12 m, in the Central Jakarta was in between 0.21 and 1.11 m, in the East Jakarta was in between 0.01 and 1.80 m, and in the South Jakarta was in between 0.95 and 1.87 m. Increasing of piezometric heads was recorded in order of 0.43 and 1.19 m occured in the West Jakarta.

Spacial distributions of groundwater level both for shallow and deep aquifer systems drawn by using measured groundwater level data during the period of December 2011 are shown in Fig. 5 and Fig. 6 (Taat Setiawan, *et al.*, 2011). It is obviously that cone of groundwater depression of shallow aquifer system occured in the northeast of Jakarta Plain (Cilincing and Kelapagading, 3 mbsl), while of the deep aquifer system occured in the northwest of the plain area (Penjaringan, 53 mbsl) and east of the plain area (Cakung, 40 mbsl).

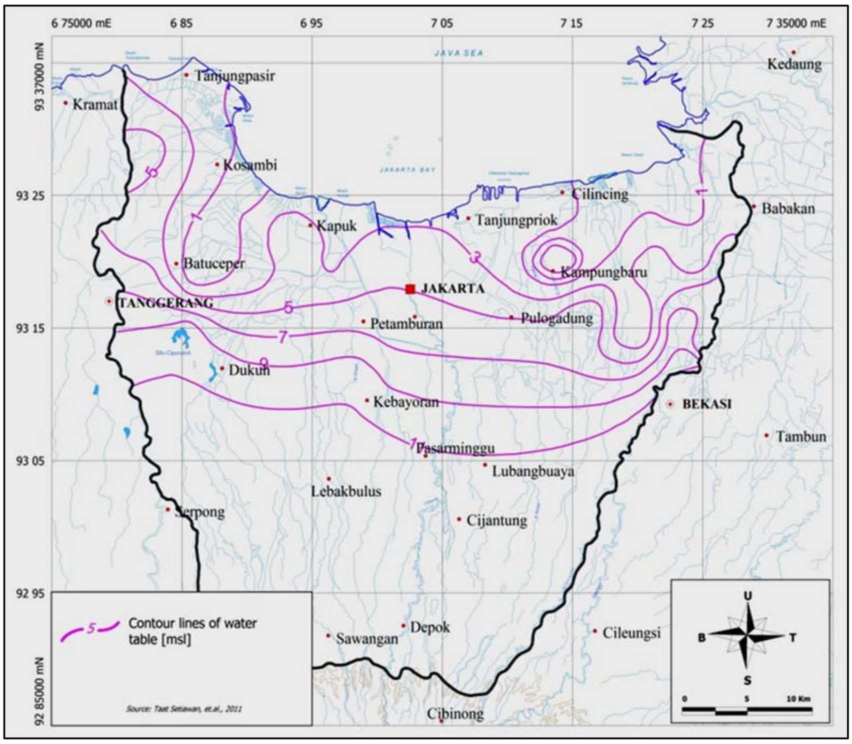


Fig. 5 A map of groundwater level of shallow aquifer system (water table)

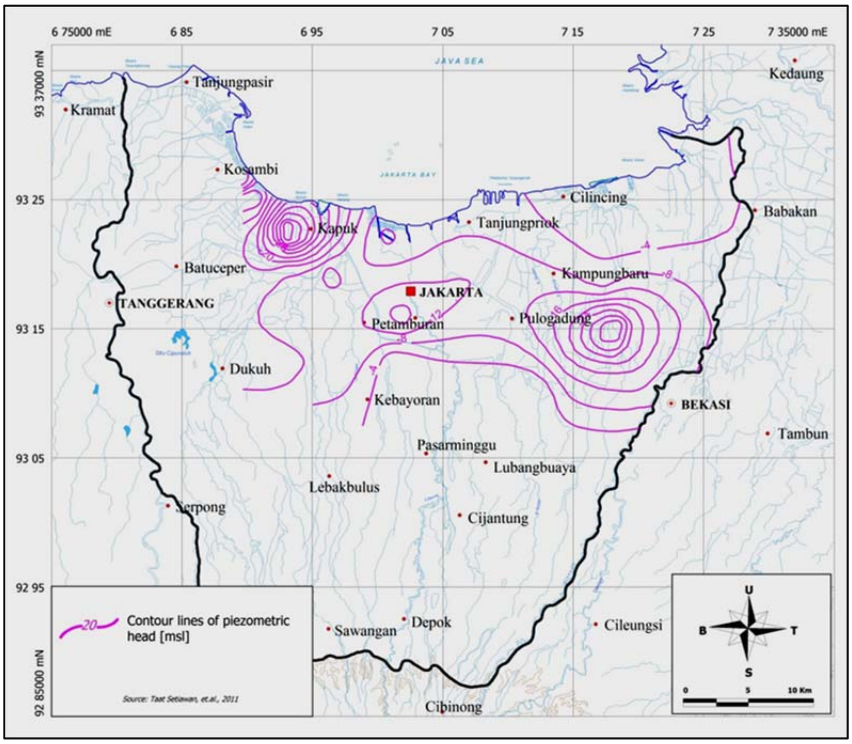


Fig. 6 A map of groundwater level of deep aquifer system (piezometric heads)

4. Distribution of groundwater salinity

Up till around 1970, a considerable volume of groundwater discharged into the Java Sea since the hydraulic gradient was predominantly directed towards the coast. After 1970, when major groundwater development commenced in Jakarta city, the hydraulic gradient reversed and consequently sea water started to slightly intrude into the aquifer system. The volume of intruding seawater was in the order of 2 MCM per year in the mid 1980s (Schmidt & Soefner, 1988).

The salinity of shallow groundwater gradually increases from below 500 µS/cm in the south up to 2,500 µS/cm in the north in the general direction of groundwater flow. In the coastal zone, the salinity of groundwater may rise up to 10,000 µS/cm. The Ca-Na-HCO_3 water type prevails, gradually changing to the Na-Cl water type with increasing salinity.

Within the confined aquifer system, three zones of deep groundwater quality may be distinguished:

1. low groundwater salinity (EC < 500 µS/cm) and predominance of bicarbonate in the south,
2. intermediate groundwater salinity (EC: 500-1,500 µS/cm) and Na-HCO_3 water type within a small zone between latitude 93.15 an 93.20 in central Jakarta,
3. highly variable groundwater salinity in the coastal zone:

brackish groundwater with chloride predominance at depths above -100 m asl,
relatively fresh groundwater with EC ranging from 500-1,500 µS/cm and Na-HCO_3 water type at depths of between -100 to -200 masl, groundwater with increasing salinity (EC>1,500 µS/cm) at depths below -200 masl.

Taat Setiawan, *et al.*, (2011) had been delineated the distribution of groundwater salinity both for free groundwater (at shallow aquifer system, depth 0-40 mbls) and artesian groundwater (at deep aquifer system, depth 40-140 mbls) based on electrical conductivity (EC) of the water, total dissolved solids (TDS) and chloride content (Cl^-) within the water.

Based on EC of the water and TDS content of free groundwater as shown in Fig. 7, the Jakarta Plain can be devided into three zones, i.e. zone of fresh water (EC<1,500 μS/cm, TDS<1,000 ppm), slightly brackish water (EC=1,500-5,000 μS/cm, TDS=1,000-3,000 ppm), and brackish water (EC=5,000-15,000 μS/Cm, TDS=3,000-10,000 ppm). Meanwhile, two zones are identified according to the chloride content within the water, that are zone of fresh water (Cl^- <500 ppm) and zone of slightly brackish water (Cl^- =500-2,000 ppm). Based on that three parameters, it can be defined three zones in the Jakarta Plain. The first is an extensive, zone of fresh water (EC<1,500 μS/cm, TDS<1,000 ppm, Cl^- <500 ppm) which is mainly covering the northern part of Jakarta Plain. The second is extensive, zone of slightly brackish water (EC=1,500-5,000 μS/cm, TDS=1,000-3,000 ppm, Cl^- =500-2,000 ppm) covering the northern part of Jakarta Plain and has the maximum distance attains 12 km from coastline in East Jakarta area. The third is locally, brackish water (EC=5,000-15,000 μS/cm, TDS=3,000-10,000 ppm, Cl^- =2,000-5,000 ppm) which is located in area of east Cilincing (North Jakarta) and area of east Kampung Baru (East Jakarta area).

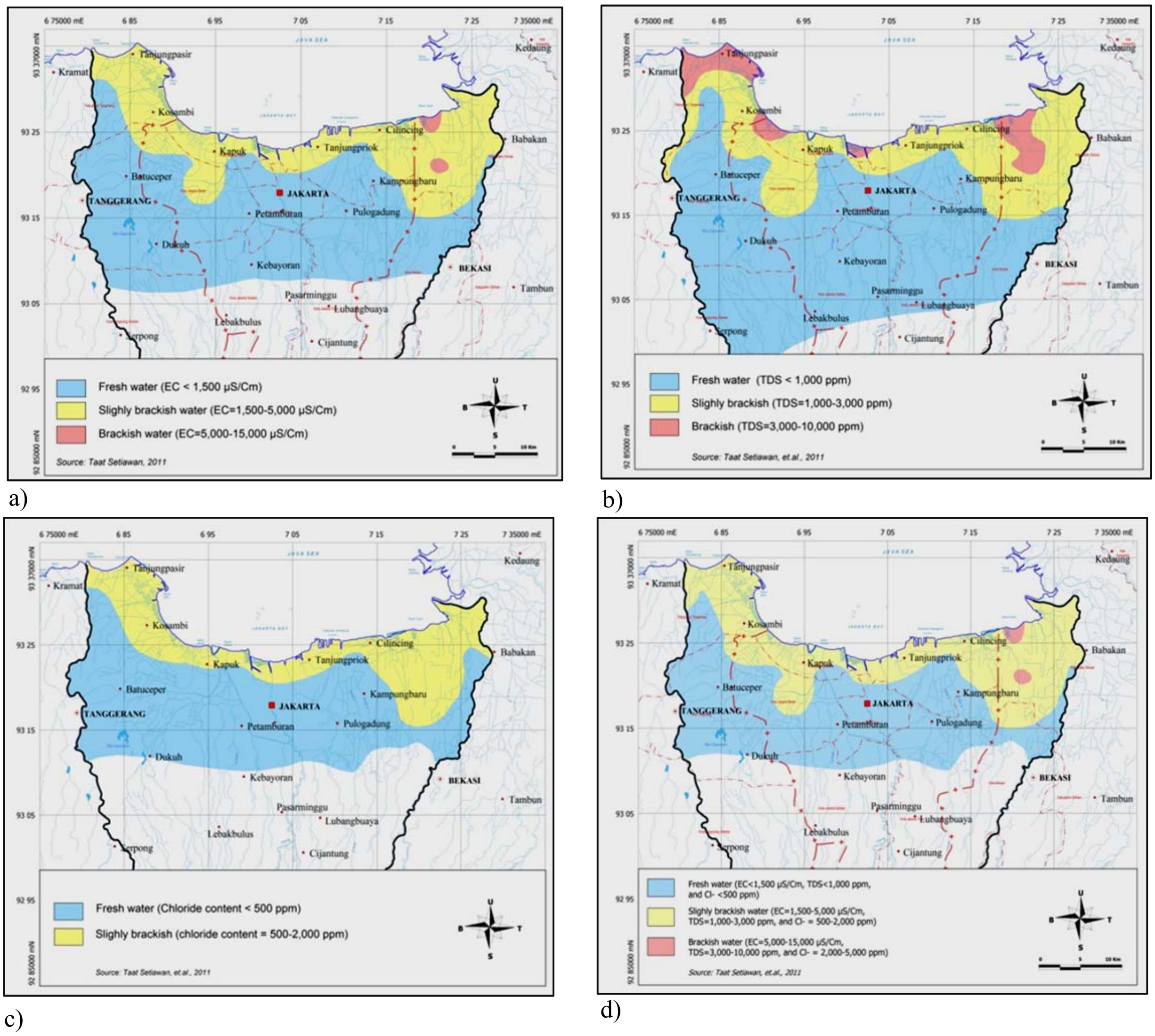
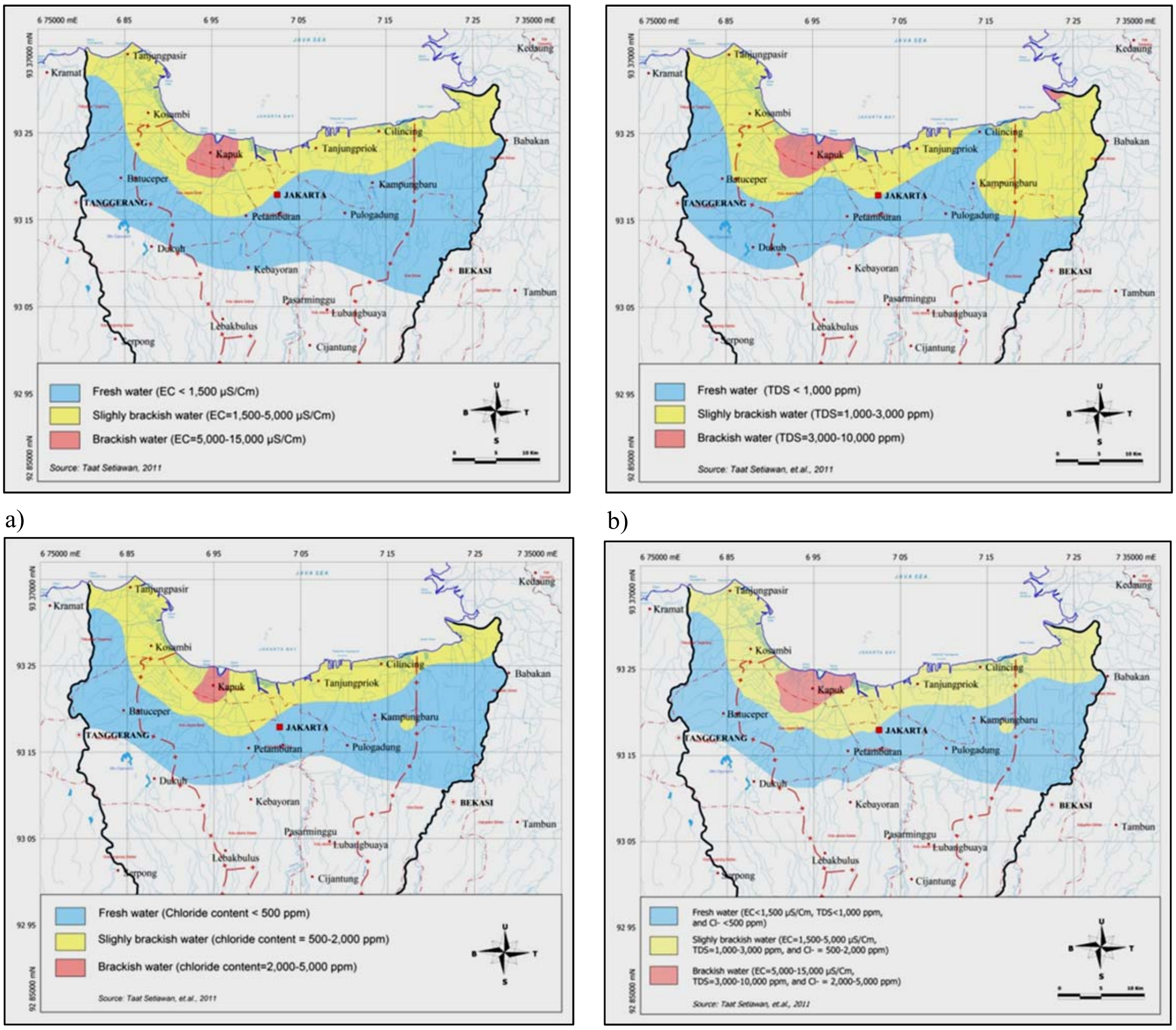


Fig. 7 A map of groundwater salinity of shallow aquifer system based on a) EC of the water, b) TDS content, c) chloride content, and d) EC, TDS, and choride content.

Of the artesian groundwater as shown in Fig. 8, based on EC of the water, TDS content, and chloride content, the Jakarta Plain can be divided into three zones. The first is an extensive, zone of fresh water (EC<1,500 μS/cm, TDS<1,000 ppm, Cl^- <500 ppm) which is mainly covering the southern part of Jakarta Plain. The second is extensive, zone of slightly brackish water (EC=1,500-5,000 μS/cm, TDS=1,000-3,000 ppm, Cl^- =500-2,000 ppm) covering most of the southern part of Jakarta Plain and has the maximum distance attains 8 km from coastline in the North Jakarta and Central Jakarta. The third is zone of brackish water (EC=5,000-15,000 μS/cm, TDS=3,000-10,000 ppm, Cl^-=2,000-5,000 ppm) which is located in Kapuk area (North Jakarta) with the maximum distance reaches 5 km from coastline.



a) b) c) d)

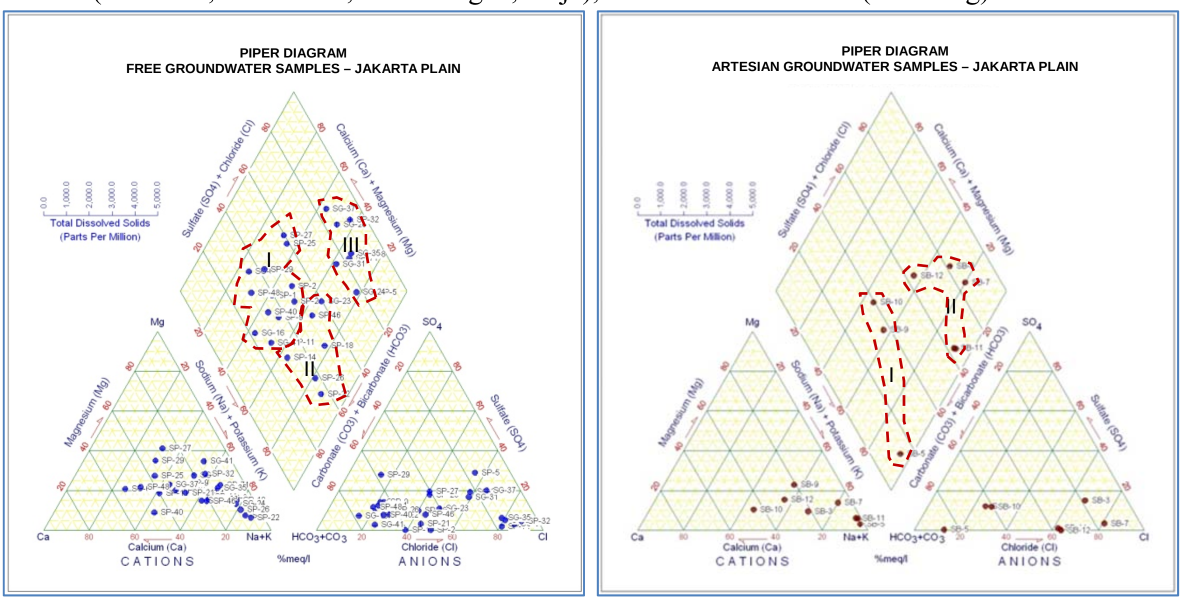
Fig. 8 A map of groundwater salinity of deep aquifer system based on a) EC of the water, b) TDS content, c) chloride content, and d) EC, TDS, and choride content.

5. Origin of brackish-saline groundwater

The former researchers noted that saltwater intrusion was mainly observed in the upper part of the aquifer system at depths above 100 masl and at distances up to 6 km in the 1980s (Soefner *et al*., 1986, Wiryono *et al*., 1999) and 10 km in 1990 (Tjahjadi, 1991) apart from the coast. Maathuis *et al*., (2000) favours the idea that the brackish groundwater of the shallow aquifer is a remainder of the time period of 4500 to 5000 years BP when sea level was about 5 m above the current level. Seawater intrusion can not occur in the deeper aquifer systems. However, mixing of old connate salty water with “background” groundwater in aquifers may occur because drawdowns have induced landward lateral flow from areas containing connate saltwater beneath the Java Sea.

Hydrochemical analysis based on Piper’s Diagram (Fig. 9) results three groundwater facies were identified for shallow aquifer system (Taat Setiawan, *et al*., 2011). The first, facies group of Ca-HCO_3 and

Mg-HCO_3 (I), generally fresh water with predominantly cations of adalah Ca^{2+} and Mg^2+ and anion of HCO_3^-. This facies is characterized by EC values ranging from 370 µS/cm to 2,160 µS/cm with an average values 915 µS/cm, and TDS values range from 306 ppm to 1,636 ppm (average 734 ppm). In Jakarta Plain, this facies is located in West Jakarta area (Kalideres, Grogol), Central Jakarta area (Tambora, Sawahbesar), and East Jakarta area (Kelapagading, Cakung, and Pulogadung). The second, facies group of Na-HCO_3 (II), generally fresh to slightly brackish water with predominantly cation of Na+ and anion of HCO3-. This facies is characterized by EC values ranging from 613 µS/cm to 1,446 µS/cm (average value: 1,081 µS/cm), TDS between 464 ppm and 4,936 ppm (average values: 1,236 ppm). The distribution of this facies covers West Jakarta area (Teluknaga, Kosambi), North Jakarta area (Penjaringan), Central Jakarta (Pademangan, Koja), and East Jakarta area (Cilincing, Tarumajaya, Babelan). The third, facies group of Na-Cl and Ca-Cl (III), generally slightly brackish to brackish water with predominantly cation of Na+ and anion of Cl^-. This facies is characterized by EC values ranging from 1,620 µS/cm to 15,840 µS/cm (average value: 4,387 µS/cm), TDS between 1,320 ppm and 10,182 ppm (average value: 3,326 ppm). This facies is located in East Jakarta area at the north of Tarumajaya and the west of Babelan. Of the artesian groundwater, two groundwater facies were idenfied. The first, facies group of Na-HCO_3 (I), generally fresh water with predominantly cation of Na^+ and anion of HCO_3^-. This facies is characterized by EC values ranging from 556 µS/cm to 1,175 µS/cm with an average values 799 µS/cm, and TDS in order of 460 ppm to 928 ppm (average 661 ppm). In Jakarta Plain, this facies is distributed West Jakarta area (Kalideres, Grogol, Petamburan, Palmerah), Central Jakarta area (Gambir, Menteng), North Jakarta area (Kemayoran), and East Jakarta area (Kelapagading, Cakung, and Babelan). The second, Facies Group of Na-Cl (II), generally fresh to brackish water with predominantly cation of Na^+ and anion of Cl^-. This facies is groundwater type with EC values ranging from 600 µS/cm to 5450 µS/cm (average value: 2543 µS/cm), TDS between 480 ppm and 4516 ppm (average value: 2,018 ppm). Areal distribution of this facies covers West Jakarta area (Kosambi), North Jakarta area (Penjaringan), Central Jakarta (Tambora, Tamansari, Pademangan, Koja), and East Jakarta area (Cilincing).



a) b)

Fig. 9 Piper’s diagram of groundwater samples for a) free groundwater, and b) artesian groundwater

According to Mandel, S. and Shiftan, Z.L. (1981), hydrochemical interpretation for saline groundwater is not really easy due to related processes causing saline groundwater. The most simply application of ratio of some ions (in meq/l) that can be used for interpretation of hydrochemical process within the groundwater. Some methods related to degree of groundwater salinity are ratio of Na/Cl and ratio of $Cl/(CO_3+HCO_3)$.

Revelle (1941) stated that $R=Cl/(CO_3+HCO_3)$ in relation with identifying saltwater intrusion is shown in Table 1.

Table 1 Relationship between R and degree of saltwater intrusion

R value	Degree of saltwater intrusion
< 0.5	Fresh water
0.5 – 1.3	Slightly saltwater intrusion
1.3 – 2.8	Moderately saltwater intrusion
2.8 – 6.6	Slightly high saltwater intrusion
6.6 – 15.5	High saltwater intrusion
15.5 – 20	Seawater

Based on ratio of Na/Cl, Mandel and Shiftan (1981) subdivides into two category, i.e groundwater with Na/Cl > 1 indicates ion exchange process where Ca and Mg substituted by Na, whereas Na/Cl < 1 indicates mixing process between seawater and fresh water which is commonly taken place in coastal aquifer system or that is of seawater intrusion process.

Based on the above two ratio methods and measured values of EC of the water, TDS and chloride contents within the water, interpretation of saltwater intrusion taken place in Jakarta Plain is shown as in Table 2.

Table 2 Interpretation of origin of brackish/saline groundwater

No.	X	Y	ID	Location	EC	TDS	Cl [ppm]	Water Facies	Cl/HCO_3	Na/Cl	(Ca+Mg)/(K+Na)	Interpretation	Geology
Free groundwater (aquifer depth <40 mbls)													
1	700509	9322172	SP-1	Ancol, Pademangan, North Jakarta	1007	728	147.1	$Na-HCO_3$	FW	FW	Near recharge	FW	Qa
2	700507	9322204	SP-2	Tongkol, Pasar Ikan, North Jakarta	1618	1372	319.9	Na-Cl	FW flushing	SWI	Near recharge	FW flushing	Qa
3	693382	9319839	SP-5	Kapuk, Cengkareng, West Jakarta	3010	2588	579.6	Na-Cl	SWI	FW flushing	Ion exchange	SWI	Qa
4	693180	9321930	SG-6	Kapuk, Cengkareng, North Jakarta	783	668	62.4	$Ca-HCO_3$	FW	FW flushing	Near recharge	FW	Qbr
5	691132	9323847	SP-7	Kamal Muara, Penjaringan, North Jakarta	4510	3712	1307.5	Na-Cl	SWI	SWI	Ion exchange	SWI	Qa/Qbr
6	689696	9325663	SG-8	Kamal Muara, North Jakarta	5270	4360	1578.4	Na-Cl	SWI	SWI	Ion exchange	SWI	Qa/Qbr
7	690428	9322722	SP-9	Tegal Alur, West Jakarta	1042	890	81.2	$Na-HCO_3$	FW	FW flushing	Near recharge	FW	Qbr
8	698513	9322483	SP-21	Penjaringan, North Jakarta	1344	1100	209.6	$Na-HCO_3$	FW	Fresh water	Ion exchange	FW flushing	Qa
9	696349	9319670	SP-22	Petamburan, West Jakarta	1396	1148	145.4	$Na-HCO_3$	FW	FW flushing	Ion exchange	FW flushing	Qbr
10	714868	9325255	SG-23	Marunda, North Jakarta	2030	1760	353.1	Na-Cl	FW flushing	FW flushing	Ion exchange	FW flushing	Qbr
11	714529	9321170	SG-24	Cilincing, North Jakarta	2560	2180	465.9	Na-Cl	SWI	FW flushing	Ion exchange	FW flushing	Qa
12	716179	9316033	SP-25	Cakung Timur, East Jakarta	884	1020	180.6	$Ca-HCO_3$	FW	FW	Near recharge	FW	Qbr
13	717246	9318161	SP-26	Cakung Timur, East Jakarta	1446	1200	149.4	$Na-HCO_3$	FW	FW flushing	Ion exchange	FW flushing	Qa
14	711008	9315494	SP-27	Pulo Gadung, East Jakarta	577	436	99.2	$Mg-HCO_3$	FW	FW	Near recharge	FW	Qa
15	706481	9319465	SP-40	Tanjung Priok, North Jakarta	913	648	80.3	$Ca-HCO_3$	FW	FW flushing	Near recharge	FW flushing	Qa/Qbr
16	710707	9322450	SG-41	Koja, North Jakarta	1264	1020	115.0	$Na-HCO_3$	FW	FW flushing	Ion exchange	FW flushing	Qbr
17	703734	9318580	SP-46	Kemayoran, Central Jakarta	1203	990	179.2	$Na-HCO_3$	FW	FW flushing	Ion exchange	FW flushing	Qa

18	698553	9313935	SP-48	Palmerah, West Jakarta	526	428	44.1	$Ca-HCO_3$	FW	FW flushing	Near recharge	FW flushing	Qav
Artesian groundwater (aquifer depth: 40-140 mbls)													
1	700512	9322161	SB-1	Pademangan, North Jakarta	4200	3012	976.5	Na-Cl	SWI	FW flushing	Ion exchange	SWI	Qa
2	693365	9319850	SB-3	Cengkareng, West jakarta	3010	2200	519.0	Na-Cl	SWI	FW flushing	Ion exchange	SWI	Qa
3	692326	9322671	SB-5	Penjaringan, North Jakarta	1175	928	56.2	$Na-HCO_3$	FW	FW flushing	Ion exchange	FW flushing	Qbr
4	691127	9323837	SB-7	Penjaringan, North Jakarta	5450	4516	1611.9	Na-Cl	SWI	FW flushing	Ion exchange	SWI	Qa
5	690439	9322715	SB-9	Tegal Alur, West Jakarta	845	796	78.5	$Na-HCO_3$	FW	FW flushing	Ion exchange	FW flushing	Qa
6	714858	9325242	SB-10	Cilincing, North Jakarta	713	580	73.1	$Na-HCO_3$	FW	FW flushing	Near recharge	FW	Qbr
7	717243	9318096	SB-11	Cakung, East Jakarta	2730	2380	617.5	Na-Cl	FW flushing	FW flushing	Ion exchange	FW flushing	Qa
8	706499	9319468	SB-12	Tanjung Priok, North Jakarta	1131	920	245.2	Na-Cl	SWI	FW	Ion exchange	FW flushing	Qa/Qbr

6. Closing remarks

a Jakarta area is already affected by groundwater related problems mainly related to over-pumping and pollution of aquifers. More specifically, four major problems i.e. lowering of groundwater level, saltwater intrusion, land subsidence, and groundwater pollution, were identified that required immediate attention.

b To prevent further groundwater over-abstraction, which may also threaten the water quality of deeper aquifers by saltwater intrusion, challenges are necessary to be performed by mean of:

1) direct measures, comprise of technical recommendation for issuing license documents, setting up reduction targets to larger groundwater users by establishing map of groundwater conservation zones, monitoring of groundwater level, monitoring of groundwater salinity (EC, TDS, Cl^-).

2) indirect measures, comprise of charge to groundwater use, provision of other water resources to alternate groundwater, issuing government regulation on groundwater management and ministry regulations on technical guidelines on groundwater management.

3) In future, a comprehensive research on saltwater intrusion is urgently required in order:

- to obtain reliable data for analysing saltwater intrusion;
- delineate saltwater intrusion within aquifer systems;
- to obtain information for planning on land remediation and groundwater utilization/management.

The research itself will be done by CGREG, GE, MEMR in cooperation with UNESCO-IHE and funded by Asian Development Bank (ADB),

Acknowledgments

The author wishes to thank to the Director of Center of Groundwater Resource and Environmental Geology, Geological Agency, MEMR in encouraging him to participate this CCOP-GSJ/AIST-CWRPI Groundwater Phase II Meeting. My warm thank also goes to the Director of CCOP Technical Secretariat who gave the opportunity to present this paper.

References

Arismunandar dan Arief, S. (2009): Penyelidikan konservasi air tanah Cekungan Air Tanah Jakarta. *Pusat Lingkungan Geologi*, Bandung.

Bemmelen, R. W., van (1949): *The Geology of Indonesia,* Government Printing Office, The Hague, 732 p.

Shivakoti, B.R. (2013): Summary of Inception Meeting of the Project - Comparative Research of Groundwater Management in the Coastal Areas in Southeast Asia, Strategies (IGES) – Groundwater Knowledge Hub, Japan.

Hadipurwo,S. (1999): Groundwater in coastplan Jakarta Bay Project, Coastal Environmental Geology of the Jakarta Reclamation Project and Adjacent Areas, *CCOP COASTPLAN Case Study Report*, **no. 2**, Jakarta/Bangkok, pp. 39 - 49.

Haryadi, T. and Taat Setiawan (2012): Groundwater study in Jakarta coastal area, inception workshop on comparative rearch of groundwater management in the coastal areas in Southeast Asia, *UNESCO-IHE, Delft*, The Netherlands.

Maathuis, H., Yong, R.N, Adi, S., Prawiradisastra, S. (1996): Development of groundwater management strategies in the coastal region of Jakarta, Indonesia. *International Development Research Centre*, Ottawa, Canada.

Matahelumual, B.C., and Dadi Harnandi (2010): Pemantauan kuantitas dan kualitas air tanah di Cekungan Air Tanah Jakarta, *Badan Geologi*.

Poespowardoyo, S. (1986): Hydrogeological map of Jakarta Quadrangle scale 1:250,000, *Directorate of Envireonmental Geology*, Bandung.

Schmidt, G., Haryadi, T., and Koehler, G. (1985): Jakarta Groundwater Study – *Groundwater Modeling,* Volume **7** (HAG 116), Directorate of Environmental Geology (Bandung) – Federal Institute of Geosciences and Natural Resources (Hannover).

Setiawan, T., Wayan Mudiana, dan Matahelumual, B.C. (2011): Penelitian intrusi air laut daerah pantai utara pada CAT Jakarta dan CAT Bekasi-Karawang *Pusat Sumber Daya Tanah dan Geologi Lingkungan,* Bandung.

Turkandi, T., Sidarto, D.A., Agustiyanto, dan Purbohadiwidjo (1992): Peta geologi skala 1:100.000 Lembar Jakarta dan Kepulauan Seribu *Pusat Penelitian dan Pengembangan Geologi*, Bandung.

Wandowo (2000): Natural isotope technology for evaluating of hydrodynamic of groundwater – study on recharge and seawater intrusion in Jakarta area *National Nuclear Agency*, Jakarta.

Schmidt, G. and Butkuss (2004): Groundwater Modeling in the Greater Jakarta Area, Indonesia *Symposium CCOP*, Tsukuba, Japan.

Shaw, E.M. (1983): *Hydrology in Practice*, Van Nostrand Reinhold (UK)

Soekardi, P. (1986): Peta Hidrogeologi Indonesia Skala 1:250.000, Lembar Jakarta *Direktorat Geologi Tata Lingkungan*, Bandung.

Hydro-Environmental Groundwater Survey in the Kanto Plain, Japan

Youhei Uchida
Geological Survey of Japan, AIST

Abstract: The Kanto Plain is the largest plain in Japan and there are a lot of large cities such as Tokyo. Groundwater in the Kanto Plain has been used since the 20th century. There were some studies of groundwater flow system in the Kanto Plain, but almost all of studies was treated only in the local part of the Kanto Plain, not the whole area of it. The purpose of this study is to clarify the regional groundwater flow system of the Kanto Plain from the distribution of the hydraulic heads and the subsurface temperature.

1. Introduction

One of main tasks of the Groundwater Research Group, Geological Survey of Japan, AIST is to publish a series of the water environment map of Japan. In this map series, we especially attempt to apply a multi-tracer technique to analyze regional groundwater flow systems. The technique is based on the data combination of groundwater level, water chemistry (quality), stable isotopes and subsurface ground temperature as tracers. Although each tracer has both advantages and disadvantages in water flow analysis, application of multiple tracers may compensate disadvantages of each tracer.

The Kanto Plain is the largest plain in Japan and there are a lot of large cities such as Tokyo. Groundwater in the Kanto Plain has been used especially since the 20th century. There are some studies of groundwater flow system in the Kanto Plain, but all of studies is limited only in a small part of the Kanto Plain, not the whole area of it. This report showed the previous studies (Miyakoshi et al., 2003; Geological Survey of Japan, AIST, 2005) that clarified the regional groundwater flow system of the Kanto Plain from the distribution of the hydraulic heads and the subsurface temperature.

2. Groundwater flow system and their subsurface thermal regime

It is known that subsurface temperature distribution is generally affected not only by thermal conduction but also by advection owing to groundwater flow (Uchida et al., 2003). The effect of thermal advection is especially large in a shallow sedimentary layer with high groundwater flux.

Groundwater temperature measured in the observation well is assumed to be identical to subsurface temperature, because there exists thermal equilibrium between the water in a borehole and its surrounding subsurface layers. Temperature profiles are one-dimensional sequential data arrays so that areally-distributed temperature profiles provide three-dimensional subsurface information. Fig.1 shows groundwater flow system and subsurface thermal regime (modified from Domenico and Palciauskas, 1973). If there is no groundwater flow or a static groundwater condition (Fig.1a), subsurface thermal regime is governed only by thermal conduction and subsurface temperature gradient is constant (Fig. 1b). When a simple regional groundwater flow system due to topographic driving (Fig. 1c) is assumed, thermal regime will be disturbed by thermal advection owing to groundwater flow (Fig. 1d). In the groundwater recharge area, subsurface temperatures and gradients are lower than those of under a static groundwater condition (Fig. 1b). In the discharge area, on the other hand, temperatures and gradients are larger than those of under a static condition.

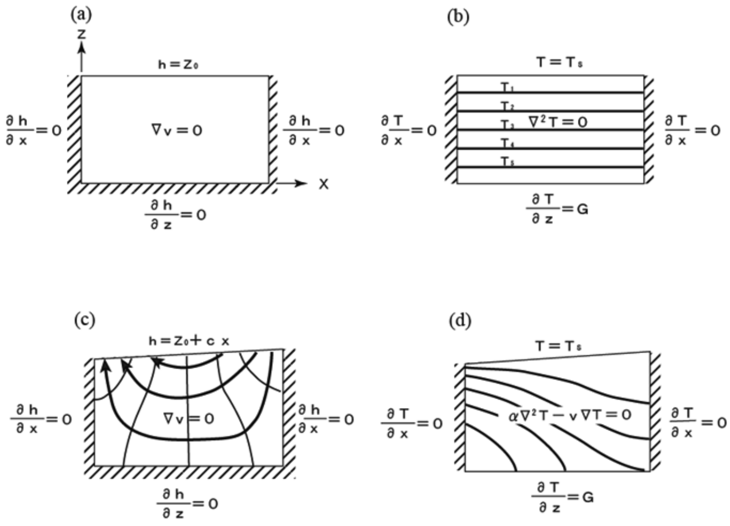


Fig.1 Subsurface thermal regime affected by a groundwater flow system. (modified from Domenico and Palciauskas, 1973)
(a) static groundwater
(b) thermal regime under condition of (a)
(c) simple regional groundwater flow system

3. Study area description

The Kanto Plain is the largest plain in Japan (about 15,000 km2, Fig. 2), and it is surrounded by the Tanzawa Mountains, the Kanto Mountains, the Ashio Mountains and the Yamizo Mountains. It is the basin structure characterized by the topography and the geology. The topography of the plain is classified into three types, lowlands along the river, uplands and hills which are located in limb of the plain. The Kanto Plain is constructed with the sedimentary layers which is in more than 3000 m thick (Suzuki, 1996). The sedimentary layers are classified into three groups: Shimousa Group, Kazusa Group and Miura Group. The Shimousa Group and the upper part of the Kazusa Group are the most useful aquifers in the plain. It is difficult to delineate the boundary between the Shimousa Group and the Kazusa Group, using the geological feature (Suzuki, 1996).

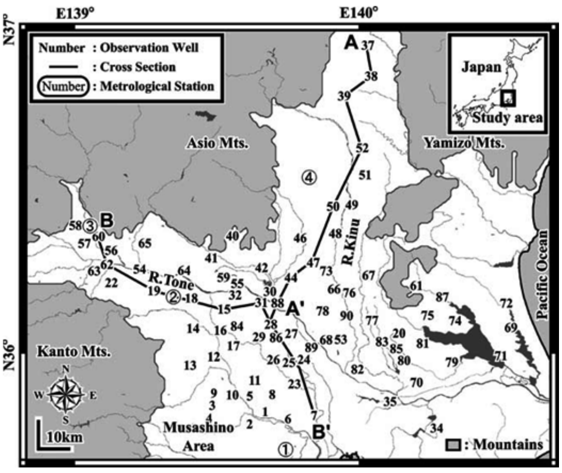


Fig. 2 A location map of the study area and distribution of the observation well.

The average of a geothermal gradient shows about 2.0–2.5 ℃/100 m in the plain, under 300 m deep (maximum about 500 m deep), from the geothermal map of Japan (Yano et al., 1999).

4. Measurement methods

In this study, subsurface temperature and hydraulic head were measured at the observation wells for monitoring groundwater level and land subsidence. The depths of the observation wells are between 30 and 600 m.

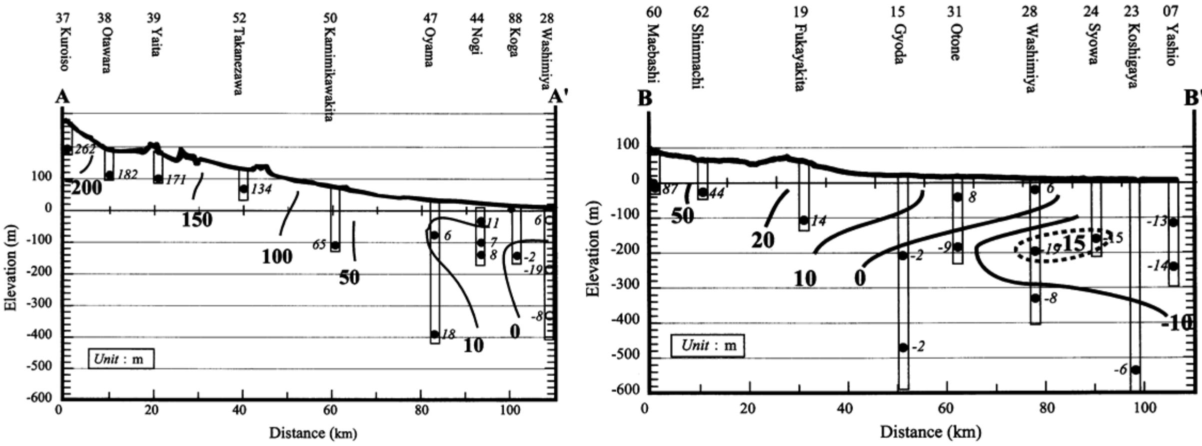


Fig. 3. Vertical distribution of the hydraulic heads in cross section along (a:left) A–A’, (b:right) B–B’ in Fig. 2. Italic number shows the hydraulic head at each screen.

Measurements were carried out from October 14, 1999 to November 20, 2000. Subsurface temperature was measured with a thermistor thermometer (resolution is 0.01 ℃). Temperature was measured every 2 m interval until 300 m in depth, and every 5 m interval in deeper than 300 m. Well diameters are less than 20 cm (mostly about 15 cm). Taniguchi (1987) analyzed free thermal convection in wells and concluded that the temperature profile in the wells was stable and could represent the subsurface thermal regime.

5. Observation Results

Fig. 3a and 3b show the vertical 2-D distribution of the hydraulic heads along the Kinu river (A–A’) and the Tone river (B–B’), respectively. The hydraulic heads are high in the surroundings of the plain such as hills or uplands, and low in the lowland which is located along the river. Areas with high hydraulic heads were located on hills and uplands of the plain, and the hydraulic heads were gradually decreased from highlands to lowlands. Especially, in the lowland which is located in the central part of the plain, the hydraulic heads are anomalous low. There were a lot of artesian wells in the central part of the plain before 1970 (Kino, 1970). At present, there are very few, because of effects of pumping (Tochigi Prefecture, Japan, 1999; Saitama Prefecture, Japan, 1999). These distributions show the existence of groundwater flow system which groundwater is recharged in hills and uplands and discharged at the lowland.

Fig. 4a and 4b show the 2-D vertical distribution of subsurface temperature along the same sections, respectively. Subsurface temperature is low in the surroundings of the plain such as hills and uplands, and high in the lowland which is located in the central part of the plain.

Fig. 5 shows a horizontal distribution of the subsurface temperature at an elevation of 50 m below sea level. Areas with high temperature are located in the lowlands along the Tone River (about 18℃), the Kinu River (about 18 ℃) and the central part of the plain (17.0–17.5 ℃). On the other hand, areas with relatively low temperature are located on hills and uplands that are high topographic areas (15.0–16.5℃).

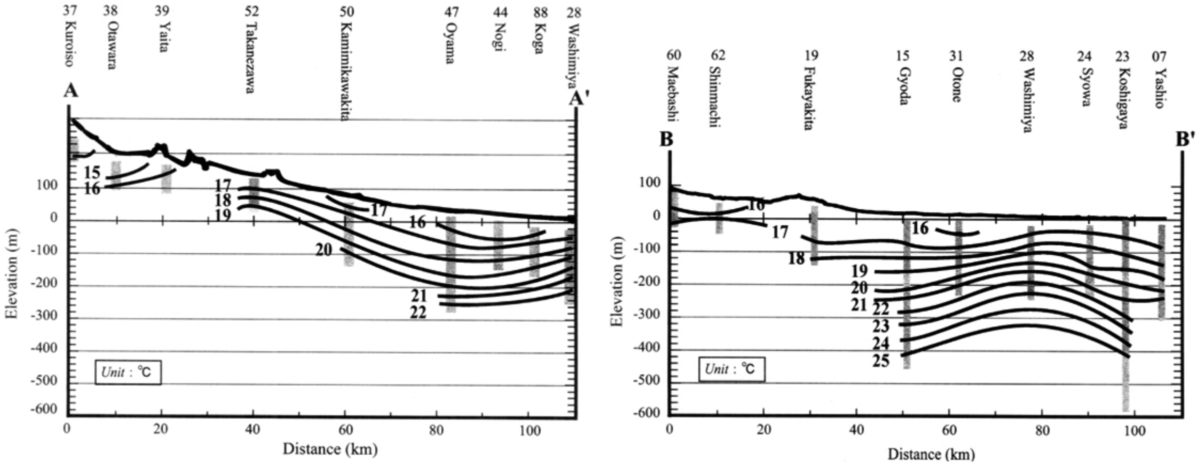


Fig.4. Isotherms of subsurface temperature in the same cross section in (a:left) Fig. 3a, (b:right) Fig. 3b.

6. Discussion

Groundwater levels and temperatures were measured at 88 observation wells in the Kanto Plain. From observation results, subsurface temperature distribution in the Kanto Plain is assumed to be strongly affected by thermal advection due to groundwater flow, which has regional difference between high temperature area and low temperature area (Fig. 4 and Fig. 5). The high temperature areas are located in the lowlands around the Kinu, Tone Rivers and the central part of the Kanto Plain. The low temperature areas, on the other hand, are located in highlands and/or mountain areas on the fringe of the Kanto Plain. The following groundwater flow systems are estimated by considering from the observed results (Figs. 3 and 4).There are two local systems discharging to the Tone River in Gumma Prefecture and to the Kinu River in Tochigi

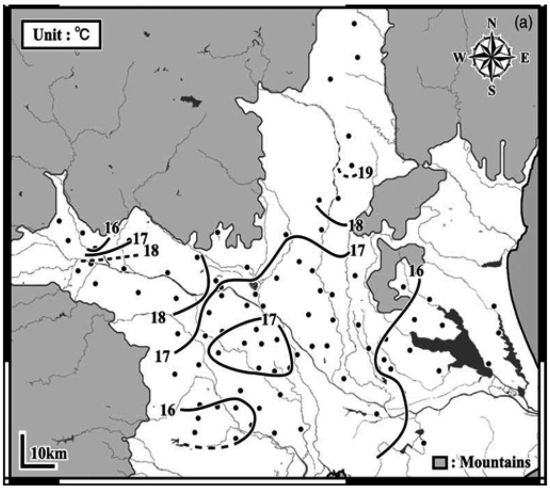


Fig.5 Isotherms of the subsurface temperature at 50 m below sea level

Prefecture. On the other hand, there is one regional system which is recharged in the peripheral areas of the plain and discharges to the central part of the plain.

After the survey, a water environment map of the Kanto Plain was compiled for understanding an outline of the regional groundwater flow system based on hydrogeology and hydrochemistry and was published by Geological Survey of Japan, AIST in 2003.

References

Domenico, P. A., Palciauskas, V. V. (1973): Theoretical analysis of forced convective heat transfer in regional groundwater flow. *Geol. Soc. Amer. Bull.,* **84,** 3803-3814.

Domenico, P. A.and Schwartz, F. W. (1990): Physical and Chemical Hydrogeology, John Wiley and Sons, New York, 824p.

Geological Survey of Japan, AIST (2003): *Water Environment Map "Kanto Plain'*. Geological Survey of Japan, AIST, CD-ROM.

Kino, Y. (1970): Hydrogeological study on the confined groundwater in the central part of the Kanto Plain, Japan. *Report, Jpn., Bull. Geol. Surv. Jpn*. **238**, 39 p.

Miyakoshi, A., Uchida, Y., Sakura, Y., and Hayashi, T. (2003): Distribution of subsurface temperature in the Kanto Plain, Japan; estimation of regional groundwater flow system and surface warming. *Physics and Chemistry of the Earth*., **28**, 467–475.

Saitama Prefecture, Japan (1999): *Reports of ground subsidence*. Saitama Prefecture, Japan.

Suzuki, H. (1996): Geology of Koto deep borehole observatory and geological structure beneath the metropolitan area, Japan. *National Research Institute for Earth Science and Disaster Prevention, Japan*, **56**, pp. 77–123.

Taniguchi, M. (1987): Mechanism of groundwater temperature formation in Nagaoka plain. *Geogr. Rev. Jpn.* **60**, 725–738.

Tochigi Prefecture, Japan (1999): *Reports of groundwater level*. Tochigi Prefecture, Japan.

Uchida, Y., Sakura, Y., and Taniguchi, M. (2003): Shallow subsurface thermal regimes in major plains in Japan with references to recent surface warming. *Physics and Chemistry of the Earth*, **28**, 457-466.

Yano, Y., Tanaka, A., Takahashi, M., Okubo, Y., Sasada, M., Umeda, K., and Nakatsuka, N. (1999): Geothermal gradient map of Japan. *Jpn. Bull. Geol. Surv. Jpn.*

Groundwater Temperature Survey in Korea

Kyoochul Ha[1], Jin-Yong Lee[2], Yu-Chul Park[2]

1, Korea Institute of Geoscience and Mineral Resources (KIGAM), 124 Gwahang-no Yuseong-gu Daejeon, Republic of Korea
2, Department of Geology, College of Natural Sciences, Kangwon National University, Chuncheon 200-701, Republic of Korea

1. Introduction

Groundwater is seriously considered as a heat source for heating and cooling as well as water resources in the country. This paper introduced groundwater temperature distribution in Korea using the data obtained from the 266 Korean National Groundwater Monitoring Network (NGMN) stations distributed in all the country. The MLTM (Ministry of Land, Transport and Maritime Affairs) and KWATER (Korea Water Resources Corporation) publish an annual report on groundwater monitoring every year, including all these groundwater data from the national groundwater monitoring stations. In this paper, groundwater temperature data obtained from the 266 national groundwater monitoring stations (including 128 shallow monitoring wells and 236 deep monitoring wells) were analyzed. Period for data analysis ranged from 1995 to 2004 but it somewhat differs according to the installation year of each station.

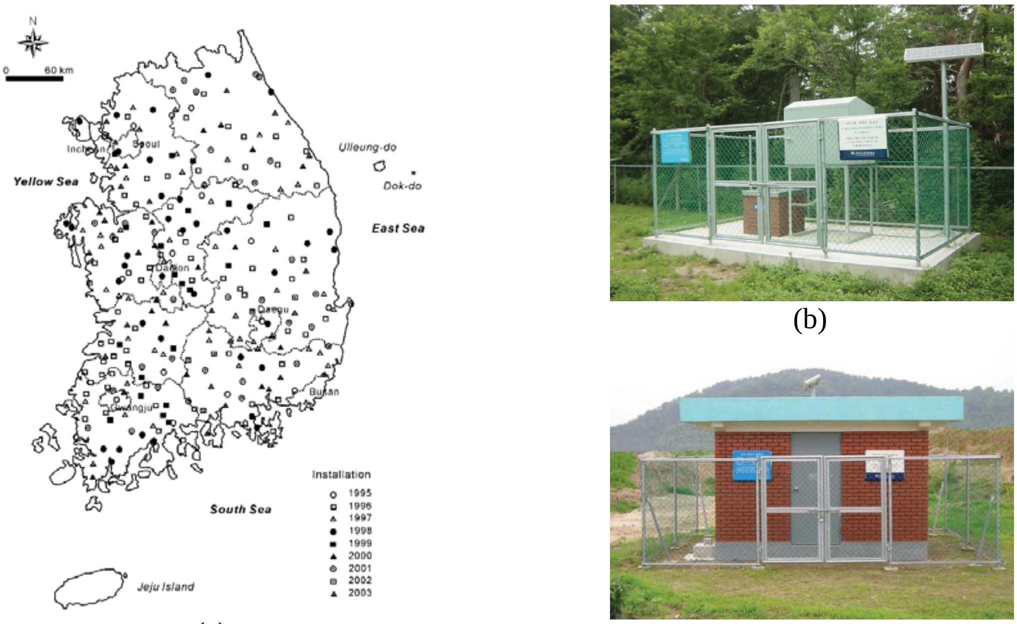
2. Groundwater temperature analyses using MGMNs

National Groundwater Monitoring Stations

KWATER (Korea Water Resources Corporation), an affiliated organization of the MLTM (Ministry of Land, Transport and Maritime Affairs), is in charge of the establishment and operation of this network. By 2004, 293 stations were completed. For each monitoring station, two separate wells are newly installed. One well, with an average depth of 11.7 m, is used to monitor shallow groundwater (alluvial aquifer) and the other, with an average depth of 69.8 m, is used to monitor deep groundwater (bedrock aquifer). To protect the monitoring wells and monitoring devices, an outer facility using bricks or steel is constructed. All the stations except some ones have two separate monitoring wells, a data logger, a remote terminal unit (RTU), and a solar energy system for supplying electricity used for groundwater data acquisition and data transfer. An integrated probe measuring water level, water temperature and electrical conductivity (EC) is installed at each monitoring well. The measuring probes were installed at average depths of 9.9 m and 21.4 m (below the groundwater surface) for shallow and deep wells, respectively.

There are two main aquifers in Korea. They are shallow alluvial aquifers and relatively deep bedrock aquifers. Unconsolidated sediments composing the shallow aquifer are distributed along the main rivers. The thickness of them ranges 2–30 m and groundwater yields for each well ranges from 30 to 800 m^3/day. The bedrock aquifers generally accompany faults, fractures, joints or boundary of rocks formed by tectonic activities and these aquifers are commonly overlain by shallow aquifers. Groundwater yields from this type aquifer greatly vary from 10 to 5000 m^3/day (Lee et al., 2007).

Groundwater level, water temperature, and electrical conductivity are measured every 6 hours using the integrated probe and these data are stored in the data logger. The groundwater data are automatically transmitted to a host server at KWATER once a day at a designated time. In addition, periodic analyses of groundwater quality are performed twice a year for all the monitoring wells. For maintenance of the facilities and the monitoring devices, a field inspection/maintenance team regularly visits each station at least 6 times a year. All the data obtained from the groundwater monitoring stations are managed by the NGMN management system on the web. The data are safely stored in an Oracle DB at KWATER. The manager of the NGMN has all access authorities for the system via manager login, including manipulation of raw groundwater data, applied analysis of the data, and issuance of any directions for the field inspection teams. Real time groundwater data and relevant information from the monitoring stations are automatically retrieved from the database and are available to the public on the web.



(a) (b) (c)

Fig. 1. (a) Location of the National Groundwater Monitoring Stations by 2004. There are two types of outer facilities for well protection, (b) and (c).

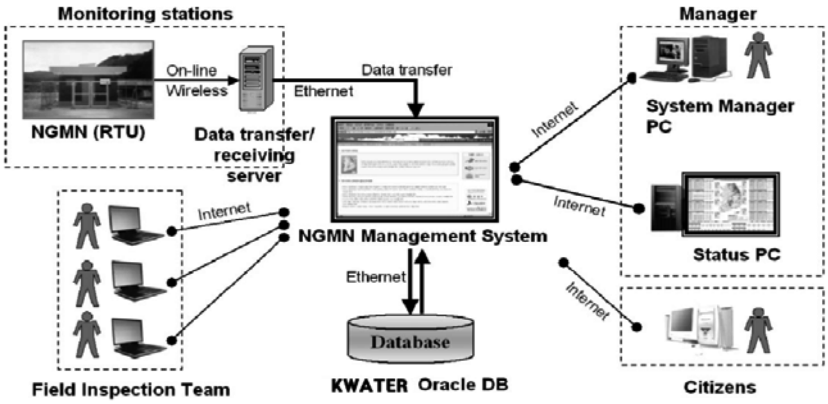


Fig. 2 Schematic of operation and management of the MGMN

Groundwater temperature distribution

The air temperatures in the peninsular are largely characterized by latitudes and altitudes (Lee et al., 2006). The mean air temperature ranged from below 7 °C in the coastal area near the East Sea to 15.5 °C in the south (Jeju Island). The lowest air temperature in the western side of the eastern coastal area is closely related to high topographic elevations (>1000 m). General distribution of the air temperature is also fairly consistent with that of the topographic elevations. Except for the eastern coastal area, air temperatures in the western half of the country are lower than those in the eastern half for the same latitude. Relatively high air temperatures in the eastern half are mainly derived from blocking of very cold winds in winter (from Siberia to the peninsular in NW–SE direction) due to high mountains and the Donghan warm current of the East Sea (Min, 1979). Mean monthly air temperatures for 1995–2003 at 6 metropolitan cities (Seoul, Incheon, Daejon, Daegu, Busan and Gwangju) ranged from -4.1 to 28.6 ℃ and showed annual periodic repetition behaviors. The temperatures were the highest in August and the lowest in January. The differences of air temperature among the cities were 6.6 ℃ in winter and 2 ℃ in summer.

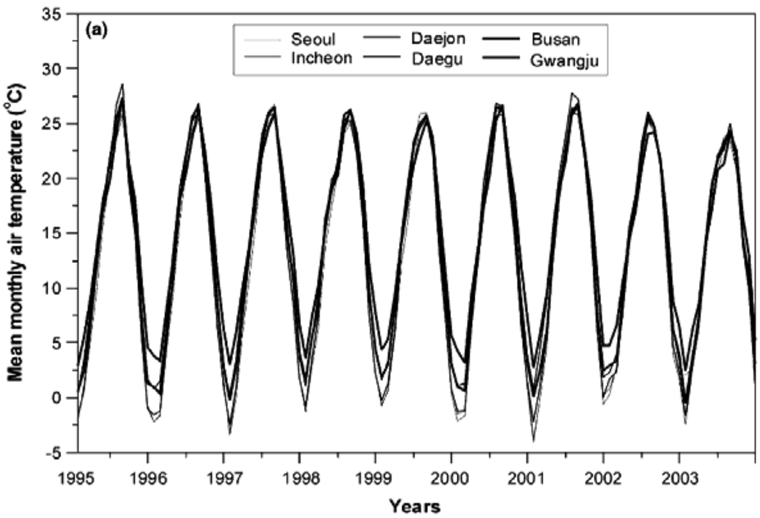


Fig. 3 Mean monthly air temperature (1995-2003)

The groundwater temperatures ranged from 10.1 °C minimum to 22.5 °C maximum with a mean of 14.1 °C. Like the air temperatures, distribution of the shallow groundwater temperatures is generally similar to that of altitudes in reverse manner. The lowest temperatures below 11 °C appeared at the center of the country, which is a perimeter of the upper mountain range of high elevations. The highest temperatures greater than 20 °C were observed at Daegu area, which is a depression basin and one of the hottest areas in summer in the country. Although the latitude and the altitudes played an important role in the temperature distribution, there also exist sporadic values not explained by the aforementioned simple factors. In this case, local artificial conditions including land use, vegetation, groundwater pumping, and geology may be potential sources for the anomalies (Hahn et al., 2004).

Nevertheless of these minor effects, the shallow groundwater temperatures were largely affected by the ambient air temperatures in consideration of very shallow water tables. An average water table for 128 shallow monitoring wells was at 4.79 m below surface. Daily fluctuation in air temperature affects the ground only up to a few meters, while seasonal fluctuations can affect a depth of 20–30 m depending on the heat transfer ability of the upper soils or rocks (Bundschuh, 1993; BSDUD, 1999; Hahn et al., 2004) (Fig. 4(a)).

The groundwater temperatures of the deep monitoring wells (installed in bedrock aquifers) showed almost similar fluctuation. The temperatures ranged from 7.4 °C minimum to 20.4 °C maximum with a mean of 14.2 °C. The location of the highest temperatures was not changed while that of the lowest temperature was slightly moved upward. It was noticeable that contours of the deep groundwater temperatures were distributed in a NE–SW direction. As previously described, the high mountains are also located in this direction. So relatively low air temperatures and this topography may affect the groundwater temperatures (Fig. 4(b)).

In the shallow wells, maximum temperatures ranged between 11.9 and 25.8 °C while minimum temperatures ranged from 3.0 °C to 16.1 °C. In the deep wells, ranges of maximum and minimum temperatures were substantially not different from the shallow wells. The range between first (25th percentile) and third (75th percentile) quartiles for the deep wells was much smaller than that for the shallow wells. This meant less spatial variation of the deep groundwater temperatures. Most of annual temperature variation was within 8 °C (76.6% of the total shallow wells). But still large annual difference over 8 °C occupied 23.4%. Maximum difference was 20.8 °C for the shallow wells. In contrast, 97.1% account for the difference within 8 °C in the deep wells and only 2.9% showed temperature difference over 8 °C. In this case, maximum difference was 17.5 °C. All these facts indicated much stable groundwater temperatures for the deep wells, as expected.

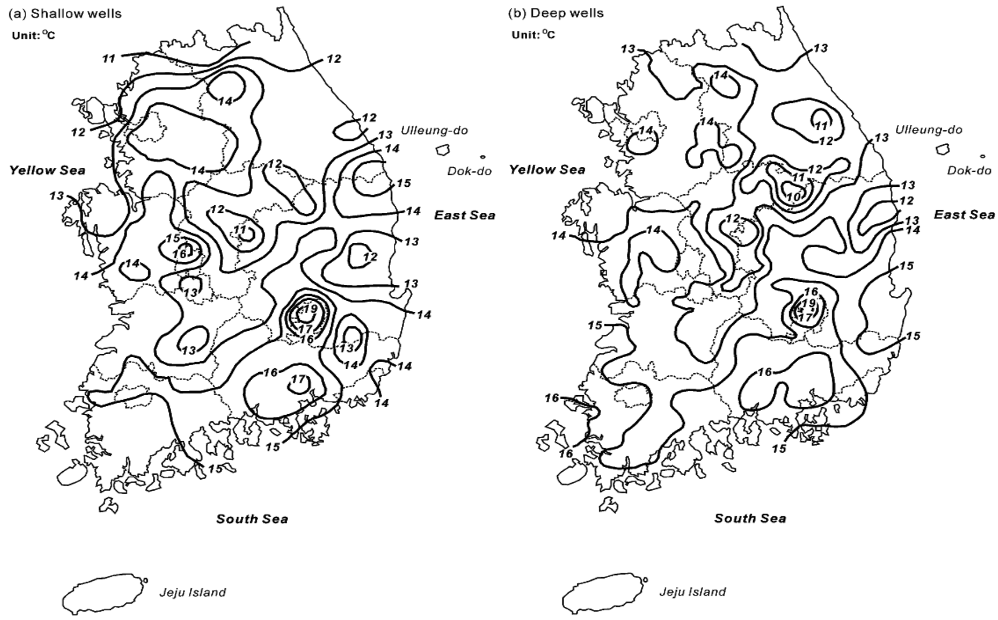


Fig. 4 Distribution of mean groundwater temperature: (a) shallow wells and (b) deep wells.

There exists phase (time) difference between air temperature and groundwater temperature (Bundschuh, 1993). As previously described, air temperature in the country is the highest in August and the lowest in January. Groundwater temperatures showed a different behavior. The highest temperatures of both shallow and deep wells mostly occurred in November–February, which are the coldest months in the country. Meanwhile, the lowest groundwater temperatures emerged in March–June, immediately before the hottest months, July–August.

These occurrences of the highest and the lowest groundwater temperatures are nearly in inverse relation to those of the air temperatures in time. Time differences between the maximum and the minimum temperatures are mostly 6 months. Time difference less than 6 months indicates relatively rapid decrease in elevated groundwater temperatures. Annual temperature variations of groundwater can be characterized by the annual amplitude and phase difference with respect to the air temperature approximating the Earth’s surface temperature (Bundschuh, 1993).

Patterns of groundwater temperatures variation

Groundwater temperatures may fluctuate with time. For a total of 364 monitoring wells (128 shallow wells + 236 deep wells), variations of groundwater temperatures were classified into four major types (Fig. 5). P (periodic) type represents periodic annual repetition behaviors with a large amplitude of annual fluctuation over 1 °C (Fig. 5(a)). Most of this type was found in the shallow groundwaters. 62.5% of the shallow wells are included in this type while only 7.6% showed this type of fluctuation in the deep wells. WP (weak periodic) type accounts for periodic annual fluctuation with only noticeable amplitude less than 1 °C (Fig. 5(b)). 17.2% of the shallow wells and 6.8% of the deep wells belong to this type. Most peculiar is F (flat) type (Fig. 5(c)). In this type, the groundwater temperatures showed nearly no variation throughout the years. Most of this type was observed in the deep monitoring wells, whose water levels were deep. Daily or seasonal fluctuation of ambient air temperatures or of surface temperature least affected the groundwater temperatures of this type. 47.9% of the deep wells belong to this type while only 3.1% account for the shallow wells.

I (irregular) type showed most erratic variation behaviors unlike the above three types (Fig. 5(d)). In this type, the amplitude in annual fluctuation is generally large without any noticeable specific trend. 17.2% and 37.7% of the shallow and deep wells account for this type, respectively. Specific reasons of this irregular variation were not investigated. They may involve local and anthropogenic factors. This type was mostly observed at the national groundwater monitoring stations (wells) located in urban cities and industrial areas. Various heating and cooling systems in these areas can affect the groundwater temperatures.

Water levels of P or WP types are the shallowest while those of F type are the deepest. Relatively higher correlations between the water levels and temperatures were observed in P and WP types while those were lower in F and I types. The negative correlations indicate an inverse relationship between them, that is, high water levels indicate low groundwater temperatures. This was likely a result of the phase difference between the two data series. But even though some meaningful cross-correlation values were obtained from the correlation analysis, simple linear regressions using bivariate plots yielded very small coefficients of determination (r2) for overall monitoring data of each well.

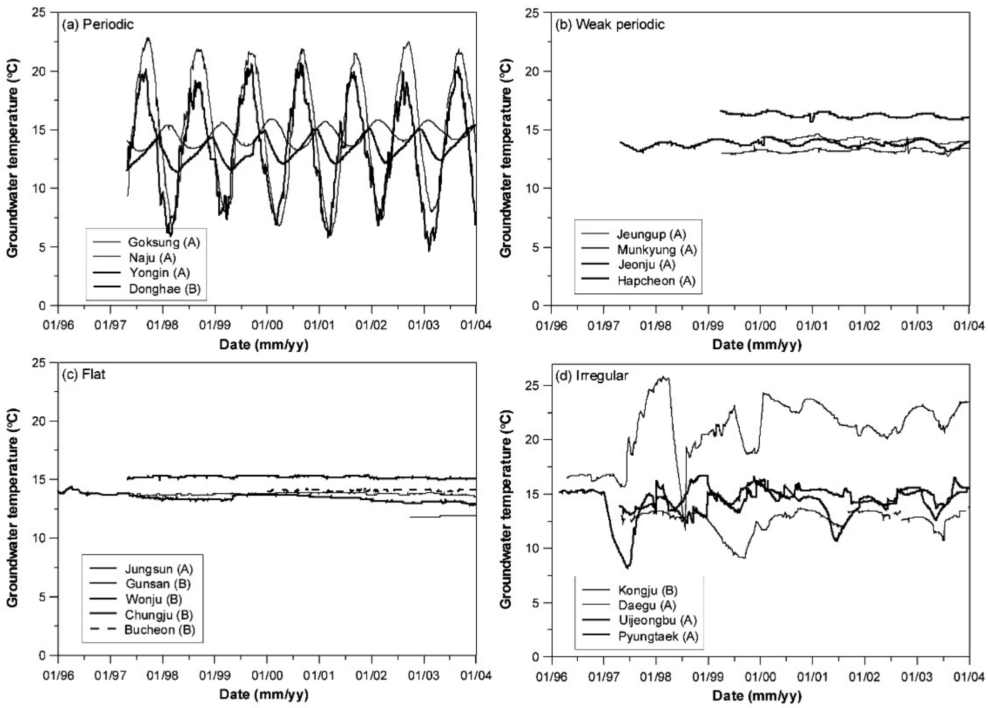


Fig. 5 Typical patterns of groundwater temperature variations: (a) periodic variation (P), (b) weak periodic variation (WP), (c) nearly no variation (F), and (d) irregular variation (I). Names of groundwater monitoring stations and shallow (A) or deep (B) wells are indicated in each legend.

3. Trend of groundwater temperatures

The mean air temperature (1996–2008) of 69 weather stations across the country ranged from 6 to 17 °C for the period as shown in Figure 6. The range of variation of each year was very similar over the whole monitoring period but the median values increased (slope = +0.029 °C/yr), although not significantly according to a non-parametric trend analysis at the 95% confidence level. However, the increasing trend of the air temperature was very distinctive at each station. As shown in Fig. 7, all the stations recorded that air temperature rose at rates between 0.015 and 0.23 °C/yr (mean = 0.08 °C/yr), which confirmed the gradual warming of the Korean peninsular in both urban and rural areas due to a global warming. The air temperature rises at every station were many times greater than the global mean (0.0074 °C/yr) for the last 100 years (1906–2005) (IPCC, 2007). Rapid urbanization and industrialization in Korea may have contributed somewhat to this remarkable increase, especially for some cities (Chung et al., 2004a; Chung et al., 2004b; Lee and Chung, 2007; Youn, 2008). The air temperature rise was expected to affect the groundwater temperature.

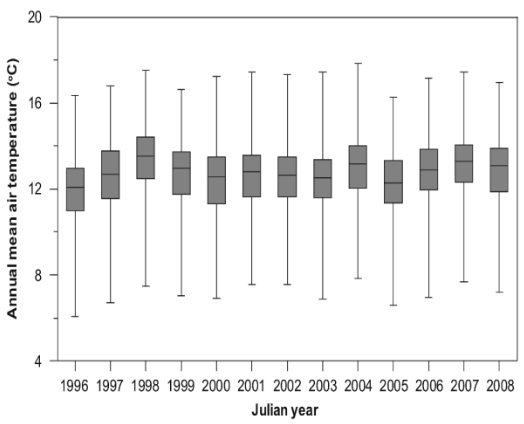


Fig. 6 Annual mean air temperature of 69 weather stations of the Korea Meteological Administration

Fig. 7 Changing rates (1996-2008) of air temperatures determined by the linear regression (unit: °C/yr).

The variation trends of groundwater temperatures are shown in Figure 8. The rates of change of groundwater temperature ranged from –0.3 to +0.7 °C/yr for shallow groundwaters and from –0.4 to +0.4 °C/yr for deep groundwaters, respectively. The mean increase rate (+0.09 °C/yr) for shallow groundwater was over double that of deep groundwater (+0.04 °C/yr) and the increasing trends of temperatures (82.8% for shallow groundwater and 68.8% for deep groundwater) were prevailing nationwide for both aquifers. These two results indicated that the groundwater temperature rises were definitely derived from the increased air temperature, i.e., global warming although the island heat effect occurring in urban areas (Taniguchi and Uemura, 2005) may contribute, to some extent, to these higher increase rates especially for shallow groundwater. Furthermore, the increasing trend became more conspicuous compared with that in the previous period. Considering the increasing rate in the mean air temperature (= 0.08 °C/yr) nationwide for the same period (1996– 2008), these increasing rates in groundwater temperature are definitely significant.

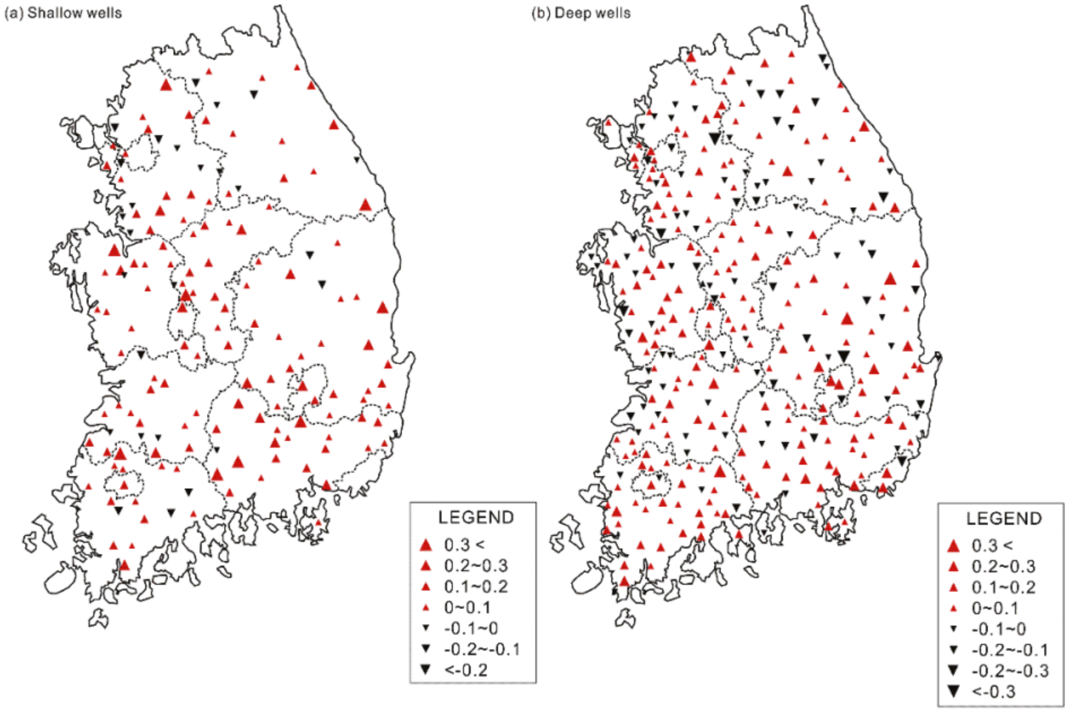


Fig. 8 Changing rates (1996-2008) of groundwater temperatures determined by the linear regression (unit: °C/yr).

4. Artificial recharge system using constant groundwater temperatures

Artificial recharge has been proposed to be the most promising method to solve the shortage in water resource brought about by climate change. There are two systems for water curtain cultivation systems for aquifer recharge: a groundwater recirculation system and a rainwater collection and injection system. Groundwater recirculation system is used for heating greenhouses from late Fall to early Spring. Used groundwater is not directly sent to aqueduct. Instead, it is sent back to aquifer in a nearby injection well to prevent depletion of groundwater resource, and to make continuous water curtain cultivation possible. Precipitation on the ceilings of greenhouses during the rainy season is collected in rainwater collection and injection system, and injected into the groundwater system to recover groundwater level that was lowered due to water curtain cultivation in the winter. Rainwater collection and injection system is an appropriate method for recent situation in which natural recharge gradually decreases due to more frequent heavy rainfall for a short duration. This kind of precipitation pattern was known to be caused by a global warming.

A pilot-scale test site was established in Nonsan area, Chungnam Province to study water curtain cultivation system for artificial recharge. The site covers the area of 1.2 km^2 excluding road, and approximately 30% (0.35km^2) of the site was used for water curtain cultivation. In the Wangjeon-ri area, 420 m^3/day/ha of groundwater is using for water curtain cultivation system estimated by monitoring data of groundwater level and stream water level. This amount of groundwater for water curtain cultivation system is corresponding to 40% of total agricultural use under the assumption of 5m during the operation period of all nationwide water curtain cultivation system.

There are 6 wells including two pumping wells, two injection wells, and two observation wells. Each pumping, injection and observation well system has for an alluvial aquifer and for a fractured aquifer. Overall protected cultivation system using groundwater curtain with geological circulation and rainwater harvesting is consisted of pumping system, water curtain system, collection system, injection system, operation system, water treatment system, and monitoring system.

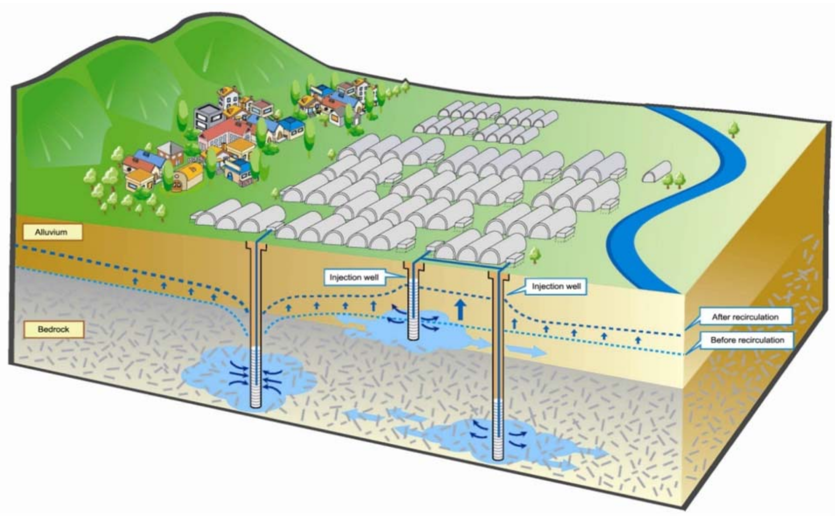


Fig. 9 A schematic diagram of water curtain cultivation system with an artificial recharge

To evaluate the hydrogeochemical characteristics, pumping tests, tracer tests (conservative tracer, dye tracer and thermal tracer), geophysical logging and water quality analysis is performed to evaluate groundwater occurrence such as velocity and groundwater pollution in this area.As a result of various tests, hydraulic conductivity of 3.47×10^{-6} m/s in fractured aquifer and 1.62×10^{-6} m/s in alluvial aquifer, and storativity of 4.52×10^{-4} in fractured aquifer and 0.15 in alluvial aquifer were estimated. Sustainable yield was estimated to be 18.51 m^3/d from step drawdown test. Analysis of tracer tests estimates effective porosity of 0.105, average linear velocity of 2.68×10^{-3} m/s and longitudinal dispersivity of 0.8 m. Transmissive fractured zone reveals to be 15-25 m below surface which is corresponding to a weathered fracture zones based on thermal tracer test and geophysical logging. The thermal tracer test using cool water reveals that the recovered from green house roof and injected cool water temperature is recovered to ambient groundwater temperature when it arrives at pumping well which means that the aquifer circulating water curtain cultivation system is effective to provide warming temperature to green house during winter time without dewatering aquifer.

Geothermal modeling was performed to study temperature recovery characteristics from pumping and injection in water curtain cultivation system for artificial recharge. Appropriate hydrological and geothermal parameters were applied to FEFLOW software to numerically model changes in pumping temperature with changing distance between pumping and injection wells, and effect of pumping temperature on overall system. Appropriate assumptions were made on the depth of aquifer, and hydrological and thermal variables. The system was modeled at distances of 15, 30, and 50 m. Thermal interference was not observed at the distance of 50m, and thermal content of the system after 2 year operation was found to be at least 134 kW.

A preliminary operation of the pilot system during the hot season using hot condition instead of cold condition resulted in the fact that geological circulating water curtain cultivation system is better than non-circulating system in terms of groundwater level, pumping rate, groundwater temperature recovery efficiency. During the practical operation during winter time in 2010, 6,100 m^3/yr of groundwater re-injected to the aquifer and if this kind of facility is expanded to the whole green house in the test basin, it will be 0.66 million m^3/yr of water can be recharged. If we assume that at least 50% of rainwater is collected and injected to injection well through the system, 4,750 m^3 of water can be estimated to inject into one injection well for a year.

References:

BSDUD (Berlin Senate Department of Urban Development) (1999): Groundwater Temperature. *Berlin Digital Environmental Atlas,* Berlin, Germany, 8 pp (chapter 02.14).

Bundschuh, J. (1993): Modeling annual variations of spring and groundwater temperatures associated with shallow aquifer systems. *J. Hydrol.* **142**, 427-444.

Chung, U., Choi, J., and Yun, J.I. (2004a): Urbanization effect on the observed change in mean monthly temperatures between 1951–1980 and 1971–2000 in Korea. *Climate Change*, **66**, 127-136.

Chung, Y.S., Yoon, M.B., and Kim, H.S. (2006): On climate variations and changes observed in south Korea. *Climate Change,* **66**, 151-161.

Hahn, J.S., Hahn, G.S., Hahn, H.S., Hahn, C.(2004): *Geothermal Heat Pump, Heating and Cooling Systems*. Hanrimwon, Seoul, Korea.

IPCC (International Panel on Climate Change) (2007): *Climate Change 2007: Synthesis Report.* IPCC, Geneva, Switzerland, 104 p.

Lee, K.S. and Chung, E.S. (2007): Hydrological effects of climate change, groundwater withdrawal, and land use in a small Korean watershed. *Hydrological Processes,* **21**, 3046-3056.

Lee, J.Y., Won, J.H., Hahn, J.S. (2006): Evaluation of hydrogeologic conditions for groundwater heat pumps: analysis with data from national groundwater monitoring stations. *Geosci. J.* **10**, 91-99.

Lee, J.Y., Yi, M.J., Yoo, Y.K., Ahn, K.H., Kim, G.B., Won, J.H. (2007): A review of national groundwater monitoring network (NGMN) in Korea. *Hydrol. Process*., **21**, 907-917

Min, B.O. (1979): A study on the climatic type in Korea by the characteristics of temperature distribution. *J. Kor. Soc. Oceanogr*. **3**, 29–46.

Taniguchi, M. and Uemura, T. (2005): Effects of urbanization and groundwater flow in the subsurface temperature in Osaka, Japan. *Physics of the Earth and Planetary Interiors*, **152**, 305-313.

Youn, Y.H. (2008): The climate variabilities of air temperature around the Korean Peninsular. *Advances in Atmospheric Sciences*, **22**, 575–584.

Land Collapse Issues in and around Kuala Lumpur

Qalam A'zad Rosle and Zakaria Mohamad
Minerals and Geoscience Department Malaysia (JMG)

Abstract: Kuala Lumpur and its vicinity which located in the Klang Valley areas are a fast growing city in Malaysia. Located in a region with a rather complex geological setting, it is underlain by number of geological formations ranging from Mid-Upper Silurian to Quaternary in age. The stratigraphic succession consist of the Kuala Lumpur Limestone Formation and Hawthorden Formation (Mid-Upper Silurian), the Kajang Formation (Mid-Upper Silurian – Devonian?), the Kenny Hill Formation (Permian-Carboniferous? – Triassic?), granite and its differentiates (Triassic-younger), the Batu Arang Basin (Tertiary) and alluvium (Quaternary). In the Kuala Lumpur city and its vicinity, the younger alluvium occupies the low lying area over the predominant Kuala Lumpur Limestone bedrock and were once the source of placer tin until into the early 1980's. Subsequent development of the city was conducted over these terrains of disturbed alluvium and the underlying limestone bedrock with its karstic features. Land collapsed or land subsidence issues remain as the main concerns to the public as well as the Local Authorities and numerous environmental NGO's. Technical agencies such as JMG as one of the technical department in governing the usage and monitoring the associated impacts of groundwater abstraction are keeping the watch. During past decades, land collapsed occurrence resulting in the formation of sinkholes due to mining activities. Vast existences of underground workings in form of tunnels, adits and shafts in the once active coal mining area of Batu Arang contributed to the occurrence of land subsidences and sinkholes formation. Recently, the ground subsidences were also encountered because of construction activities particularly during the excavation of the dual function SMART tunnel. While rapid development, agricultural and sand mining activities resulting in the dewatering of the peat swamp areas may also contribute to the occurrence of ground settlement or subsidence within the area. Ongoing hydrogeological study is undertaken by JMG as to ascertain the possible cause of ground settlement or subsidence. Study indicates that the coastal plain of the Langat Basin experience widespread ground surface settlement in the range of 0.02-0.20 meter from initial level. This however, has no probable direct linkage to the groundwater abstraction activities within the basin.

1. Introduction

This report is presenting the issues of land collapsed that is limited to the occurrence of sinkholes and land subsidence in Kuala Lumpur and its surrounding in relation to the geological, hydrogeological condition and groundwater abstraction. The author is also referring the Langat basin and the Batu Arang basin as part of the discussions related to the issues. The former which is a vast alluvial plain is located southwesterly from Kuala Lumpur in the district of Kuala Langat. Whereas, the latter is located to the northwest of the city in the district of Kuala Selangor at which both basins are located in the State of Selangor. As the capital city of Malaysia, Kuala Lumpur which is located in Klang valley is a fast developing metropolis with bustling traffic and real estate development. Developed on a once rich tin mining ground of placer tin found in the unconsolidated alluvium, city dwellers may have not known of their fragile ground. This is made worst due to the fact that below the overlying alluvium, is the ever problematic limestone bedrock with unforgiving karstic features.

2. Geology

Located in a region with a rather complex geological setting, the geology of the area is part of the western belt stratigraphic sub-division that comprise of number of geological formations ranging from Mid-Upper Silurian to Quaternary in age. The stratigraphic succession consist of the Kuala Lumpur Limestone Formation and Hawthorden Formation (Mid-Upper Silurian), the Kajang Formation (Mid-Upper Silurian-Devonian?), the Kenny Hill Formation (Permian- Carboniferous?-Triassic?), granite and its differentiates (Triassic-younger), and alluvium (Quaternary), as shown in Figure 1 and Table 1. Structurally, the area is controlled by series of NW-SE and NE-SW structural trend with prominent negative lineament truncating through.

The Kuala Lumpur Limestone Formation distribution is limited in the central part of Selangor, is a weakly metamorphosed limestone and marble outcropping prominently at Batu Caves, Selayang, Bukit Takun and Bukit Anak Takun in Rawang. From engineering perspective, the limestone in the Klang Valley is characterized by the presence of kIV to kV category tropical limestone karst (Zeinab *et al.*, 2009, Ooi, L.H., 2013), as shown in Figure 2, Figure 3 and Figure 4. The low grade metamorphism is believed due to igneous intrusion during Late Permian-Early Triassic. Generally, the limestone bedrock occupy the lowland area of the Klang valley. The limestone terrain is flanked by the existences of granite batholiths in the east and west. Some portion of the limestone shows presence of schistocity as evidenced from core box sample from the Sungai Way, now known as Bandar Sunway.

Further southwest in the State of Selangor, is located the vast Langat Basin with slightly different geological setup (Figure 5). The basin with total area coverage of approximately 2,100 km^2 can be subdivided into 1,115 km^2 of mountainous to hilly terrain and 945 km^2 of coastal plain. It is also considered as one of the highly developed basin in Peninsular Malaysia (Detlef, B., 2001). The low lying coastal plain is covered by the Quaternary alluvium that comprise of several unconsolidated sedimentary formations namely the Beruas Formation (young Alluvium), Gula Formation, Kempadang Formation, Simpang Formation (old Alluvium) and Boulder Beds. These young unconsolidated sediments comprise essentially of peat, clay, silt, sand, with minor gravel deposited in continental and marine environment. It is established that at least three layers of aquifer presence within the alluvium sequence in the Langat basin where fresh water aquifers located relatively further inland with brackish to saline aquifers close the coastline.

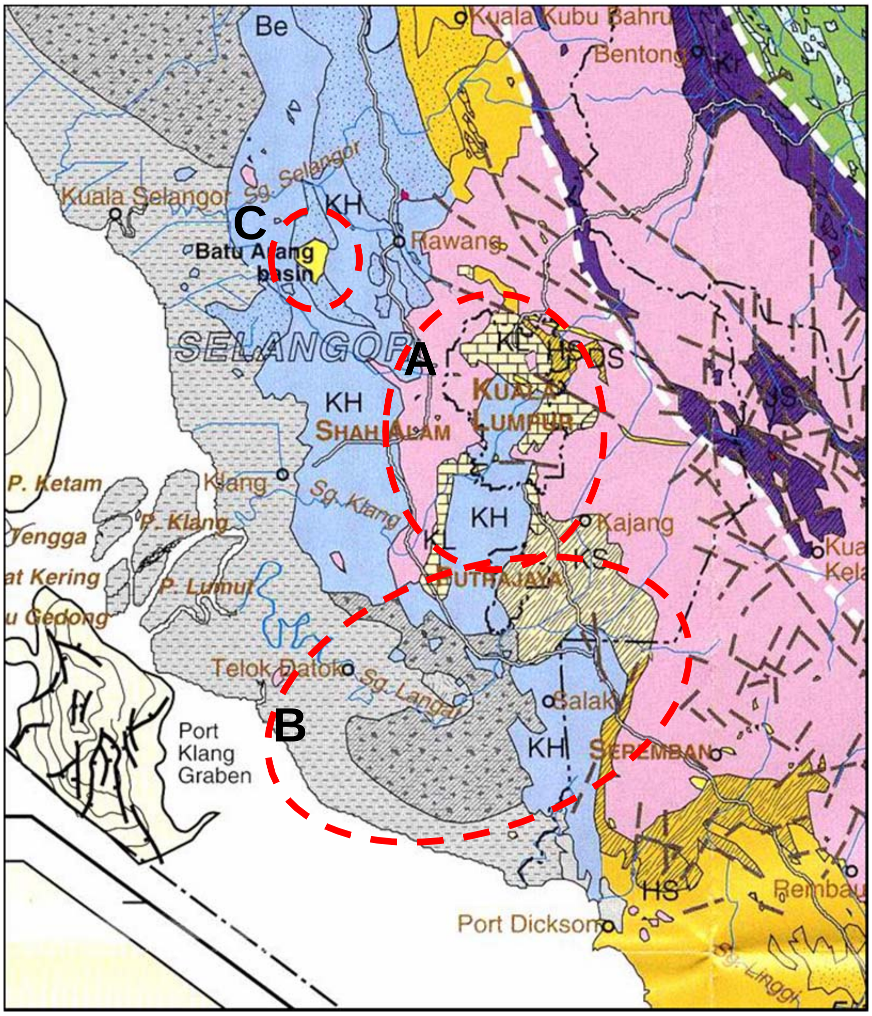


Figure 1: Geological map of the Kuala Lumpur and Kuala Langat Area (Source; Geological Society of Malaysia, 2008). (A): Kuala Lumpur, (B): Langat Basin and (C): Batu Arang Basin.

Table 1: Stratigraphic column of the Kuala Lumpur and Kuala Langat area.

Legend	Geological Formation	Age
(grey)	Alluvium	Quaternary
(yellow)	Batu Arang	Upper Oligocene-Pliocene
KH	Kenny Hill	Carboniferous
KL KS	Kuala Lumpur Limestone Kajang Schist	Silurian-Devonian
HS	Hawthorden Schist	Ordovician
DS	Dinding Schist	Cambrian

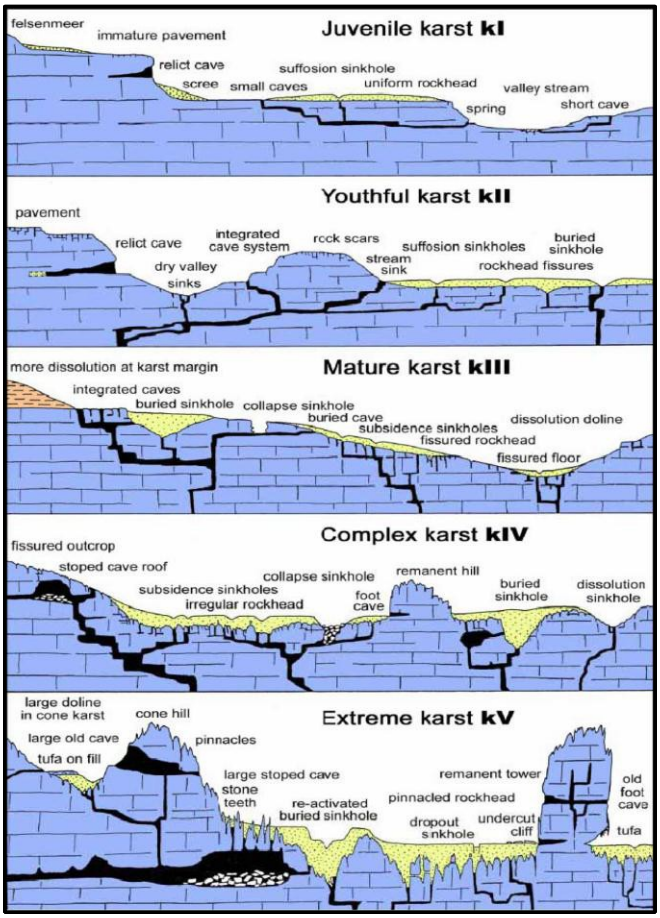


Figure 2: Morphological feature of karstic limestone within the five classes of engineering classification of karst. The Kuala Lumpur Limestone Formation fell into the category Complex karst kIV to Extreme karst kV (classification of Waltham and Fookes, 2003, source from Zeinab, *et al.*, 2009).

Figure 3: Flat-top feature of the sub-surface Kuala Lumpur Limestone exposed during mining activity in the Klang valley. Prominent dissolution features characterized by reddish staining formed on vertical rock surfaces (Source from Tan, S.M., 2005).

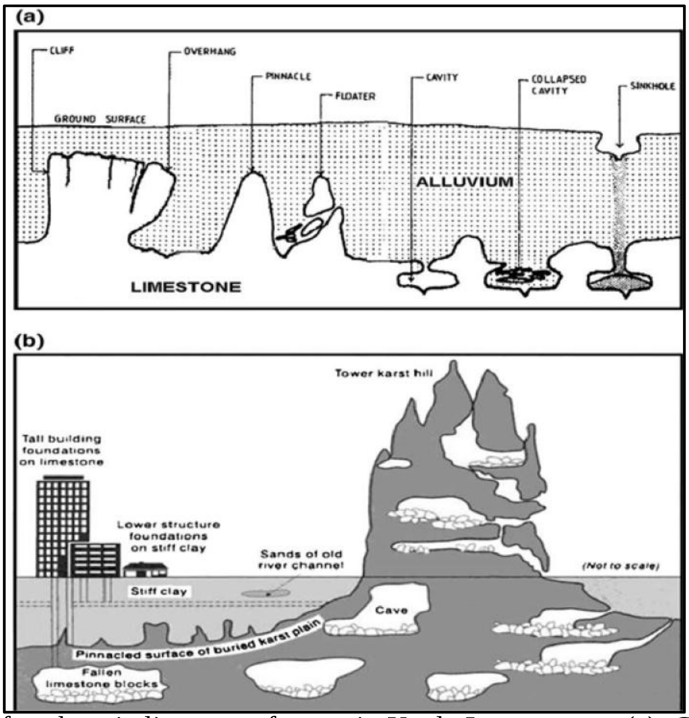


Figure 4: Subsurface karstic limestone feature in Kuala Lumpur area (a). Construction foundation issues associated with subsurface limestone conditions in Batu Caves, Kuala Lumpur (b). (a), after Chang and Hong, 1986. (b) after Douglas, 2005. (Source from Zeinab, *et al*., 2009).

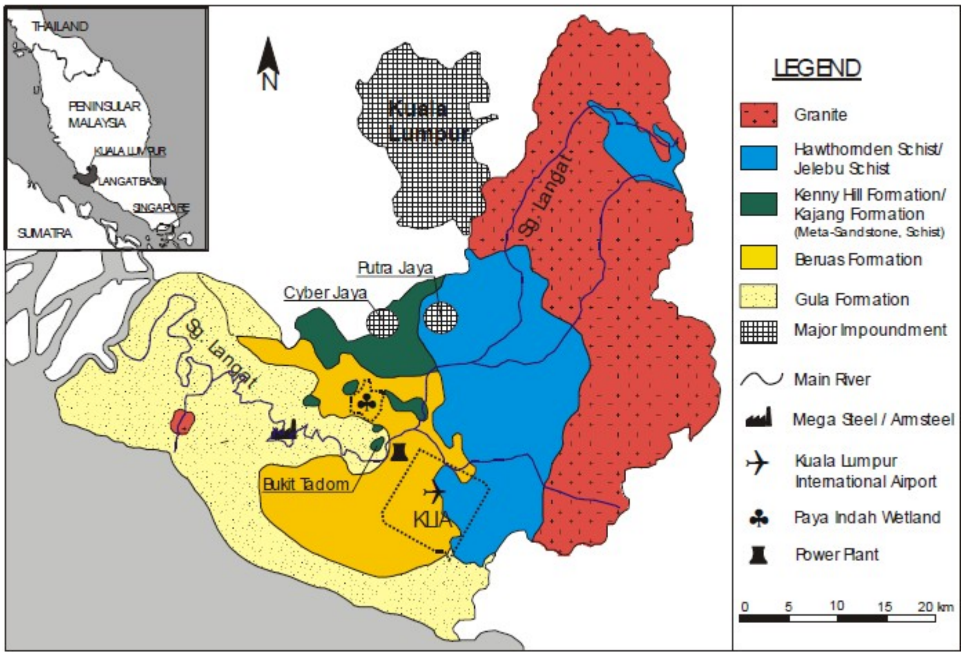


Figure 5: Geology of the Langat basin with some of the important landuse within the basin (Source: Detlef B., 2001).

To the northwest region of Kuala Lumpur is located one of the few inland Tertiary basin found in Peninsular Malaysia, the Batu Arang basin, as seen in Figure 1 and Figure 6. Stratigraphically, the sedimentary succession can be divided into two major sequences. First, the lower sequence that comprise of interbedded shales, clays, siltstone, sandstone and two layers of coal seams laying unconformably on the Kenny Hill Formation believed to be Late Oligocene to Miocene in age. This sequence also widely as the Coal Measures or the Batu Arang Beds (Raj, J.K., *et al*., 2009) Second, is the younger Boulder Beds of Pleistocene in age that unconformably overlying the former. The latter sequence comprise predominantly of boulders, pebbles and sub-angular fragments of quartzite embedded in sandy to gravelly matrix. Generally, the lithology of the Batu Arang basin outcrop as gently dipping, broad plunging syncline towards southwest.

Coal mining activities were once thriving in the area with both surface and underground method were employed. Mining was active from 1915 to 1960 thus leaving networks of tunnel, shafts and adits over the basin's coverage. Reportedly, surface depression and minor sinkholes occurrence were detected in the area since in the mid 1980's.

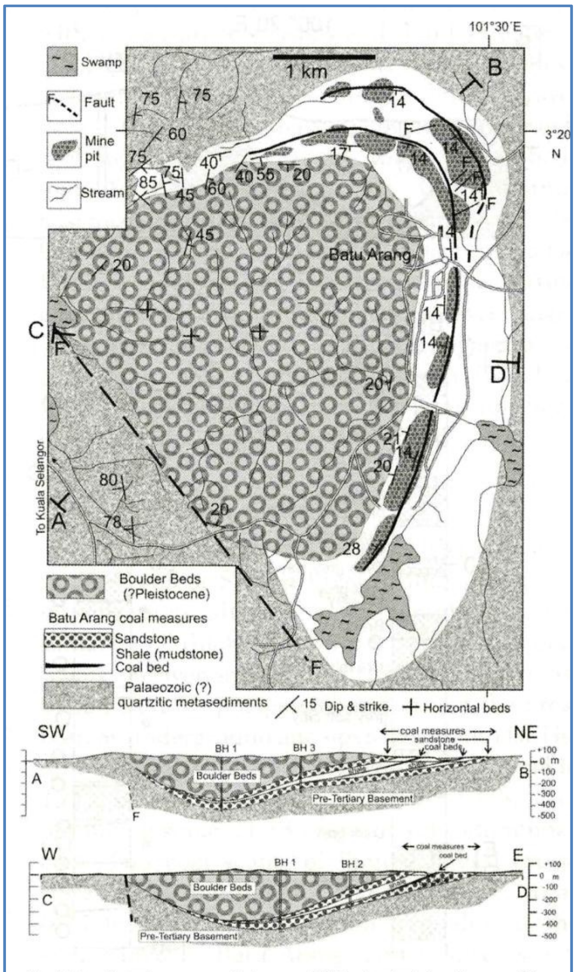


Fig. 7.3: Batu Arang area, Selangor. (A) Geological sketch map. (B) Geological cross-sections. After Raj (1998). Locations of cross-sections shown in A.

Figure 6: Geology and cross section of the Batu Arang area (Raj, J.K., *et al*., 2009).

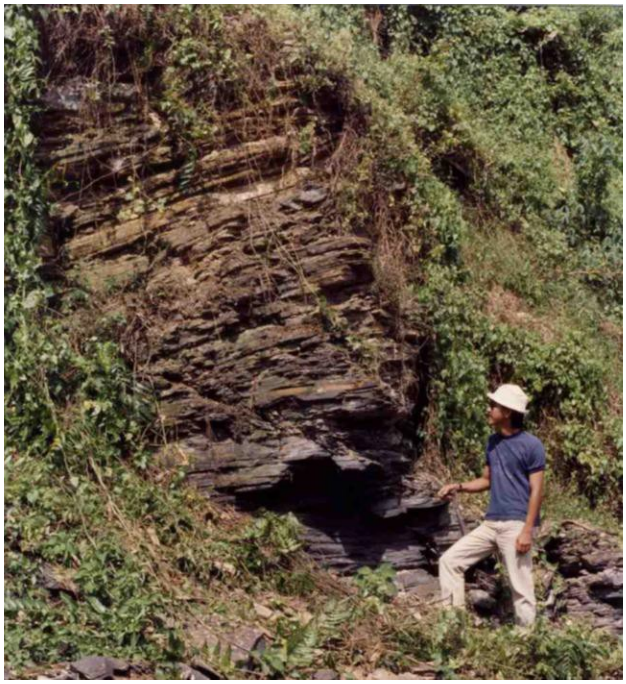


Figure 7: Outcrop of gently dipping shale beds in Batu Arang area (Photo courtesy of Prof. Dr. J.K. Raj, University of Malaya).

3. Hydrogeology and Groundwater Abstraction

Underlain predominantly by limestone, hydrogeology of the Kuala Lumpur area is attributed to the presence of limestone and its karstic features as the existence of cavities and networks of tunnels that may hold large amount of groundwater storage. Shallower hydrogeological regime is within of alluvium cover that predominantly comprise of highly heterogenous layers of disturb alluvium with content from slime to sand (Tan, S.M., 2005) and possibly minor gravel. Thickness of this disturbed overburden ranging from 30 to 50 meters. Figure 8 shows yield from less than 5.0 m^3/hour to more than 20m3/hour is attainable. Under the authority of the Kuala Lumpur City Council (DBKL), there is however no regulating body pertaining to groundwater abstractions and usage within the city limit. JMG however, plays an important role in providing technical advices and consultancy prior to well development. Most of the groundwater usage within the city area is by the construction industry and industrial sector.

In the Langat basin, hydrogeological aspect of the area is mainly associated with presence of the alluvium cover. Most of the groundwater abstractions in the state of Selangor occur here with industrial sector being the primary user. Yield of between 10 m^3/hour to more than 20 m^3/hour is attainable from the alluvial aquifer, as shown in Figure 8. Study by JICA and JMG in the early 2000's indicate a large amount of groundwater resource from three different layers of aquifer present within the basin and came up with a safe yield for the basin at 10 mgd/day (million gallon per day). Mega Steel Sdn. Bhd., a major player in steel industry in the country is the prime user of groundwater in the area with an allowable abstraction rate of 6 mgd/day. Due the extent of the industrial activities within the basin, demand for groundwater usage has increased each year with a proposed safe yield of 11 mgd. However, due to the lack in up to date data and detailed technical evaluation pertaining to the groundwater capacity of the Langat basin, 10 mgd remain the allowable rate to date. In the Selangor state, groundwater abstraction and usage is sanction under the State Legislative body whereby Lembaga Urus Air Selangor (LUAS) and JMG are the agencies responsible in licensing and technical requirement specifications. Table 2 shows the amount of groundwater abstraction from the Langat basin alone from 2005 to 2012. Concerns also raised by various parties particularly affiliated to the environmental group with land subsidence remain the main issue besides other general environmental degradation.

In the Batu Arang Basin area, hydrogeological condition is associated with the predominant presence of the Tertiary sedimentary deposits and the vast network of underground tunnel within the basin. However groundwater usage in the area is very limited as record shows only two exploration wells were developed with yield more than 20 m^3/hour, as shown in Figure 8. The subsurface ground condition of the Batu Arang area, groundwater quality and previous cases of land collapsed may as well hampered the exploitation of groundwater in the area.

Table 2: Ground water abstraction amount from the Langat basin from 2005-2012. (Source from LUAS, 2013)

Year	Volume (m^3)
2005	1,037,951.20
2006	3,072,947.60
2007	12,490,730.00
2008	7,465,274.00
2009	6,201,506.40
2010	2,107,988.40
2011	16,176,124.00
2012	12,557,171.60

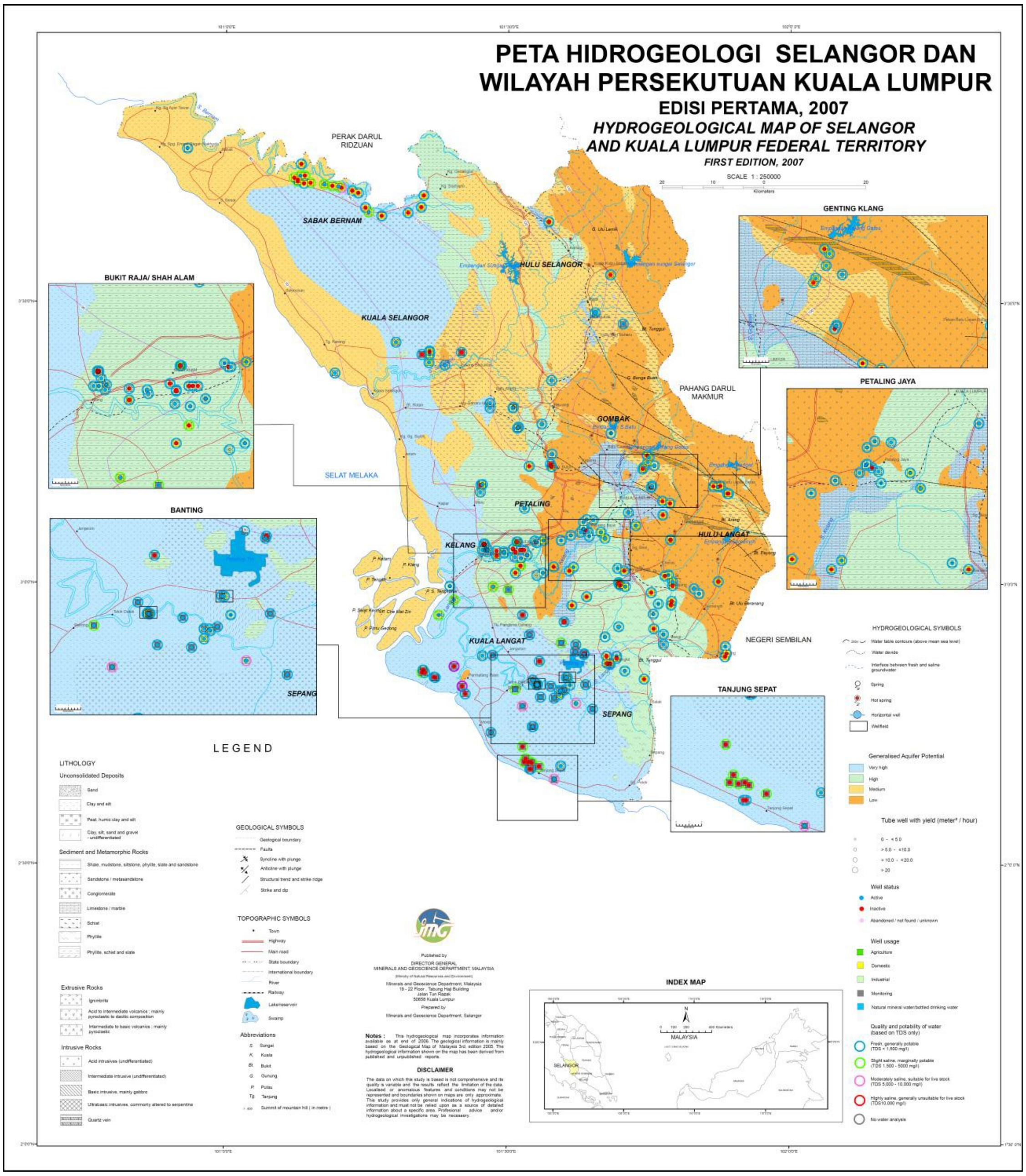


Figure 8: Hydrogeological map of Selangor and Kuala Lumpur (JMG, 2007).

4. Land Collapsed History

4.1 Land Collapsed in Kuala Lumpur and Klang Valley

The archived event of sinkholes and land subsidence were not available as many of the records may have vanished during the years. Land collapse, formation of sinkholes and land subsidence may have resulted due to various factors. Seldom out of the many cases are purely related to natural geological and environmental condition, most of the occurrence of land collapsed recorded are triggered by human activity. Construction and mining related activities among others such as drilling works, bore pilling, groundwater withdrawals due to open cast pit and in some cases because of burst pipe during civil works.

In the Klang valley and the Kuala Lumpur area, work by Tan, S.M., (2005) listed some of the recorded prominent land collapsed events, as shown in Table 3. Previous recorded event of land subsidence by JMG formerly known as Geological Survey of Malaysia was the 1979 land subsidence at Serdang Lama and the 1983 land subsidence at kilometer 22 Kuala Lumpur-Seremban southbound highway, as shown in Figure 9 and Figure 10. Groundwater withdrawal was the cause of the ground subsidence. Mining activities in the nearby area adopting the open cast method resulting in groundwater migration from the higher ground into the pit thus causing the ground to collapsed.

Table 3: Recorded occurrence of land collapsed in Kuala Lumpur and its vicinity.
(Source from Tan, S.M., 2005 for 1968-2004 events,Geological Survey of Malaysia and various sources).

No.	Location	Year	Remarks
1.	Selangor Science Park, Cyberjaya	2013	Soft sediments settlement
2.	Jalan Universiti, Petaling Jaya	2010	Sinkholes (burst pipe)
3.	Taman Putra Prima 8A, Puchong	2010	Sinkholes
4.	Taman Cuepacs, Segambut	2009	Sinkholes
5.	Jalan San Peng	2009	Sinkholes (pipe leakages)
6.	Jalan Cheras, Kuala Lumnpur	2004	Construction related
7.	Jalan Tun Razak, Kuala Lumpur	2004	Construction related
8.	Subang Hitech Park	1998	Groundwater abstraction
9.	GESB	1995	Drilling and pilling activities
10.	Jalan Lidcole	1995	Drilling and pilling activities
11.	Datuk Keramat	1995	Construction
12.	Jalan P. Ramlee	1993	Construction related (bore piling activity)
13.	Taman Cheras Indah	1984	Sinkholes, foundation damages
14.	Kuala Lumpur-Seremban Highway (southbound)	1983	Groundwater withdrawals due to mining activity
15.	Undisclosed location of PKNS housing scheme	1983	Building on ex-mining land, foundation settlement
16.	Taman Sri Serdang	1981	Building on ex-mining land
17.	Cambell Shopping Complex, Jalan Dang Wangi, Kuala Lumpur	1972	Construction related, pilling works
18.	Jalan Raja Laut	1968	Foundation failure over weak limestone bedrock
19.	Cases in Jinjang and Kepong, Kuala Lumpur	Undated	Sinkholes

Figure 9: Serdang Lama landsubsidence, 1979 (Geological Survey Report, No. E(F)4/1979).

Figure 10: The Kuala Lumpur-Seremban southbound highway land subsidence, 1983 (Geological Survey Report, No. E(F)5/1983).

No major land collapsed cases were recorded after the 1980's as mining activities were ceased beyond that. However, various cases of land collapsed reoccurred as construction took place on the ex-mining land that occupies most of the flat lying open spaces. Insufficient foundation requirement seated on soft mined-out area with tailings and ponds that were later filled to provide platforms for construction give way to ground subsidence and to the worst case of sinkholes formation in the later stage. With the Federal Government funded project of dual function SMART tunnel that bores through the predominantly Kuala Lumpur Limestone Formation, more later cases of land collapsed were recorded in vicinity of the tunnel alignment tunnel in between 1998-2005, as shown in Figure 11. Numerous formations of sink holes and ground settlement occurred within the city limits resulting in structural damaged of buildings, paved roads and underground utilities as well as several other cases that associated with various civil workings, as shown in Figure 12, Figure 13, Figure 14 and Figure 15. The impacts can be translated into substantial amount of loses and disturbance to the livelihood of city dwellers. Road surface settlement subsequently lead to chaotic traffic flow within the ever buzy city streets. The issues were resolved by the City Hall and the project proponent accordingly.

More recent event of land collapsed was the Selangor Science Park in Cyberjaya, at which an overpass under construction was destroyed as columns supporting the road deck sunk into the ground underlain by soft sediment formation, as seen in Figure 15. With the current ongoing tunnel excavation for the ultra-modern Klang Valley Mass Rapid Transit System (KVMRT) project that kicks off with the ground work in late 2012, the authorities and the city dwellers should expect some occurrence of land collapsed and sinkholes formation in areas underlain by limestone and covered with alluvium with mitigation measures are in the mind of the technical experts.

Figure 11: Numerous sinkholes and ground settlement occurrences within the Kuala Lumpur city limit during the construction of the SMART tunnel between 1998-2005. The events resulting substantial damage to properties and causing traffic disruption. (Photo from undated The Star news articles).

Figure 12: GESB sinkholes in 1995, possible cause of sinkholes due to nearby drilling and pilling works. (Source: Tang, S.M., 2005).

Figure 13: Sink holes developed in Jalan Universiti due to pipe burst destroying vehicles and injury to commuter. (Source: The Star Malaysia, 27/04/2010).

Figure 14: Small scale sinkholes development and formation in a housing scheme at Jalan Putra Prima , Puchong. (Source: Taman Putra Prima 8A Community website).

Figure 15: Recent overpass collapse in Cyberjaya Science Park. Construction was carried out in the alluvium cover of the Langat basin. (Source: The Star, Malaysia).

4.2 Land Collapse in Batu Arang Area

More significant event of sinkholes formation perhaps was the 1991 land collapse in the township of Batu Arang, located approximately 30 kilometer northwest of Kuala Lumpur, as shown in Figure 16 and Figure 17. After the abandonment from coal mining that lasted until the mid 1960’s, the area was once again extracted of the rich geological resources. In the late 1980’s, permission was granted for quarrying of shales as raw material by the Associated Pan Malaysian Cement (APMC) cement production plant. Open cast method of quarrying was adopted resulting in the formation deep pit resulting in the possible drawdown of groundwater in the vicinity of the open cast pit, Figure 18A and Figure 18B. Besides formation of sinkholes, widespread occurrence of land subsidence over the Batu Arang township resulting in damage to existing building structure over time, Figure 18C and Figure 18D. However, study by a technical committee formed to oversee the problem stated that there is no direct evidence linking the sinkholes formation to groundwater withdrawals due to the quarrying activities. The cause of ground collapsed in the area was found to be of gradual down-warping (ground convergence) into underground openings, whilst sinkholes formation due to caving of overburden material and being able to move laterally into the adjacent underground opening (Hassan, M.A., 1993 and Raj, J.K., 1993). Primary factor contributing into this phenomenon has been the loss of strength of the coal seams and overburden material. Limited roof support and stowage in the previous underground workings may also resulting in the ground subsidence and formation of sinkholes as evidence indicate some of the cases occur over area with bricked or timbered workings (Hassan, M.A.,1993 and Raj, J.K., 1993). Post mining activity flooding of the underground openings may have expedite the weakening of the brick and woodworks structure submerged underwater for a long period. Future development of ground subsidence and formation of sinkholes is expected in the Batu Arang area base on the previous cases as data from past survey and mapping indicate (Hassan, M.A.,1993 and Raj, J.K., 1993).

Figure 16: The 1991 sinkhole formation in a field near the Batu Arang town. (Photograph courtesy of Prof. Dr. Raj, J.K., University Malaya).

Figure 17: Smaller size sinkholes formation in the nearby field. (Photograph courtesy of Prof. Dr. Raj, J.K., University of Malaya).

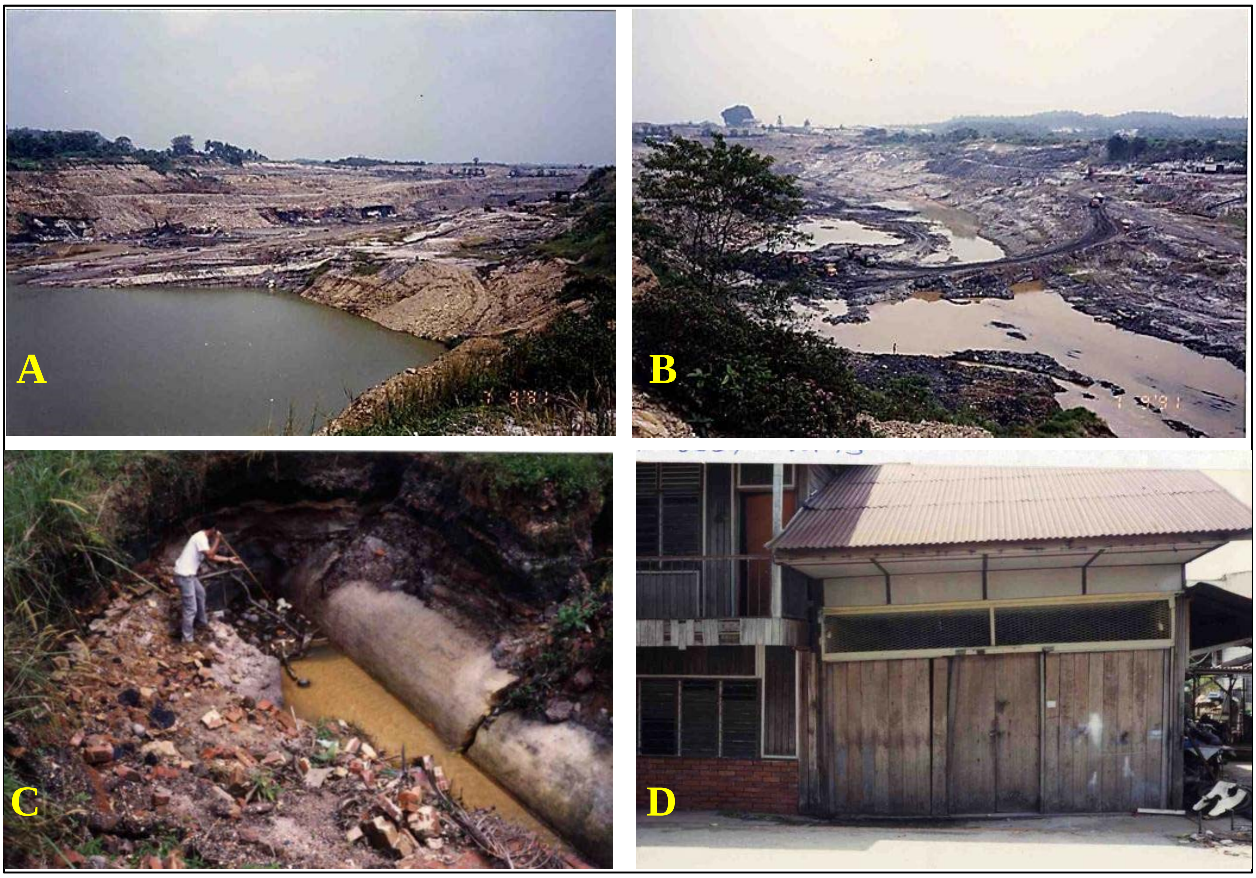


Figure 18: Photo A and B showing the open cast quarrying of shale bedrock. Photo C showing collapsed culvert due to river bed collapsed. Photo D showing ground collapsed and sinkhole formation below buildings resulting in damage to building structure. (Photographs is courtesy of Prof. Dr. Raj, J.K., University of Malaya).

Following the event of land collapsed, ground subsidence and formation of sinkholes, concerns over the well beings of the residents, the Batu Arang area was declared unsafe by the state authority. About 10,000 residents were relocated to the new nearby township of Bandar Baru Batu Arang (NST, 2nd August, 1992).

4.3 Land Collapse in Langat Basin

In the Langat basin, subsequent to the study by JICA and JMG in the early 2000's, periodical land subsidence monitoring program was conducted by staff of the JMG. Using Topcon Auto Level ATF6S Series, datum points and bench markers installed in strategic locations were surveyed. Evidence of widespread land subsidence throughout the area is prominent, as shown in Figure 19. Figure 20 shows the location of datum point (DP) and bench markers (BM) installed within the Langat basin. Data from 2001 to 2009 indicate that a widespread occurrence of land subsidence occurred. A substantial amount of surface depressions were recorded ranging from 0.02 to 0.20 meter, as shown in Figure 21. The findings however, remain uncertain of their relationship with the current groundwater abstraction within the basin. This is due the fact that all of the bench markers was installed in the near surface shallow layer of peaty organic soil. Agriculture activities in the fertile top layer of soil in the Langat basin in many cases were drained for cultivation. Development of new housing schemes, commercials centre and construction of infrastructure such as highways also contributed to the excessive draining of the top layer thus causing possible widespread surface subsidence as groundwater withdrawals from upper layer of the peat and organic rich soil resulting in consolidation and loss of volume. While the major abstractions of groundwater are from the deeper aquifers, evidence of subsiding due to the collapse of these layers is yet to be established.

Figure 19: Recent photos showing evidence of ground subsidence within the Langat basin. Photo at the top and bottom showing raised datum point and groundwater well structure relative to the ground surface respectively.

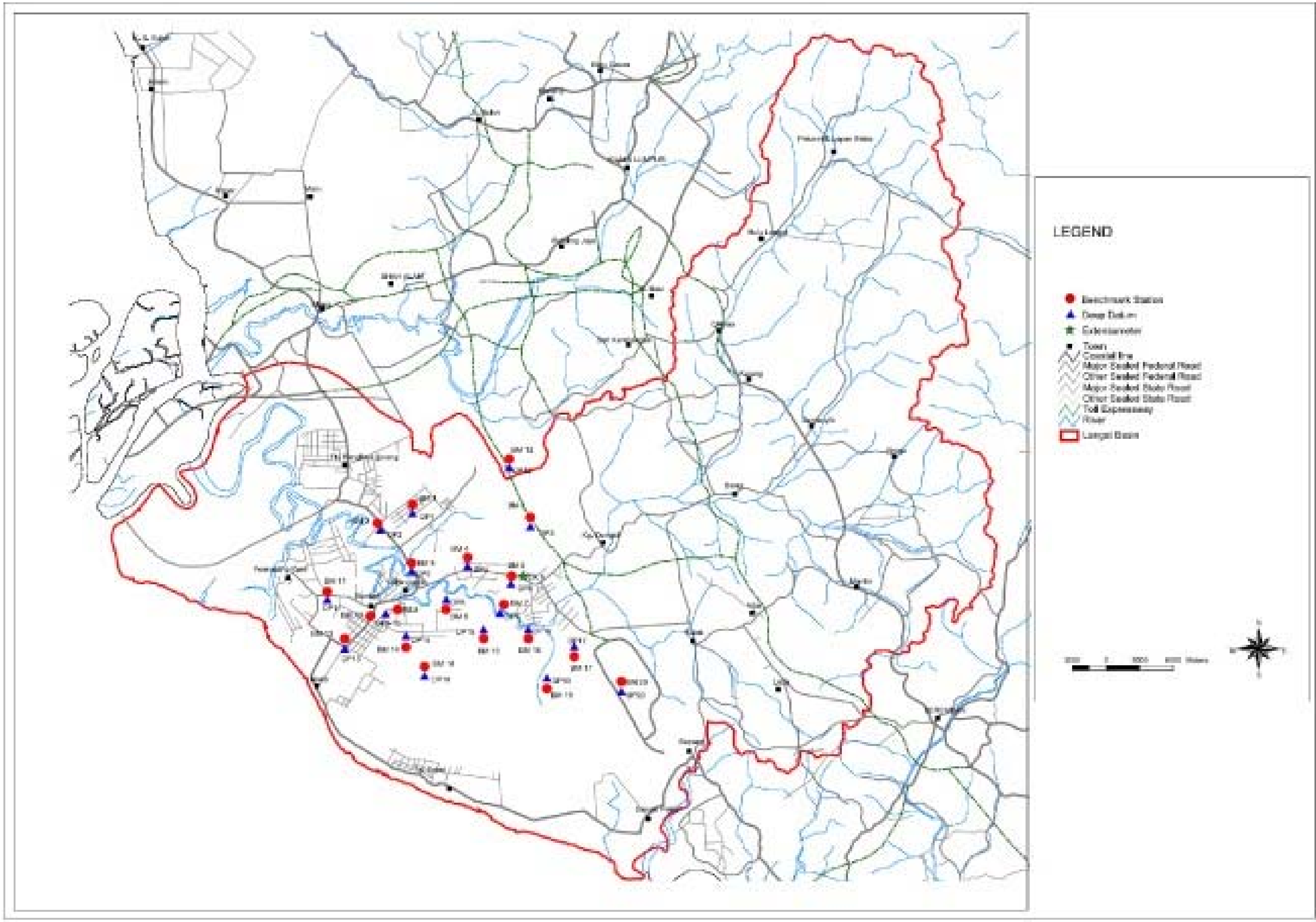


Figure 20: Location of land subsidence monitoring station (JICA-JMG, 2002).

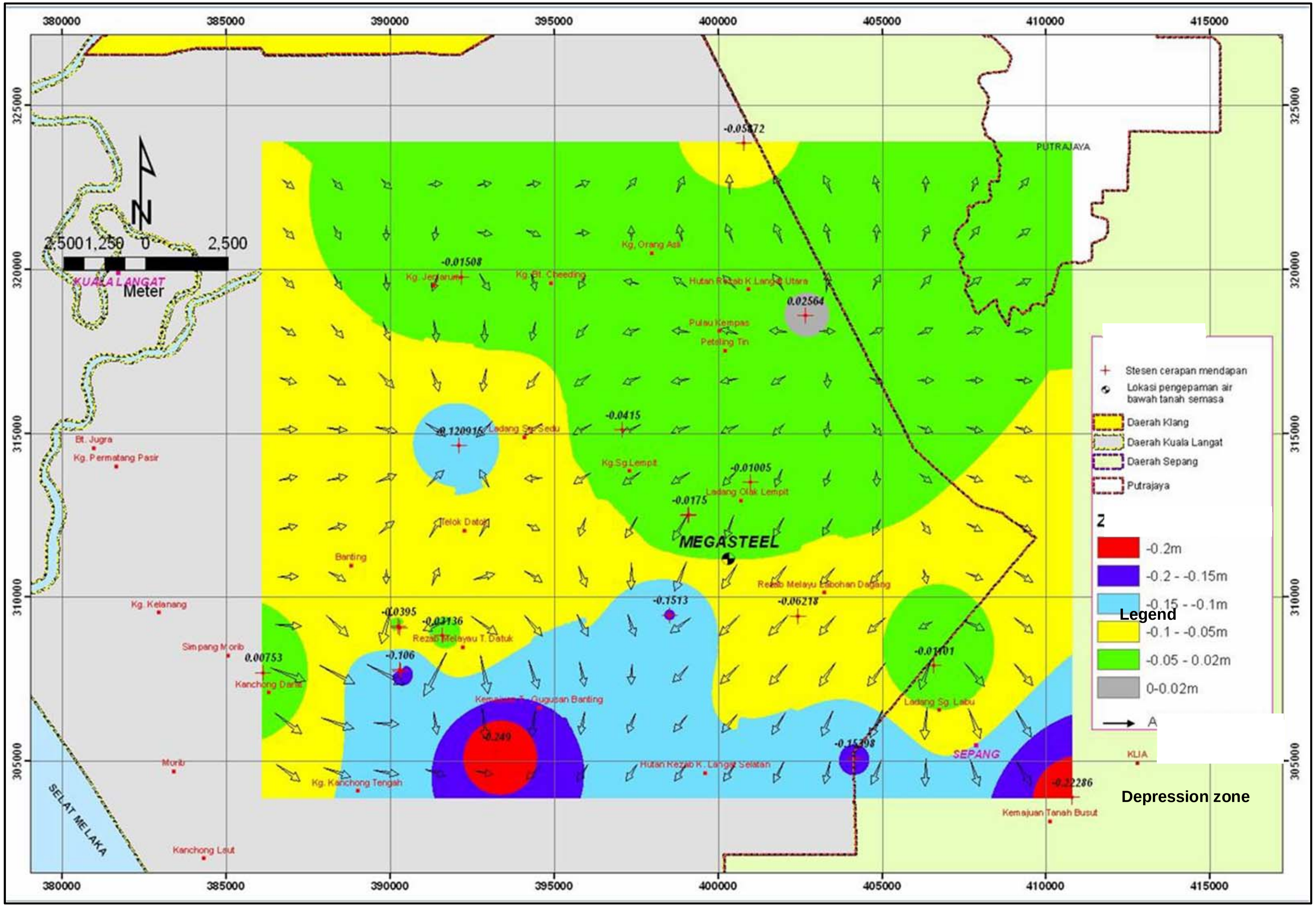


Figure 21: Isopach map showing differential surface depression zone within the Langat basin (JMG 2009).

5. Conclusions

Land collapsed issues or land subsidence within the Kuala Lumpur in particular and the Klang valley in general had been attributed to the presence of the limestone bedrock in the area. Presence of layer of disturbed alluvium cover contributed further to the fragile ground condition resulting in the occurrence of ground subsidence and the formation of sinkholes that commonly triggered by lowering of groundwater table due to civil works. Past mining activity in the Batu Arang area, resulting in the formation of vast network of underground working thus creating an unstable ground condition that is prone to eventual land collapsed. As for the Langat basin, while development and agricultural activities contributed to the draining of the peaty soil layer, groundwater abstraction may play and important role too in contributing the current issue of widespread land subsidence in the area at which further detail study is necessary to establish the condition. While development is thriving in the Klang Valley and Selangor in general, activities on these fragile ground must be well regulated, with land collapsed issues amongst to be taken into the hands of the authority and technical experts as to safeguard the environment and the inhabitants.

References:

Detlef, B. (2001): Groundwater exploration adjacent to the Kuala Lumpur International Airport/Malaysia-challenges and chances of exploring a fractured rock aquifer. Coffey Geotechnics Pty Ltd, Australia.

Hutchison, C.S and Tan, D.N.K. (2009): *Geology of Peninsular Malaysia*. The University of Malaya and The Geological Society of Malaysia.

Ooi, L.H. (2013): Geology is Important - The Art & Science of Underground Works in Karst - 29-30 Jan 2013. IGM Outreach Program 2013.

Mohamad Ali Hassan (1993): Subsidence history and future subsidence in the Batu Arang area, Selangor Darul Ehsan-some further thoughts. *Ann. Conf. Geol. Soc. Malaysia.*

News Straits Times, August 2nd 1991.

Raj, J.K. (1993): Coal mining and ground surface subsidence at Batu Arang, Negeri Selangor Darul Ehsan. *Ann. Conf. Geol. Soc. Malaysia*.

Shu, Y.K. (1983): Subsidence at 22 KM, Kuala Lumpur-Seremban Highway. *Geological Survey Report*, **E(F)5**.

Shu, Y.K. and Chow, W.S. (1979): Land Subsidence at Serdang Lama, Selangor Volume I. *Geological Survey Report,* **E(F)4**

Tan, B.K. (2006): Urban Geology of Kuala Lumpur and Ipoh, MalaysiaEnvironmental. *IAEG2006 Paper*, **24**.

Tan, S.M. (2005): Karstic Features of Kuala Lumpur Limestone. *Bulettin IEM.*

Zeinab, B. *et al.,* (1996): An Overview of Subsurface Karst Features Associated with Geological Studies in Malaysia. *Mountainous Terrain Development Research Center Department of Civil Engineering and Faculty of Engineering, University Putra Malaysia.*

Groundwater Resources Development in Myanmar

Win Myint

Department of Geological Survey and Mineral Exploration, Ministry of Mines,

the Republic of the Union of Myanmar

1. Introduction

Myanmar is situated in Sourth-East Asia between latitudes 9° 32' and 28° 31' N and longitudes 92° 10' and 101° 11' E and has a total land area of 676, 577 sq.km (261, 227 Sq mi). It extends 1,931 km (1,200 mi) north to south and 925 km (575 mi) east to west. It has a total coastline of 2,276 km (1,414 mi) and total international land borders of 5,858 km (3,641 mi) with five countries as follows: China (2,185 km, 1,357 mi), Thailand (1,799 km, 1,118 mi), India (1,403 km, 872 mi), Laos DPR (238 km, 148 mi) and Bangladesh (233 km, 145 mi). Most of the land frontiers are defined by mountains.

1.1 Population

The present population of Myanmar is estimated at 54.3 million and rural population is about 70% of total. The projection for 2015 will become 63.4 million and it is expected to increase by around 50% by the year 2025. The present average population density of the country is nearly one person per hectare.

1.2 Country Economy

Myanmar is an agro-based country, and agricultural sector is the back bone of its economy. Agricultural sector contributes 43% of GDP, 15% of total export earnings, and employs 63% of the labour force.

1.3 Land Utilization

Twenty five percent of the total area of the country is a culturable land. Presently, there are about 26.89 m acres (1.88 m ha) of net sown area in Mynmar. Expansion of new agricultural land, remaining 0.89 million acres (0.36 m ha) fallow land and 15.22 million acres (6.16 m ha) cultivable land is being encouraged. The following is some data for land utilization in Myanmar (2005-2006).

Land Utilization in Myanmar (2005-2006)	**(m ha)**
Net sown area	10.88
Fallow land	0.36

Cultivable waste land	6.16
Reserved forests	16.72
Other forests	16.88
Others	16.65
Total	67.65

1.4 Administrative Regions

The administrative regions of the country consists of seven States Divisions as follows:

1.	Kachin State	8.	Magway Region
2.	Kayah State	9.	Mandalay Region
3.	Kayin State	10.	Mon Region
4.	Chin State	11.	Rakhine State
5.	Sagaing Region	12.	Yangon Region
6.	Tanintharyi Region	13.	Shan State
7.	Bago Region	14.	Ayeyarwady Region

2. General Geology

Myanmar relative to its size, possesses an impressive record of rocks representing practieally as the standard periods of the geologic column. It is conveniently divisible into four geological regions each of which by its own right is a geotectonic belt possessing a separate stratigraphic succession and a deformational history. They are from east to west: the Eastern Highlands, the Central Belt, the Western Ranges, and the Rakhine Coastal Belt.

2.1 Eastern Highlands

The Eastern Highlands which include the northern and eastern mountainous tract of the Kachin State in the north, the Shan Plateau in the middle, and the Tanintharyi ranges in the south. The presence of Precambrian orthogneisses and low-grade meta-sedimentary rocks (Chaung Magyi Group), Paleozoic and Mesozoic carbonates, clastics, and igneous rocks enable this province to remain as a highland, locally with Karst topography in the limesones areas. The Chaung Magyi sediments were laid down probably in a eugeosyline, the Paleozoic carbonates and clastics in a shallow sea, and Mesozoic clastics and evaporates in enclosed and intermontane the opirogenic movements at the end of Mesozoic. Since then, it has been a fairly stable block. Large linear granitoid plutons of mainly Upper Mesozoic and Lower Tertiary ages intruded along the western marginal zone of this province. These plutons were subduction-related igneous bodies that intruded along the weak junction zone between the tectonic provinces during late Mesozoic and Early Tertiary.

2.2 Central Lowlands or Central Cenozoic Belt

The Shan Plateau and Western Mountains were uplifted during late Cretaceous and early Tertiary times. The Central Belt was then a subsiding trough which was gradually infilled with vest thickness of sediments possibly exceeding 75,000 feet. Fluviatile and deltaic sedimentation continually advanced to the south. In general, the northen portion of the Central Belt is characterized by the continental sedimentation whereas the southern part is marine. In the late Tertiary, tectonic movements resulted in broad folding and occasionally thrusting of the Tertiary sediments (general north-northwest strike for folds; north-northwest and north-east fault systems); the Bago Yoma hills were uplifted during this period and divided the southern part of the Central Belt into two alluvial valleys. Recently, the Ayeyarwaddy/Chidwin system has built up a huge alluvial delta to the Andaman Sea. Earth movements have continued and have affected the deposition of the Quaternary alluvium.

The General type area for the Tertiary sediments is the Minbu Basin in the Central Myanmar. Here, the Eocenes, Peguan and Irrawaddian Series are separated from one another by unconformities. The Central Volcanic Line has divided this province into two halves since about Miocene. This igneous line starts from the Jade Mines area in the north, through the Wuntho igneous mass, Lower Chidwin Volcanoes, Salingyi, Shinmadaung, Mt. Popa, east of Zegon and Tharyarwady, to Myaungmya area in the south. The well-known Sagaing Fault, a right-lateral strike-slip fault, that runs north-south for a distance of nearly 600 miles is located near the eastern edge of the province.

2.3 Western Ranges or Indo-Burma Ranges

It comprises Naga Hills, Chin Hills and Rakhine Yoma. They are underlain by a thick, mildly deformed, tightly folded and weakly metamorphosed sequence of flysch type deposits, which apparently were deposited in as subduction trench that lay between the Eurasian plate and northeastward-subducting Indian plate. Exotic limestone ranging in size from tiny blocks to mappable units, ophiolites and metamorphic tectonites are locally present within the disrupted flysch deposits. The Western Ranges arose as the results of folding, over thrusting and uplifting during the Early Himalayan Orogeny at the close of Eocene.

2.4 Rakhine Coastal Belt

The Rakhine Coastal lowland is underlain by Upper Createaceous type deposits and lower Tertiary rocks in the south and by Upper Tertiary clastic sedimentary rocks of molassic character in the north. The strata are tightly folded and form chains of low hills. It is the southern continuation of the Assam Basin in northeastern India where a thick Tertiary succession is also present. The Minbu and Assam Basins are fairly similar not only stratigraphy and lithology, but also in the occurrence of oil and gas, especially in the Oligocene and Miocene formations.

3. Physiography and Drainage

The physiography of Myanmar closely reflects its geology. Then the country can be divided into four physiographic units corresponding to the geological units listed in the previous section. Major drainage lines in Myanmar are from north to south.

The deeply dissected Shan Plateau rises to an average elevation of about 914 m (3,000 ft) above sea level. The western edge is clearly marked off from the Central Belt by a north-south cliff or fault scarp, which often rises 610 m (2,000 ft) in a single step. Much of the surface of this plateau is of a steeply rolling, hilly nature. In other parts mountain masses rise abruptly to heights of 1,829 m (6,000 ft) or more. Several of the shorter streams in this plateau flow sluggishly throurgh broad valleys, but the largest river, the Thanlwin, is deeply entrenched. It flows as series of rapids and waterfalls through, steep, narrow valleys.

To the south towards the Isthmus of Kra, the ranges of the Malay Peninsula are repeated northward to merge with the plateau. This area, roughly corresponding to the tail of kite, is sometimes treated as a separate region. It is, however, topographically associated with the Shan Plateau.

The major part of the Central Belt is composed of ancient valleys that have been covered by deep, alluvial deposits through which the Ayeyarwaddy, its tributary the Chindwin, and the Sittoung rivers flow. The lower valeys of the Ayeyarwaddy and Sittoung rivers form a vast low lying delta area of about 25,900 sq.km (10,000 sq.mi). The Delta continues to move seaward at a rate of 5 km (3 mi)per century because of the heavy silting brought down by the rivers. The relief of the northern portion of the Central Belt where the ridges of the Himalayan Mountains curve southward and become the mountain system of Myanmar eastern frontier. These mountains are very high and rugged and Hkakabo Razi on the northern frontier, which rises to almost 6,096 m (20,000 ft) and is the highest peak in the nation. Mount Saramati on the India border at 3,810 m (12,500 ft) is the second highest.

The Western Mountain Belt is composed of ranges that originates in the northern mountains and continues southward to the extreme southern corner of the country. Here they disappear under the sea only to reappear some 322 km (200 mi) offshore as India’s Andaman Islands. These ranges are known by several names along the Myanmar-Assam border, but in the nouthern of the belt, where they lie entirely within Myanmar, they are known as the Rakhine Mountains. As in the Shan Plateau, the landscape is dominated by a series of parallel ridges separated by streams flowing in the restricted valleys. Here, however, the slopes are very steep, and the mountains are far more rugged than any in the Shan Plateau. Mount Victoria, for example, rising to about 3,048m (10,000 ft), is the highest peak in the Rakhine Mountains and the third highest in the nation.

The Rakhine Coastal Strip is a narrow, predominantly alluvial belt lying between the Rakhine Mountains and the Bay of Bengal. In its northern portion, there is a broad area of level land formed by flood plains of several short streams that come down from the mountains. In the south the coastal strip narrows and is displaced in many places by hill spurs that reach the bay. Offshore there are many large islands and hundreds of small ones, a number of which are low-lying and level enough to permit intensive rice cultivation.

4. Climate and Rainfall

Myanmar has three distinct seasons. The cold season emerges from November to January, dry season starts from February to April followed by the wet season. Myanmar receives its annual rain mainly from south-west monsoon from mid of May to mid of October. Ninety precent of the annual rainfall in different regions of Myanmar are monsoonal. The rainfall varies in intensity and time of year and is depending on the locality and elevation. Rainfall receives 2,030 mm to 3,050 mm in the deltaic area, 2,030 mm to 3,810 mm in the north, about 1,520 mm in the Shan State, rising to 5,080 mm in the Rakhine and Thanintharyi coastal regions and only about 760 mm in the central dry zone. And incidentally such localities experiences temperature of 40° C during summer, and dropping to 10° C to 16° C during winter and below 0° C in some hilly regions. The loss by evaporation is ranging from 1,500 mm to 2,000 mm. Due to uneven climatic condition, scarcity of water during dry season becomes a main issue over most of the areas of the country.

5. Water Resources Potential

The South-East Asia (SEA) has 15% of the total world's volume. Demand on water resources has increased due to rapid urbanization and industrialization of the region. It has also indicated that the deterioration in water quantity and quality makes low reliability of supply, high cost of water and more. Although SEA has rather rich resources in the world but those resources and their potentials are being reduced at an alarming rate.

Among the water resources rich countries, Myanmar could still be classified as a low water stress country. There are four major river systems, namely, the Ayeyarwaddy, the Thanlwin, the Chindwin and the Sittoung. Besides there are some river systems in Rakhine State and Thanintharyi Region. These river systems contribute for the surface water resources of the country. Due to favourable climatic condition and physiographic features, there are eight river basins those cover about 90% of the country's territory. Total surface and groundwater potential of Myanmar are approximately 828 km^3 and 495 km^3 per year respectively. Details are mentioned in Table 1. However, in many cases the usefulness of groundwater resources is limited due to their being non-renewable, saline or brackish, and hence not suitable for irrigation. If only renewable groundwater suitable for irrigation development is considered, the potential is reduced to 28.3 billion m^3.

The assessment of water resources potential both for surface and groundwater is carried out on the basis of river basins. In terms of water resources, Myanmar stands the 14th position at global level and the 5th position at Asia region.

Table 1. Myanmar's annual average water resources potential by each river basin, 1980-1993.

Region/river basin		Surface water (mcm/Yr)	Groundwater (mcm/Yr)
Region 1.	Chindwin	104,720	57,578
Region 2.	Upper Ayeyawady	171,969	92,599
Region 3.	Lower Ayeyawady	229,873	153,249
Region 4.	Sittoung	52,746	28,402
Region 5.	Rakhine	83,547	41,774
Region 6.	Tanintharyi	78,556	39,278
Region 7.	Thanlwin	95,955	74,779
Region 8.	Mekong	10,580	7,054
Total		827,946	494,713

6. Groundwater Resources in Myanmar

On the basis of stratigraphy, there are eleven different types of aquifers in Myanmar (see Table 2). Depending on their lithologies and depositional environments, groundwater from those aquifers has disparities in quality and quantity. Of these, groundwater from Alluvial and Irrawaddian aquifers is more potable for both irrigation and domestic use. Groundwater is also extracted from Peguan, Eocene and Plateau limestone aquifers for domestic use in water scared areas, even though these are not totally suitable for drinking purposes.

The groundwater resources of Myanmar by administrative region can be summarized as follows.

6.1 Kachin State (northern areas)

Groundwater is found mainly in Oligocene-mid-Miocene and Eocene rocks. It is mainly brackish and rarely fresh. In the valley areas, groundwater from alluvial deposits is fresh and yield may be high, but it is found only in local areas.

6.2 Sagaing Region (north-western area)

In the northern part of the region, groundwater is situated in Oligocene to mid-Miocene rocks and is brackish in quality. Groundwater in the Chindwin Basin is of mid-Pliocene age and occurs in a contained area. The water is suitable for drinking and irrigation purposes. Groundwater in the southern part of the region is suitable mostly in alluvial beds of Quaternary age, mainly fresh water, and has a good yield. The water is also suitable for drinking and irrigation purposes.

6.3 Shan, Kayah, Kayin and Mon States and Tanintharyi Region (east and south-eastern area)

Groundwater occurs mainly in limestones of the Carboniferous-Permian age. In the eastern part of the area, it lies in beds of Mesozoic and Precambrian ages. Groundwater in volcanic rocks is found in the south-eastern part. Generally, it is fresh and mostly suitable for drinking and irrigation. To exploit economically, drilling method may be limited.

6.4 Rakhine and Chin States (western area)

In the eastern part of the states, groundwater occurs in Eocene rocks. The groundwater is mainly brackish and fresh water is rarely encountered in this area. On the western side groundwater is of Oligo-mid-Miocene and is brackish in quality. Natural reserves of fresh water are limited and seawater intrusion may be encountered.

6.5 The Central Area (Mandalay and Magway Regions)

Fresh groundwater is found in Quaternary and Mio-Pliocene rocks. But salinity of groundwater in Mio-Pliocene beds increases with depth. It is suitable for drinking and irrigation purposes. Small supplies of groundwater have been achieved from boreholes tapped in Upper and Lower Peguan in some areas. They are of Miocene and Oligocene ages. Groundwater in these sediments is mostly saline and rarely fresh.

6.6 The Delta Area (Yangon and Ayeyarwaddy Region)

Groundwater occurs in alluvial beds of Quaternary age. It is mostly fresh and brackish in some parts and suitable for drinking and irrigation purposes. In a coastal area the water quality may be saline.

6.7 **Bago Region (southern area**)

The central area of the Region is Bago Yama and it has the rocks of Oligo-Miocene age bearing mainly brackish water. Natural reserves of fresh water are limited. In the eastern and western parts of the Region, groundwater of alluvial beds is exploited. Groundwater reserves are considerable and suitable for drinking and irrigation puposes.

Table 2. The Major Aquifers in Myanmar

Sr. No	Name of Aquifer	Major rock units	Area of occurrences	Remark
1	Chaung Magyi Aquifer	Low grade metamorphic rocks	Eastern Highland	To be study in detail
2	Cambrain-Silurain Aquifer	Molohein Group Pindaya Group Mibayataung Group	Eastern Highland	To be study in detail
3	Lebyin-Mergui Aquifer	Graywecke, quatzite, argillite, slate, mudstone, gravel etc;	Western boundary of Eastern Highland and Taninthari ranges	To be study in detail
4	Plateau Limestone Aquifer	Limestone & dolomite	Eastern Highland	GW is being extracted in some places
5	Kalaw-Pinlaung-Lashio Aquifer	Loi-an Group & Kalaw Red Beds	Western boundary of Eastern Highland and Taninthari ranges	To be study in detail
6	Cretaceous Aquifer	Flysch units and limestone units	Western Ranges Northern Kachin	To be study in detail
7	Flysch Aquifer	Interbedded units of sand, siltstones, shale and mudstone	Western Ranges	Probable GW source area
8	Eocene Aquifer	Sandstones, siltstones and shales	Periphery of Central Lowland	Probable GW source area
9	Pegu Group Aquifer	Sandstone, siltstones and shales	Central Lowland and Rakhine Coastal Plain	Mostly saline & brackish water, some fresh water in recharged areas
10	Irrawaddian Aquifer	Mainly sands, sandstones with gravels, grits, siltstones and mudstones	Central lowland and Rakhine Coastal Plain	Thick aquifer fresh GW with high iron content
11	Alluvial Aquifer	Sands, gravels and muds	Major river basins and its tributaries, base of mountains and ranges	Fresh GW, seasonal water table changes

7. Groundwater Resources Development in Myanmar

Currently, several government agencies and departments under different Ministries are engaged independently both in surface and groundwater use but the extent and type of use are different from one another.

7.1 Tube wells for Domestic Water Supply

Groundwater is the principal source of domestic water supply in Myanmar. There are a large number of shallow dug wells throughout the country except in hilly regions. Most of them dry up in the hot season though.

According to the records, the first tube well of Myanmar was drilled in 1889. However, rural water supply works were started in Myanmar in 1952. Between 1952 and 1976, RWSD (predecessor of WRUD) constructed 6,261 tube wells serving some 4.5 million rural people. These works were funded by the Government. Negotiations initiated in 1976 with resulted in the fourmulation of a tube well programme in the dry zone which comprised the construction of 3,100 tube wells for the three divisions of Sagaing, Mandalay and Magway. This programme was implemented in 1977/78 with the combined resources of the Government and external agencies, namely, WHO, UNICEF and ADB.

So far, WRUD (successor of RWSD) has completed 23,513 shallow tube wells and 14,375 deep tube wells serving nearly 15 million rural people since 1952. The domain of rural water supply activities by WRUD and its predecessors, with its own national resources or external resources, UNICEF in particular, covered nationwide installation of water supply facilities such as shallow and deep tube wells, piped water reticulation systems, river water pumping stations, gravity flow systems and improvements of ponds and dug wells and so on.

DDA has also gained tangible achievements since its intervention in this sector in 1997. Urban and rural development tasks are carried out by 285 township committees and 42 urban development affairs committees under the supervision of DDA. Measures have also been taken to ensure water supply for 4,023 villages (in 2000/01 to 2002/03) out of the targeted 8,042 villages in Sagaing, Mandalay and Magway Regions under a ten-year project, but no accurate and comprehensive data have yet been compiled.

7.2 Tube Wells for Irrigation

The use of groundwater for irrigation started only recently in Myanmar. In 1989, the Irrigation Department (ID) of the Ministry of Agriculture and Forests (now MOAI) started the groundwater irrigation project in Monywa District, Sagaing Region funded by UNDP and IDA. Since 1991, this project has irrigated a total area of 8,094 hectares (20,000 acres).

In 1992, RWSD of the Agricultural Mechanization Department (AMD), Ministry of Agriculture (now MOAI) started the drilling programme for groundwater irrigation, mainly for double paddy cropping in the dry season.

During the fiscal year 1992/1993, a total of 93 bored wells in 14 townships irrigated 1,370 acres (554 ha) of no-monsoon paddy land in Yangon and Bago Region as a result of AMD programme and of cooperation with local farmers. Local farmers bore the expense of 85 bored wells which irrigated 910 acres

(368 ha) of paddy land in Yezagyo Township, Magway Division. AMD provided technical assistance and machinery for this purpose.

Table 3. Various Agencies and Departments engaged in water use sector

Agency/Department	Ministry/City/Other	Duty and Function
Irrigation Department	Agriculture & Irrigation	Provision of irrigation water to farmland
Water resources Utilization Department	Agriculture & Irrigation	Pump irrigation and rural water supply
Directorate of Water Resources and Improvement of River System	Transport	River Training and navigation
Myanmar Electric Power Enterprise	Electric Power	Electric Power generation
Department of Hydroelectric Power	Electric Power	Hydro Power generation
Factories under the Ministry of Industry	Industry (1) and Industry (2)	Industrial
Myanmar Fishery Enterprise	Livestock, breeding & Fishery	Fishery works
City Development Committee	Yangon/Mandalay	City water supply and sanitation
Department of Development Affairs	Progress of Border Areas & national Races and Development Affairs	Domestic and rural water supply and santation
Private users	UN agencies, NGO & private entrepreneurs	Domestic water supply navigation & fisheries
Department of Meteorology and Hydrology	Transport	Water assessment of main rivers
Forest Department	Forestry	Reforestation and conservation of forest
Public Works	Construction	Domestic & indusrial water supply and sanitation
Department of Human Settlement and Housing Development	Construction	Domestic water supply

Department of Health	Health	Environmental health, water quality assessment and control
Central Health Education Bureau Dept. of Health Planning	Health	Social mobilization, health promotion, behaviour research
Yangon Technological University	Science and Technology	Training and research

In 1993, RWSD implemented the 99 ponds groundwater irrigation to irrigate 8,181 acres, (3,311 ha) of cropland through free flowing artesian wells in Yinmabin Township, Sagaing Region, Central Myanmar. Its free-flowing artesian wells amounted 109.91 cusec at the time of completion of the project in 1995.

These groundwater development facilities were under the control of agencies concerned before 1.4. 1995 and WRUD has borne full responsibility for them thereafter.

In tadem with the Govenment's agricultural policy, WRUD, on its parts, has hitherto installed groundwater facilities of 2,885 shallow tube wells and 4,684 deep tube wells covering the beneficial area of 1,388 acres (36,984 ha) at the any fesible sites nationwide. At present WRUD is one and only govenment agency for groundwater irrigation development in Myanmar.

Futhermore, free- flowing artesian wells in Ayadaw Township, Sagaing Division are being drilled by WRUD to irrigate farmland, where hydrogeological conditions are favorable.Local farmers have to bear the expense of drilling and well components for this purpose.

7.3 Water Quality of Three Major Aquifers

According to the hydrogeological studies quoted in the previous sections, water chemistry of three major aquifers (Alluvial, Irrawaddian and Peguan) from Sagaing, Madalay, Magway, Bago, Yangon and Ayeyarwady Divisions can be identified.

The alluvial aquifer bears the groundwater types of bicarbonate-sulphate, chloride-bicarbonate, bicarbonate-chloride with sulphate-bicarbonate, chloride-sulphate and sulphate-chloride. The total dissolved solid content of groundwater in alluvial aquifer ranges from 146 ppm to 3,000 ppm and E.C. values vary from 224mmho/cm to 4,895 mmho/cm. The SAR values are from 0.78 to 9,047 and Kalium ion content is 0.19 ppm in lowest and 1.22 ppm in highest. Sodium ion content is 1.90 ppm to 14.37 ppm.

The Generalized groundwater of Irrawaddian aquifers is bicarbonate-chloride, bicarbonate-sulphate, and chloride-bicarbonate types. The total dissolved solid content of groundwater in Irriwaddian aquifer ranges from 258 ppm to 1,283 ppm and E.C. values vary from 392 mmho/cm to 1,953mmho/cm. The SAR values are from 0.65 to 3.60 and Kalium ion content is 0.11ppm in the lowest and 1.55ppm in the highest. Sodium ion content is 2.48ppm to 18.73ppm.

The majority of groundwater tapped from Peguan aquifers is bicarbonate-chloride-sodium, bicarbonate-sulphate sodium, and chloride-bicarbonate sodium types. The total dissolved solid content of groundwater in this type of aquifer have distinct high value ranging from 2,247 ppm to 3,640 ppm and E.C. values vary from 3,386mmho/cm to 22,292 mmho/cm. The SAR values are from 0.69 to 22.97 and Kalium ion content is 0.137ppm in the lowest and 9.03 ppm in the highest. Sodium ion content is 14.40 ppm to 158.20ppm.

7.4 Drinking Water Quality Surveillance in Myanmar

WRUD, in collaboration with UNICEF, carried out reconnaissance survey of drinking water quaility in 2001 and tested 11 parameters, namely total coliform, fecal coliform, pH, turbidity, EC, total hardness, iron, chloride, nitrate, fluoride and arsenic of 4,969 samples covering 97 township of 10 sites and Divisions by using Wagtech International Lts., UK and Merck Arsenic Test Kit of Germany.

7.5 Groundwater Use

The State is systematically disseminating advanced techniques and supports to develop the nation's economy. A large number of irrigation facilities have been built within a short span of time. By the end of May, 2007, 199 dams were irrigating over one million hectares of cropland.

In addition to the dams, various means have been applied to supply water for agriculture. River water pumping stations, underground water tapping stations and mini dams have been constructed throughout the nation. A total of 305 river water pumping projects has been implemented in 13 states and divisions, irrigating some 187,000 ha of cultivated land. In addition 7,479 tube wells are used to irrigate 37,000 ha of farmland.

So the water use in Myanmar is appreciably increased especially in agriculture. Other water use such as domestic and industrial sectors are very small compared with agriculture water use. Surface and groundwater use are mentioned separately as follows.

A.	**Surface Water Use**	**Total (m acreft)**	**Total (km^3)**
1.	Domestic	0.82	1.01
2.	Industrial	0.14	0.18
3.	Irrigation	22.43	27.66
	Total	**23.39**	**28.85**
B.	**Groundwater Use**	**Total (m acreft)**	**Total (km^3)**
1.	Domestic	0.82	2.24
2.	Industrial	0.04	0.05
3.	Irrigation	0.45	0.56
	Total	**2.31**	**2.85**
	Grand total	**25.70**	**31.70**

It was found out that about 89 percent of the water use was for agriculture, about 10 percent was for domestic consumption and 1 percent was for industrial purpose. According to the prepared by Agriculture Sector Review Project in 2003, it notes critical level of demand on both surface and groundwater resources in several districts. Eleven districts of the dry zone in central Myanmar and the Ayeyarwaddy delta in lower

Myanmar are found to be medium to severse-scarce according to UN criteria levels of water scarcity with the respect to groundwater use.

8. Recommendation and conclusion

8.1 Recommendation for action at the national and international level for the promotion of water conservation

1. It is imperative to give adequate importance to the water conservation in the development process at the highest level of the government. There was a greater need for more emphasis to be made on the importance of water conservation in the socio-economic and sustainable development of water resources. And water conservation issue should be accorded high priority in the policy making process of national government and concerned international organizations.
2. National workshop, particularly at policy making level, should be organized to raise public awareness and promote better understanding among all stakeholders to be affected by policies and regulations on water conservation.
3. Government should strengthen its institutional, legal and technical capabilities and make full use of economic principles with the assistance of regional and international organization to enhance water conservation in the country.
4. International organization should provide assistance to the country in conduction national training workshop on the use of best knowledge and practices of water conservation.
5. United Nation Organizations and other international organization should assist member countries in strengthening its own capabilities to achieve better system of water conservation, through the provision of advisories services.

8.2 Conclusions

Although Myanmar has abundant water resources for sufficiency of her nation, parts of the country, especially in large cities, has suffered shortage of fresh water. In the near future Myanmar may reach the stage in which water becomes the scarce resource due to the increase of water demand brought about by rapid population growth, expansion of irrigation and industrial production. Given the finite amount of renewable fresh water resources available, shortage of fresh water supply would become a major constraint for development and social well being unless due attention for equitable and economically efficient utilization and conservation policies could be developed to satisfy the water demand of various competing water use sectors.

Conflict of interest will become more among such competing users as urban water supply, power generation, flood control and inland navigation. As the competition of water could only become more intense in the future, it would be useful to country to address efficient water use technologies and water conservation measures for the sustainability of its resources. Effect of population on fresh water, both surface and underground, results in reduction of water avail in reduction of water availability for various uses.

It is the national concern, regarding the depth of monitoring systems on law enforcement on protecting water resources from industrial and agricultural effluents to keep the extent resources intact. Frugal consumption using efficient utilization of water is a prudent technology that should apply extensively in the country. Insufficient facilities for treatment of industrial effluents, particularly toxic chemicals, pose a threat to the nation's health, environment including eco-systems.

Despite the government encouragement on utilizing bio-fertilizers, availability of such less hazardous are limited and chemical fertilizers are unavoidably used extensively for boosting crop production. Stringent laws and regulation should be imposed to handle the risk of industrial effluents and wastewater. The government and incumbent agencies should realize the essences of efficient water utilization and water conservation comprehensively and impart that knowledge to the users or consumers. Accordingly to instill them impart this consensus to safeguarding national resources. Currently, national practices on efficient utilization and water conservation measures are inadequate and thus it is the national causes to harness the danger of deteriorating water resources through collective efforts of suppliers, users, the policy makers and international co-operation as a whole.

Groundwater in Papua New Guinea

Simon Egara
Mineral Resources Authority

1. Physical Outline

Mainland of Papua New Guinea is approximately 1,250 km long decreasing in width from 730 km is the west along the Irian Jaya border to 50 km at its eastern tip. To the north and north- east lie the island groups of the Bismarck Archipelago, and the North Solomon Islands, with the smaller archipelagos of the Trobriands, d'Entrecasteaux and Louisiades off the eastern end of the mainland.

The principal topographic features of the mainland, the Bismarck Archipelago and North Solomons are the highly dissected mountain ranges reaching 4,500 meters in elevation on the mainland and punctuated by numerous intramontain basins. In addition the western hall of the mainland includes the extensive lowland plains and swamps of the Sepik/Ramu and Fly rivers respectively north and south of the main mountain ranges.

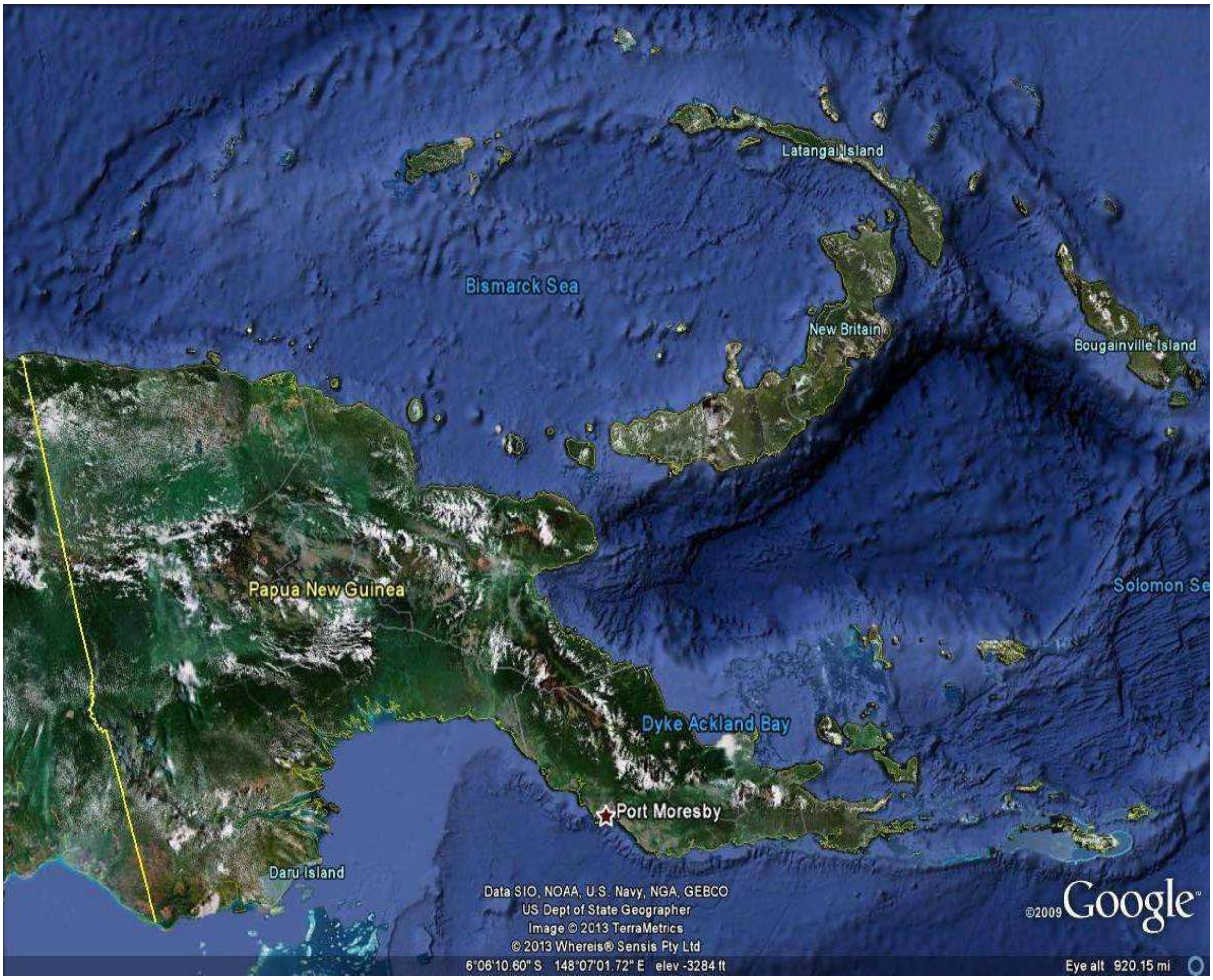
The eastern end of the mainland and many of the island groups are bordered by coral islands, reefs and raised fossil coral terraces.

1.1 Highland Areas

The Highland areas are dominated by massive ridge and valley land-forms. The area may be conveniently be classified by two physiographic characteristics: Local relief and altitude. The northern part forms a belt of uniform mountainous country, and extends from the Thurnwald Ranges in the west to the Bismarck Ranges in the east. It includes the highest, most rugged and remote areas in Papua New Guinea. The central part, extending to the Goroka – Kainantu area in the east, is characterized by relatively low local relief, a succession of intramontain plains and broad upland valleys and contains several huge strato-volcanoes. The eastern part of the highlands comprises the Owen Stanley Range and its flanking ranges, running the entire length of east Papua New Guinea. It is similar to the northern part, and can in fact be regarded as its eastern extension. It is dominated by massive ridge and valley land forms.

Highland land forms are also found in the Papua New Guinea islands, namely the d'Entrecasteaux, New Britain, New Ireland and Bougainville islands.

Due to high slopes in the highland regions a relatively small fraction of the precipitation is usually available for infiltration into the soil. Most of it either evaporates or quickly discharges into streams and rivers as surface runoff. The steep slopes also imply that, where there are potentially aquiferous rocks, the water table is only accessible near rivers where it approaches the surface.



1.2 Swamp Area

Large areas of Papua New Guinea are covered in swamps. The Papuan Gulf area and the lower part of the Fly River, together with the middle and lower part of the Sepik Valley are the most extensive. Other areas are the lowland parts of the Lakekamu, Kapuri and Biaru Rivers, the lower parts of the Vanapa and Laloki Rivers, the coastal areas of Table Bay, Mullins Harbor and Kate-karua Bay, and the Ramu catchments. Swamps are also found in New Britain along the Via River and Ribeck Bay, and may exist in flat valleys in the Highland areas as for example the Wahgi swamps and Lake Kutubu.

The water in these swamps is usually of poor quality, being easily polluted by products of plant decay.

1.3 Coastal Areas

The major beach sands owe their existence to the great abundance of suspended materials brought down by the rivers. The combinations of high precipitation, mountain ranges and intensive erosion are highly favorable for the development of the beaches. They are found mainly along the south coast due to the post-glacial differential rise in sea level. Along the south coast it led to drowning of river inlets, reduction of stream velocities in the lower reaches and formation of embayment which provided ideal locations for deposition. The aquifers are found on beach ridges, beach plains, tidal flats and raised coral reefs. The north coast was largely unaffected by this sea level rise because of its steepness and active uplift. The Sepik plain and Cape Vogel basin were exceptions to the general trend.

Fossil coral reefs are uplifted coral reefs and terraces. They occur in great numbers along the south coast of New Britain, the east coast of New Ireland, the northern part of Bougainville, the Trobriand and Marshall Bennett Islands, and also along the Sialum and Madang coasts. These reefs are ample evidence of the relative movement of land and sea.

1.4 Volcanic Areas

Papua New Guinea has a great variety of volcanic landforms. On the mainland, they occur in two irregular clusters. The largest is centrally located within and south of the central highlands region. A smaller one occurs in south-eastern part of the Cape Vogel basins. A third cluster is on the d'Entrecasteaux Islands. In addition, there are two chains of volcanoes in the Bismarck Sea.

These volcanic areas present special problems for groundwater development. The volcanic ash is extremely permeable, with the result that a great part of the precipitation infiltrates the soil, and rapidly drains the volcanic area.

1.5 Karst Regions

Three areas in Papua New Guinea are dominated by karstic landforms. These are a belt from the Gulf of Papua in the south-east to the Irian Jaya border in the north-west on the mainland, the western and eastern part of New Britain, and the north-western part of New Ireland. Besides these, several smaller occurrences of karsts are found in the highlands, the Saruwaged Range and the western most part of the northern coastal ranges.

The upper part of Alice River (Ok Tedi) drains an area characterized by limestone. An investigation of this catchments for hydropower potential revealed considerable uncertainties about some of the sub-catchments areas. In the earlier part of that study, it was apparent that the runoff was much greater than the rainfall in some places, and less in others. This was ascribed to inaccurate maps, subsurface leakage to or from other catchments, or errors in the estimation of the mean catchments rainfall.

When more accurate maps and more data are available, it became clear than because of the very high rainfall in this area (from 6,000 to 8,000 mm yearly) and the absence of any lakes, the areas drain into the surrounding catchments via sink holes, solution cavities etc., in the limestone which underlies the area.

In this region, the Hindenburg Wall also complicates the assessment of the drainage area because of numerous springs that issue from its base and scarp, due to chemical weathering of the limestone area above the Wall.

1.6 Markham Valley

Mountain Rivers often carry heavy loads of sediment. Where these rivers reach the low-lying flood plain of a valley or the coast, the stream velocity is suddenly reduced, leading to the deposition of sediments. The result is the formation of alluvial fans. The rivers will have gradients similar to the fans, and flow in highly unstable, wide, braided flood-plains with constantly shifting sand bars and channels. Active fan building takes place under the present humid tropical rain forest conditions and is widespread in the tectonically most active part of Papua New Guinea.

Extensive fan building is found in the Markham-Ramu Valleys south of the actively rising Saruwaged and Finisterre Ranges and along the coastal areas between the Huon Peninsula and Astrolabe Bay to the north of these ranges. Other important fan areas are the Angabunga River, the Fly River and the Sepik River.

Numerous streams from the Saruwaged Range discharge into the valley, forming a series of fans. A significant portion of the river and stream water is lost by seepage and infiltration into the groundwater reservoir. Since, the sediment yielded by these mountains contains a large coarse fraction and makes a good aquifer.

2. Vegetation

One of the outstanding characteristics of the country is the extensive coverage of forest vegetation. Paijmans (1976) recognizes seven major vegetational environments; four coastal and lowland zones below (1,000m) account for 28% of the coverage and are controlled by drainage conditions, water regime and type of water; three other zones (72% cover) are controlled principally by climatic changes with increasing altitude.

About 15-20 percent of the total vegetation cover comprises climax and disclimax savanna. Climax savanna is a reflection of seasonal rainfall conditions in the Markham Valley an along parts of the south coast of the mainland particularly the south west corner of the Gulf of Papua coast between Kerema and Kwikila. In the highland areas savanna is the result of local climatic and soil conditions.

Disclimax savanna has been created extensively in the central highland areas of the mainland and along coastal stretches of the mainland and islands as a result of human pressure in particular the traditional practice of shifting agriculture.

3. Climate

Since the country lies between 0° and 12° south latitude under Koeppen's classification the climate may be generally described as rainy tropical (Af). Geographic location, altitude and aspect may vary this generalization to give savanna (Aw), temperate (Cf) and other more local climatic types.

The seasonal movement of the Intertropical Convergence zone with its associated tropical air masses control the two principal wind directions which strongly influence the rainfall patterns of the country. From May to October, the south-east trades predominate whereas from December to March, prevailing winds are from the north-west. The high mountain barriers across the path of these winds, whose fetch covers thousands of kilometers over tropical seas, induces regular heavy orographic convective rainfall or northern and southern slopes and in the mountains themselves. Thermal convective rainfall is characteristic of the Fly and Sepik lowlands. Mean rainfall figures on the mainland range from less than 2,000 mm along the coast to over 8,000 mm in some mountain areas. The island groups to the north and north- east incur rainfall between 3,000 and 7,000 mm annually.

Areas with less than 2,000 mm lie south-west of the Fly river; west of Lae in the Markham Valley lying in the rain shadow of the Finnisterre – Saruwaged mountains to the north and the main central ranges to the south; and south-east parts of the north coast where the coast lies parallel to south-easterly and north-westerly wind directions and local topography affects wind flow. The least rainfall, less than 1,000 mm, falls in the Port Moresby coastal area where the coastline runs parallel to the south-east Trade winds and lies in the lee of the Owen Stanley range during the north-westerly period.

Seasonal variation of rainfall generally reflects location with reference to the prevailing wind, and local topography. North coast maxima tend towards the period of north-west winds, south coast maxima during the south-east trades.

Evaporation rates range from less than 1,000 mm to over 2,000 mm annually depending on temperature and humidity regimes. Areas of highest evaporation rates are coincident with those of lowest rainfall and vice-versa. Annual evaporation rates based on adjusted class A pan values range from 1,250 mm in western highland areas to over 2,000 mm in the Markham Valley, Goodenough Bay and the Port Moresby region.

Mean daily temperature range between 34°C and 21°C for coastal and lowland locations to sub- zero values above 3,000m. Seasonal variations are small.

4. Surface Water

The coincidence of high and precipitous mountain ranges and high rainfall leads to high runoff over most of the country. Rivers are often steep and actively involved in fluvial erosional processes. The young mountain ranges are deeply incised by rapidly down-cutting streams whose sediment load is deposited as alluvial fans or in the swamps and deltas of the Sepik, Ramu, Fly, Kikori and Purari rivers and the depositional plains along the south east coast. Large volumes of surface water are retained in the Sepik and Fly swamps. Extensive limestone and karst areas exist in the Kikori-Lake Kutubu area of the southern fold mountains, the Victor Emmannual fold belt, the Saruwaged range, New Britain and New Ireland. There is little surface drainage in these areas despite high annual rainfall.

Runoff has been estimated for areas above 900m elevation at 2,500 mm, 800 – 1,300 mm and 2,100 mm. At present there is now generally reliable estimate of runoff for the country as a whole.

5. Groundwater

5.1 Historical

Groundwater investigations at a professional level started in the mid 1960's. From 1974 hydrogeological services have been provided by the Geological Survey on a regular basis. Lack of staff has not allowed for general hydrogeological studies. Most work is in an advisory capacity, field studies being carried out at the request of public and private developers and then on an ordinary consulting basis. Investigations provide the developer with information regarding the potential and quality of sub-surface waters and aquifers. Wells and well-fields are designed and construction monitoring and testing of wells is undertaken.

Data on wells and bores are stored in a well-archive, ad comprise identifications for well location and ownership, data on drilling and well capacities. Data on water quality will normally only be collected if such is needed for ensuring health standards for public water supply. For small wells, the owner may decide that chemical analysis is not worth the costs. All wells that Geological Survey knows about are registered. Minor wells drilled by plantations and settlement may be known only occasionally to the Survey. Today, close on 5,000 wells are registered.

Continuous data recording, from special observation wells are not made, but plans exist to include such time-series data from a few wells. Because the existing data archive is relatively small, no efforts have been made to store the hydrogeological data in a computer archive.

5.2 Prospecting Methods

Geophysical techniques are the principal prospecting methods, supplemented by local geological investigations. Electric log methods (self potential and point resistivity) are commonly used. Resivitity is particularly useful in coastal areas where the high porosity and permeability of coral limestone permit intrusion of saline water. Occasionally refraction seismic sounding may be used.

5.3 Main Aquifers

Five broad hydrogeological units may be defined:

a) Pre-Quaternary bedrock b) Volcanic rocks

c) Limestone karst

d) Coastal sediments

e) Unconsolidated sediments

5.3.1 Pre-Quaternary Bedrock

Metamorphic, intensive igneous and sedimentary rocks form the basement of most of the axial ranges of Papua New Guinea. They are characterized by generally low primary porosity and permeability, and most available groundwater occurs in open joints and fractures, although some sandstone formations may form porous rock aquifers. The groundwater potential is relatively low and these rocks are generally avoided during groundwater investigations. Most areas underlain by these rocks are mountainous and sparsely populated and the demand for water is small.

5.3.2 Volcanic Rock

Andesitic and basaltic lavas and pyroclastics of the Cainozoic volcanic centres comprises this broad hydrogeological unit. The massive lava flows are generally poor aquifers, but where dissected by closely spaced, open joints are capable of storing and producing large quantities of groundwater. The brecciated surface of some lava flows, as well as interbedded pyroclastics, reworked pumiceous tuffs and buried alluvium are potentially good aquifers provided they are not too weathered. Buried soils and fine grained tuffs form barriers to groundwater movement and may result in perched groundwater or act as confining beds.

Although there are widespread areas of volcanic rocks in Papua New Guinea, many of which have good groundwater potential, few bores and wells tap this type of aquifer. The main reason for this lack of development is the relative low success rate of past drilling in volcanic rocks. For example at Kuriva resettlement scheme, 40 km northwest of Port Moresby, the success rate is about 45 percent for bores sun in weathered, jointed agglomerate. The most intensely developed volcanic aquifer underlies the township of Rabaul, which is located on the floor of a caldera. Much of the volcanic debris underlying the town is reworked pumiceous tuff which forms a good aquifer. Some bores produce about 45 m3 per hour with very little drawdown (Pounder, 1973).

Springs are common in the volcanic areas and constitute a significant proportion of village water supplies on Bougainville, New Ireland, and New Britain. During World War II, the Japanese developed a number of springs in and around Rabaul, and many of these are still utilized. The most common spring locations are at the basal contact of unconsolidated pumiceous tuff overlying massive agglomerate, lava or bedrock, or at the base of open jointed lava flows overlying buried soils or fine grained tuff horizons. Spring discharges are small, generally less then 2 m3 per hour; most springs are perennial, but some of the smaller springs dry up over extended rainless periods.

5.3.3 Karst Limestone

There are extensive areas of limestone throughout Papua New Guinea on which karst features are developed. In most of these areas the limestone has many caves and sink-holes and although the annual rainfall may be greater than 2,500 mm there is very little surface drainage. These areas have high groundwater potential.

With the exception of areas of poorly developed karst on some of the larger coral islands e.g. Trobriand Islands, there are unknown bores or dug wells tapping the karst limestone aquifers. Spring developments are, however, common in the Southern Highlands District. Spring discharge in the limestone are variable, but most tapped springs discharge less than 2 m3 per hour. Larger springs with flows of the order of 2.8 m^3/second have been observed in some areas. Many of the karst limestone areas are sparsely populated with little demand for water at present.

5.3.4 Coastal Sediments

Coastal sediments in Papua New Guinea include two main lithologies: raised coral limestone which is generally referred to locally as “karanas” or “coronus” and alluvial and marine detrital sediments, including gravel, sand and mud. This hydrogeological unit is characterized by the risk of salt water intrusion. The unit generally extends les than 500 m inland from the coast, where is grades into karst limestone or unconsolidated sediments. The karanas is riddled with solution cavities and is commonly loosely cemented resulting in high porosity and permeability. On low islands and coastal plains composed of karanas, the water table is usually only a few meters above means sea level, which means that the fresh water/salt water interface may be relatively shallow. For example, at Kavieng, which is located on a raised coral platform about 3 m about mean sea level, the water table is less than one meter above mean sea level and the salt/fresh water interface (defined by a geoelectric survey) forms a irregular surface 1-12m below mean sea level (Kidd, 1974).

Because many towns and large villages are located on the coast there is a considerable demand for good clean water supplies. Groundwater has the potential to supply this demand, but development of the groundwater resource requires close supervision in order to preserve the fresh water/sea water balance. Already a number of villages and towns have suffered salt water contamination of their bores, which in most cases has been caused by drilling the bore too deep.

5.3.5 Unconsolidated Sediments

Alluvial, lacustrine and fan deposits make up this broad hydrogeological unit, which is confined to valleys and depressions. The two largest areas are the extensive alluvial plains of the Fly and Sepik-Ramu basins where population is sparse and groundwater is little developed. In the large basins the alluvium is mainly silt and sand with some gravel, whereas in the smaller mountain rimmed basins and tectonic depressions, such as the Markham and Wahgi Valleys, coarse gravels or lacustrine muds are abundant. Groundwater is generally obtained from clean and aquifers in the large basins, and clean sand and gravel aquifers in the smaller basins. Both confined and unconfined aquifers are common, but there are few flowing artesian bores.

Most water bores so far developed in Papua New Guinea are located in this unit: the rate of successful bores is high. Bores producing 40 m3 per hour with a drawdown of one to two meters are common and specific capacities are generally high with the exception of some bores in the large basins, such as the Sepik-Ramu basins, where fine sediments predominate. Quantities of groundwater withdrawn from this unit vary from less than 1 m3 per day in some small village bores to 8,000 m3 per day from ten bores in the Lae city water supply scheme.

Shallow water table in the lower wetter areas permit the development of sanitary dugwells. On the higher parts of alluvial fans and high river terraces the water table may be deep, making dugwells impracticable and adding extra length to drilling.

6. Groundwater Quality

On the bacterial quality, most groundwater in Papua New Guinea is good. However, shallow dugwells in highly permeable sediments located near latrines or waste disposal sites are susceptible to bacterial contamination.

The chemical quality of the groundwater is also generally good. The amount of total dissolved solids varies but is usually below the 1,500 parts per million standard set by the World Health Organization (WHO) with the exception of a few bores near thermal areas and close to the sea, where some excessively high values have been recorded.

Bicarbonate is the dominant anion in groundwater obtained from all five hydrogeological units, with chloride becoming dominant in some coastal areas which are subject to salt water contamination. Calcium and sodium are generally the most common cations.

Some groundwater aquifers near recently-active volcanoes and fumarolic areas are warm and have high fluoride contents. For example, groundwater from the eastern sector of Rabaul township has fluoride content in excess of (and in three bores, double) the 1.5 parts per million maximum allowable level for drinking waters (MacGregor, 1965).

Most groundwater in Papua New Guinea is hard to very hard according to the World Health Organization (WHO) classification.

7. Gaps in Knowledge

Since no regional investigations for groundwater have even been undertaken and investigations to date have been of very localized interest there is clearly a vast area of the country whose groundwater potential can only be guessed at.

Groundwater investigations are likely to continue on the same basis as previously. There is currently no plan to undertake any regional programme of groundwater research, largely due to the widespread abundance of surface water and lack of man power, funds and equipment.

8. Government Services

The Geological Survey of the Ministry of Mining provides support for the development of groundwater resources by investigation of potential sites. The investigations provide developers with information regarding the potential and quality of sub-surface aquifers. The wells or well-fields are designed, and construction including monitoring and testing of test- wells is performed.

Between 1976 and 1979 hydrogeological work was carried out by one hydrogeologist, one technical assist and an occasional work by geologists and geophysicists, amounting to 2.5 man- years annually. 10-20 schemes are investigated each year. (Bureau of Water Resources, 1979). This trend still continues to date with one national hydrogeologist. A graduate geologist has now been recruited to undertake studies in hydrogeology to qualify as a hydrogeologist.

9. Utilisation and Projected Needs

As the country has an abundance of surface water and as there are few large-scale consumers such as heavy industry, groundwater resources have not been extensively developed. However there is increasing use of groundwater as a source of reliable high quality water particularly for urban water supply. The high bacterial content of many rivers–caused by village wastes and free-range pigs–has encouraged some development of groundwater. A survey of village water supplies conducted in 1974 indicated that 34 per cent of the villages visited relied on groundwater from bores, dug wells or springs (Jacobson and Kidd, 1974).

There has been some development of groundwater for stock watering and irrigation, particularly in the Markham Valley (Jacobson, 1971) where there are over 100 bore holes. Recent investigations have been undertaken in the Safia Valley (Northern Province) to determine groundwater potential for a large cattle ranching project (George, 1978).

Urban Groundwater Development in Progress.

Town	Production	Cubic	Status
Lae	1979	3,520	Producing
Madang	1979	1,231	Producing
Vanimo	1979	450	Producing
Rabaul	1979	2,000	Producing
Popondetta	1979	1,000	Producing
	1989	2,000	
Kavieng	1979	1,000	Producing
	1989	2,000	
Kimbe	1980	1,000	Producing
	1989	2,000	

The Asian Development Bank is currently undertaking a feasibility study of alternative schemes for a long term rural and urban water supply development throughout the country. The adoption of all or part of the recommendations may require development of high quality groundwater resources.

10. Economic Factors in Groundwater Development

Difficult drilling conditions and high costs of mobilization, casing and transport make commercial groundwater development in Papua New Guinea expensive. An average shallow bore and hand-pump-installed by a commercial driller costs more than K15,000, while bores in areas of deep aquifers (deeper than 30 m) may cost over K50,000. These are high costs for a Local Level Government budget in which water supply very likely has low priority. Costs to the local authority can be reduced by as much as 50 percent if drilling is undertaken by Government owned rigs under the direction of the Geological Survey, provided that the drilling program is sufficient to warrant the expense of transporting equipment into the area. A sanitary dugwell or spring development may cost less than K30,000 complete with hand pump, and thus is preferred to drilling wherever possible. Funding for groundwater development may become available if the realizes the importance of it.

Abundance of surface water is likely to satisfy most rural requirements and large scale enterprises in most areas for the foreseeable future.

Water Resource Assessment for Prioritized Areas

Lutgardo S. Laraño
Senior Science Research Specialist, Mines and Geoscience Bureau (MGB)

1. Introduction

1.1 The History of Water Resource Assessment

The National Water Resources Board (NWRB) and the Mines and Geosciences Bureau (MGB) are both government agencies mandated with powers in regulation, exploitation, development and conservation and protection of the country's water and mineral resources. In its regulatory functions, NWRB assess the available resources as basis for allocation and granting of water permits for various uses**.** while, MGB collaborates with NWRB in connection with the hydrological and geological aspects and requirement in assessing the available water resources.

In the 1980's, a groundwater resources study was conducted by the National Water Resource Council and the National Hydraulic Research Center. The study aims at quantifying the amount of groundwater available. This will allow proper allocation of the resource to users and determine the densities of well advisable in a particular area. One of the outputs of those projects is the groundwater availability map for the different provinces. In addition, the entire water management area was divided into sub-areas wherein safe yield, groundwater mining yield and withdrawal discharge density were calculated. The computed safe yield in each sub-area was used as a basis for groundwater allocation in the province.

Currently, extraction of groundwater in some areas in the country has already exceeded the allowable extraction rate or safe yield. Unrestrained utilization of groundwater thru additional allocations of groundwater in these areas would result in further deterioration of water quality, decline in piezometric level, saline intrusion and possible land subsidence. Considered to be in critical condition are the areas of Metropolitan Manila and Cebu and their adjoining municipalities as granted permits in these areas had already reached mining yield level. This prompted a moratorium on granting of water permits in these areas.

For validation, the water resource assessment study for these two critical areas was proposed and be part of the Institutional Strengthening of NWRB, one of the activities of Water Resource Development Project (WRDP) funded by the World Bank.

1.2 Purpose and Objectives

This assessment of water resources in Metro Manila and Metro Cebu will be applied as a tool for water use regulation. This will be replicated in other critical areas in subsequent studies.

The specific objectives of the project are as follows:

(1) Inventory and updating of water related data and information.

(2) Mapping of updated water resources data and information.
(3) Evaluation of available water in prioritized critical areas of rapid growth expansion using modern techniques for evaluation; and
(4) Upgrading of capability of NWRB staff, through on-the-job training on water resources assessment, which include water balance computation and groundwater modeling, pumping test analysis, and earth electrical resistivity survey and interpretation.

The study was made following the sequence of activities below:
(1) Collection review and critiquing of available data and information;
(2) Field investigation and verification;
(3) Definition of aquifer geometry and characteristics;
(4) Groundwater modeling
(5) Calibration of groundwater model; and
(6) Training of NWRB staff on the use of the model, conduct of earth resistivity survey and interpretation of results, use of geographic information system in groundwater study, and conduct of pumping test and analysis of results.

2. Data Collection and Review

Prior to collection of data and information, coordinating meetings with concerned agencies were made. This is to inform and explain to these offices the necessary data and information needed in the study and to seek permission to enter into their properties, particularly well pumping stations. Other agencies were approached through writings. Among the government agencies coordinated were MWSS, MGB, LWUA, PAGASA and WELDAPHIL.

Secondary data and information obtained can be classified as reports, maps and drawings, well inventory data, water quality data, climatic data and hydrologic data.

Primary data were obtained through field investigations. A well inventory was conducted basically to acquire information on the current water level and water quality. For each well inventoried, the location (geographic coordinates), static water level and water quality were recorded. Among the water quality parameters examined on-site are electrical conductivity and total dissolved solids. Geo- resistivity surveys were conducted both in Metro Manila and Metro Cebu.

3. The Study Area

3.1 Geographic Setting

The study area is situated within the latitudes 14º 06’ 07.54’’ to 14º 56’ 46.88” north and longitudes 120º 49’ 57.60” and 121º 17’ 20.98” east in Luzon Island, Philippines. From north to south, includes the following: the southern fringe of the Central Plain of Luzon that covers some towns of the Province of

Bulacan; the cities and municipalities of Metro Manila; the western municipalities of the Province of Rizal; the northern towns of Laguna Province; northwestern portions of Laguna Lake; and portions of the Cavite Highlands. The total land area covered by the study area is about 2,212km². Fig. 1 shows the coverage of the study area.

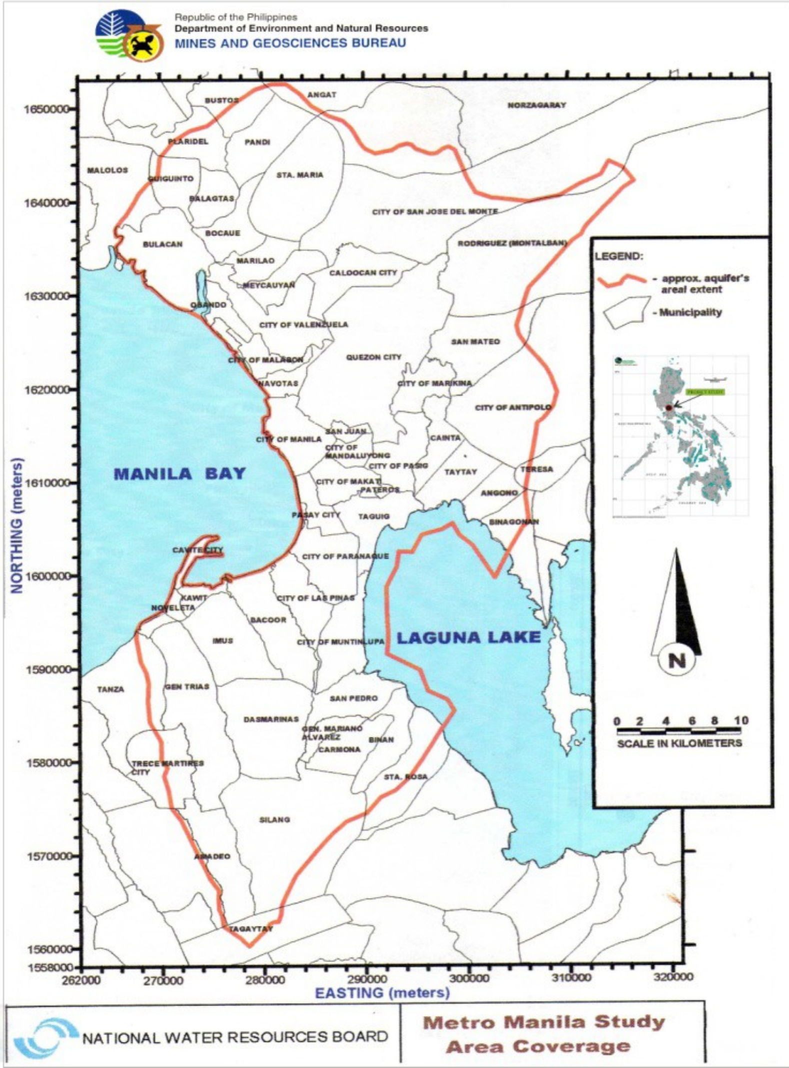


Fig.1 A map of the study area

3.2 Topography and Drainage

The delineated study area is bounded by the Meycauayan River in the north and extends towards the east through watershed dividing ridges leading to the western slopes of the South Sierra Madre Range. At the eastern side, only the catchment area (including Antipolo proper) that drains westward to the Marikina River Valley and the western side of the Binangonan Peninsula form part of the study area. The Cañas River that starts from Tagaytay and terminates south of Cavite City into the Manila Bay bound the southwestern portion of the study area. The Santa Rosa River that originates from eastern Cavite Highlands and drains into Laguna de Bay bound the southeastern side of the study area.

In general, the topographical high areas in the study area are the Cavite Highland in the south and the Sierra Madre in the northern and eastern portion (Fig. 2). The river systems in the study area that drains these two (2) topographically high areas generally flow to the Manila Bay and the Laguna de Bay. In the north, the Meycauayan River is the main river draining the slopes of the South Sierra Madre Mountain Range. In the center is drain by Marikina River one of the main tributaries of Laguna de Bay. In the southwestern sides, the Canas River that serves as the main drainage of Cavite Upland. While, the Sta Rosa River serves as the main drainage of the eastern side of Tagaytay and the Canlubang-Sta Rosa, Laguna Areas.

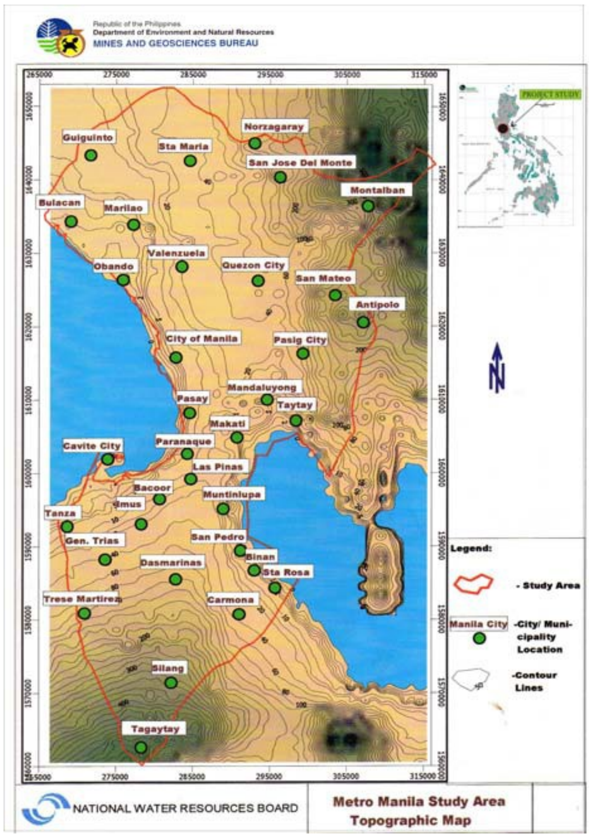


Fig. 2 A topographic map

3.3 Geology and Stratigraphy

For simplicity, this study has adopted the geologic concept suggested by Quiazon (MGB, 1971). The study area for Metro Manila in underlain by the following formation and grouped to age (oldest to youngest), origin and hydrogeologic significance.

Pre-Quaternary Formations

- Kinabuan Formation (Cretaceous to Paleocene)
- Maybangain Formation (Paleocene to Oligocene)
- Antipolo Diorite (Oligocene)
- Angat Formation (Early Miocene)
- Madlum Formation (Middle Miocene)

Quaternary Volcanic-derived Sediments

- Guadalupe Formation (Pleistocene)
- Alat Conglomerate Member
- Diliman Tuff Member
- Laguna Formation (Pliocene to Pleistocene)
- Taal Tuff (Pleistocene)

Quaternary Alluvium

- Manila bay Coastal and Deltaic Deposits (Recent)
- Marikina Valley Alluvium (Recent)
- Laguna lake Shore Alluvium (Recent)

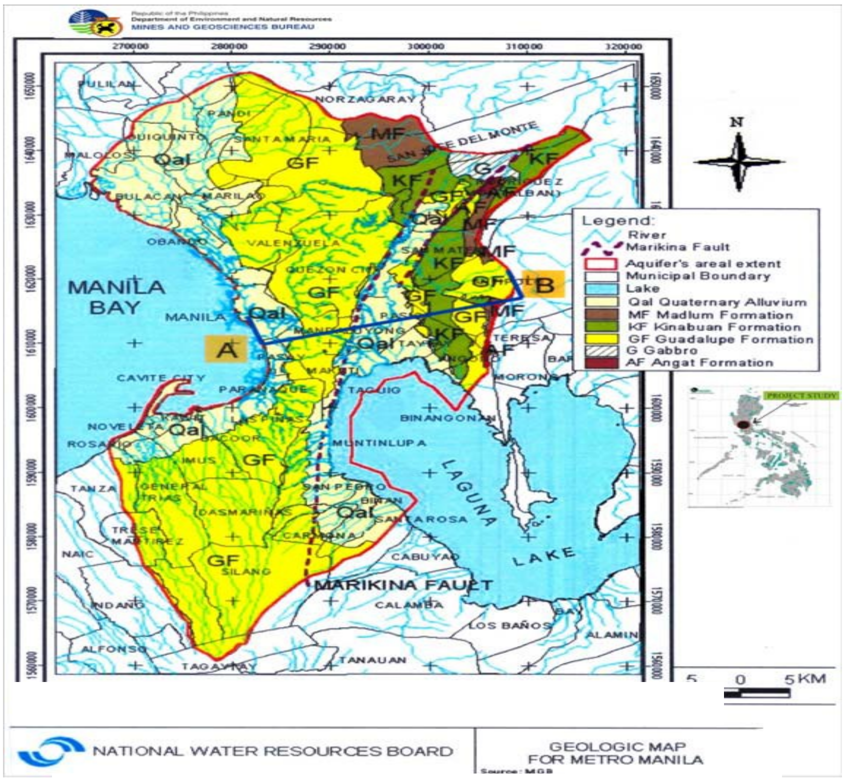


Fig 3 A geologic map of Metro Manila

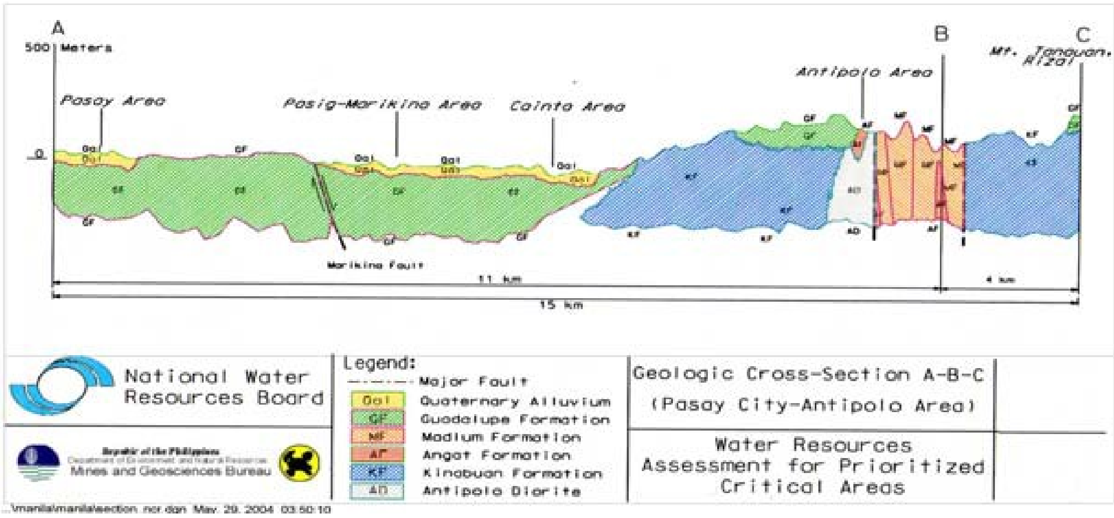


Fig. 4 Geologic profile

All of the Pre-Quaternary age rocks form the hydrogeological basement of the study area. All members under this group have been described to have very low yielding water potential, except at localized fracture zones. Uncomformably overlying the Pre-Quaternary basement rocks and underlying the Quaternary Alluvium is the Quaternary Volcanics, which has three members, the Guadalupe Formation, the Laguna Formation and the Taal Tuff, these three formations form the main host of the underlying aquifers of Metro Manila and the surrounding areas. These Quaternary Volcanic Sediments consist of intercalations of clay, silt, sand, and gravel lenses that have been described to dip gently toward the west in the central portion of the study area. The Quaternary alluvium is generally consists of unconsolidated sediments of gravel, sand, silt, and clay. These deposits are also considered important aquifers in the study area. Fig. 3 is a simplified geologic map of Metro Manila and Fig. 4 represents the geologic section along selected zones.

3.4 Fault System

The major fault system in the study area trends in the most north-south direction. The Marikina Valley Fault System (MVFS) is the most prominent fault structure in the study area. The fault system consists of two sub-apparelled gravity fault, the West Valley Fault and the East Valley Fault. The former also referred to as the Marikina Fault is traceable from Tagaytay on the south cutting through Cupang- Bicutan area all the way to Montalban on the north. The East Valley Fault (sometimes referred to as the Binagonan Fault) runs almost parallel to the main fault from Angono, Rizal and Terminates close to the northern end of the main Fault in Montalban

3.5 Climate

The Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) uses the classification of climate in the Philippines based on rainfall temporal distribution of the Corona's classification system. Fig. 5 provides a climate map of the Philippines.

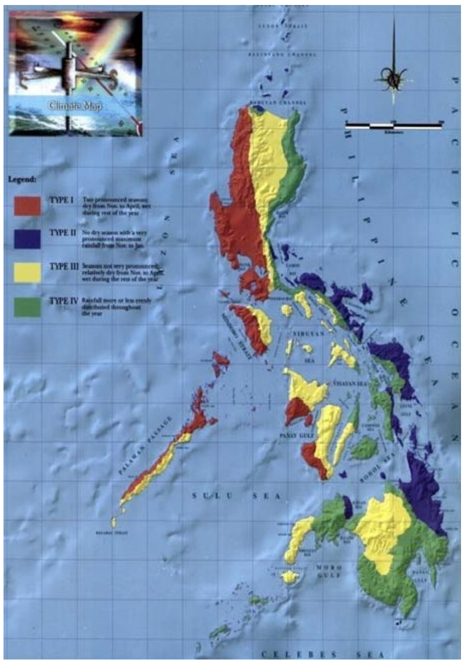


Fig. 5 A climate map of the Philippines

A greater part of the study area falls under the Type I climate that is characterized by having two pronounced season, dry from November to April and wet during the rest of the year. High elevation areas on the east experience a shift from Type I to Type III that is characterized by seasons that are not very pronounced, relatively dry from November to April and wet during the rest of the year. Based on the available PAGASA climatological- normals (1971 to 2000), the mean annual rainfall over the study area is around 2,000 mm varying from 1,750 (NAIA, Pasay) on the west to 2,500 mm on the north and eastern highlands.

4. Population and Water Demand

Based on the estimate of future population, domestic water demand was projected. Commercial, industrial and agricultural water demands were also estimated. The table below presents the projected future population.

Table 1 The projected future population

City/Municipality	Projected Population (x 1000)				
	2005	2010	2015	2020	2025
Cities					
1) Las Piñas	609	759	953	1,114	1,290
2) Manila	1,473	1,345	1,286	1,146	1,011
3) Makati	443	432	426	391	356
4) Mandaluyong	281	277	280	264	246
5) Marikina	436	472	530	556	576
6) Muntinlupa	468	558	639	682	720
7) Parañaque	507	554	637	683	725
8) Pasig	555	595	658	679	694
9) Valenzuela	560	624	719	773	823
10) Caloocan	1,339	1,471	1,701	1,833	1,956
11) Pasay	359	353	344	313	282
12) Quezon	2,285	2,343	2,533	2,554	2,549
Municipalities					
1) Malabon	369	390	414	411	404
2) Navotas	244	253	267	264	258
3) Pateros	57	56	57	55	52
4) San Juan	109	98	93	82	71
5) Taguig	588	711	897	1,055	1,227
MetroManila Total	10,682	11,291	12,434	12,855	13,240

Source: The Study on Water Resources Development for Metro Manila in the Republic of the Philippines, JICA

Table 2 Population projection outside Metro Manila

City/Municipality	Projected Population				
	2005	2010	2015	2020	2025
Bulacan					
1) Bulacan	70,066	81,167	94,2197	109,561	128,570
2) Guiguinto	79,848	97,271	117,192	139,610	164,526
3) Malolos	206,231	249,942	299,964	356,421	419,486
4) Marilao	122,417	151,704	184,713	221,434	261,498
5) Norzagaray	106,288	144,618	187,817	233,916	278,931
6) Obando	58,697	68,283	79,163	91,995	107,868
7) Pandi	55,,524	66,351	78,386	92,919	108,957
8) San Jose Del Monte	394,219	498,918	617,003	745,664	882,555
9) Santa Maria	170,802	208,070	250,682	298,636	351,932
Cavite					
1) Cavite City*	97,000	94,000	92,000	89,000	85,000
2) Bacoor*	362,00	421,000	492,000	564,000	638,000
3) Imus*	240,000	289,000	334,000	379,000	424,000
4) Kawit*	67,000	71,000	75,000	79,000	80,000
5) Noveleta*	35,000	37,000	41,000	44,000	47,000
6) Rosario*	83,000	90,000	104,000	119,000	135,000
7) Carmona	54,985	65,482	76,958	89,338	230,060
8) Dasmariñas	472,321	595,793	727,799	863,616	102,544
9) Gen. Mariano Alvarez	126,839	149,095	204,542	200,705	997,394
10) General Trias	133,446	167,803	173,717	242,410	279,865
11) Silang	173,148	200,668	231,360	265,610	303,900
12) Tagaytay City	55,062	68,291	82,466	97,215	112,067
13) Tanza	129,978	157,383	187,014	218,451	251,174
14)Trece Martires	46,984	55,229	64,349	74,347	85,220
Laguna					

City/Municipality	Projected Population				
1) Biñan	238,246	280,118	326,435	377,190	432,370
	2005	2010	2015	2020	2025
2) San Pedro	279,114	332,792	391,626	455,080	522,491
3) Santa Rosa	225,965	271,293	320,787	373,795	429,504
Rizal*					
1) Antipolo	692,000	984,000	1,376,000	1,860,000	2,453,000
2) Angono	90,000	104,000	124,000	142,000	160,000
3) Binangonan	209,000	228,000	264,000	296,000	323,000
4) Cainta	338,000	454,000	587,000	733,000	894,000
5) Rodriguez (Montalban)	130,000	144,000	173,000	201,000	228,000
6) San Mateo	33,000	36,000	218,000	225,000	290,000
7) Taytay	226,000	255,000	303,000	349,000	392,000

Source: The Study on Water Resources Development for Metro Manila in the Republic of the Philippines, JICA 2003

Considering the future population, the water demand was estimated. The total water demand is the sum of domestic, commercial, industrial and unaccounted-for-water. This also represents the average water demand for the study area. The tables below present the total water demand up to year 2025.

Table3 Total water demand within MWSS service coverage

Cities/Municipality	Total Water Demand MLD				
	2005	2010	2015	2020	2025
West Zone					
NCR					
1) Pasay	97,174	101,538	108,966	113,125	118,286
2) Caloocan	270,435	306,923	402,069	494,688	598,571
3) Las Piñas	98,913	190,577	245,000	298,438	366,000
4) Malabon	127,391	137,308	147,759	153,594	160,857
5) Valenzuela	160,000	180,769	212,759	239,531	271,000
6) Muntinlupa	67,609	130,385	153,448	171,094	195,857
7) Navotas	68,478	73,462	82,759	89,844	97,000
8) Parañaque	125,217	172,692	198,448	218,594	240,429
Cavite					
1) Cavite City	30,870	29,038	28,103	27,500	27,000
2) Bacoor	59,783	100,577	115,000	129,219	145,429
3) Imus	24,130	46,154	52,586	59,688	72,143
4) Kawit	19,130	20,577	21,034	21,875	22,286
5) Noveleta	5,217	5,769	7,414	9,531	11,429
6) Rosario	17,609	19,423	22,414	25,781	29,714
East Zone					
NCR					
1) Mandaluyong	169,783	175,962	189,483	202,500	221,000
2) Marikina	154,522	162,692	182,069	195,938	212,286
3) Pasig	197,826	209,808	232,069	247,344	265,143
4) Pateros	18,261	18,077	18,621	18,750	18,857
5) San Juan	69,348	69,808	73,448	77,813	84,571
6) Taguig	44,348	62,115	133,966	226,094	349,000
Rizal	-	-	-		
1) Antipolo	40,435	69,423	187,069	379,531	681,000
2) Cainta	35,000	62,115	88,103	138,125	206,571
3) Angono	-	-	11,379	25,625	42,143
4) Binangonan	-	-	21,207	46,250	74,000
5) Rodriguez	13,261	15,769	26,724	39,844	55,000
6) San Mateo	19,348	23,269	36,724	52,969	71,429

7) Taytay	22,391	27,308	46,724	70,000	96,286
Common Concession Area					
Cities/Municipality	Total Water Demand MLD				
	2005	2010	2015	2020	2025
NCR					
1) Quezon City	898,913	931,346	1,014,310	1,072,656	1,148,571
2) Manila	661,304	640,192	654,655	662,656	689,571
3) Makati	270,000	278,654	296,724	314,219	341,143

Source: The Study on Water Resources Development for Metro Manila in the Republic of the Philippines, JICA, 2003

Table4 Total water demand outside MWSS water service coverage

Cities/Municipality	Total Water Demand (m3/d)				
	2005	2010	2015	2020	2025
Bulacan					
1) Bulacan	10,772	13,037	16,199	19,866	24,055
2) Guiguinto	12,278	15,947	20,136	25,313	30,784
3) Malolos (Capital)	35,108	47,156	60,814	78,093	95,796
4) Marilao	23,586	31,958	42,397	53,594	66,309
5) Norzagaray	16,340	23,703	32,268	42,408	52,188
6) Obando	9,023	11,191	13,604	16,679	20,183
7) Pandi	8,535	10,877	13,466	16,841	20,383
8) San Jose Del Monte 1	75,965	105,101	141,636	180,463	223,784
9) Santa Maria	29,076	39,254	50,819	65,429	80,367
Cavite					
1) Carmona	7,809	10,542	13,121	16,707	20,741
2) Dasmariñas	71,433	102,075	132,530	173,729	215,951
3) General Trias	16,484	30,425	31,274	41,505	51,757
4) Silang	26,819	34,378	42,132	53,432	65,800
5) Tagaytay City	9,038	12,761	16,446	21,440	26,657
6) Tanza	18,942	26,151	32,977	42,535	52,600
7) Trece Martires City	7,103	9,465	11,716	14,953	18,455
8) Gen. Mariano Alvarez	19,877	26,322	32,639	41,666	51,448
Laguna					
1) Biñan	28,697	37,143	68,778	106,294	129,084
2) San Pedro	38,460	50,930	79,131	104,657	137,187
3) Santa Rosa	28,293	38,122	68,628	105,337	128,229

Note: Project Estimate

5. Water Resources

5.1 Surface Water

The Angat River and Umiray River are the main sources of water supply of Metro Manila, contributing about 98% of the total water production. In addition to the above supply, MWSS abstracts water from lpo, La Mesa and groundwater. At present, MWSS supplies a total of 4,000 MLD. Fig.6 presents in plan these identified potential surface water sources.

MWSS is embarking to augment its present supply capacity by optimizing the use of the existing water sources and developing new sources. These involve the following:

(1) Wawa River Supply;

(2) Angat Water Utilization Improvement,

(3) Laguna Lake Bulk Water Supply.

Other alternative water sources for Metro Manila are identified as follows:

(1) Kaliwa River Basin (Laiban Dam);

(2) Kanan River Basin (Kanan No. 2 Dam

(3) Pampanga River Basin; Pampanga River Basin;

(4) Marikina River Basin; and

(5) Taal Lake.

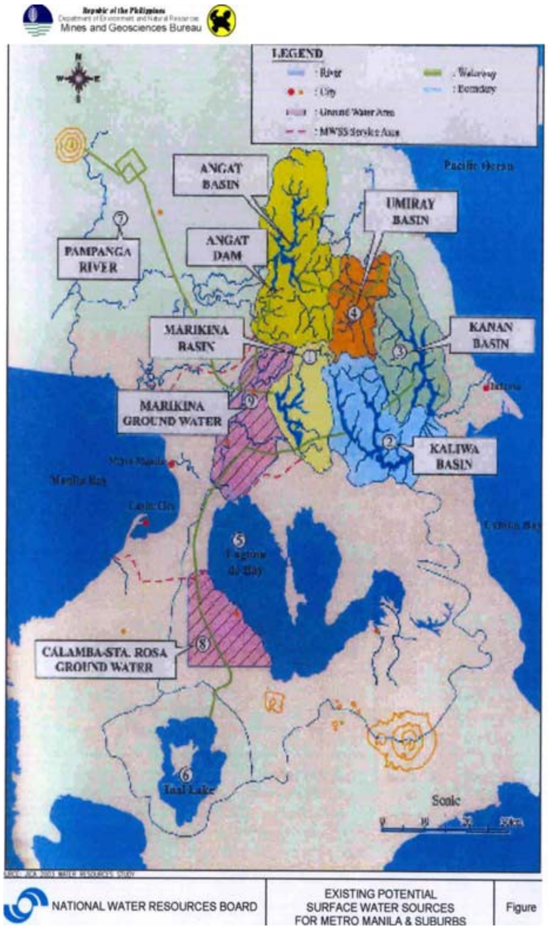


Fig. 6 Surface water resource for Metro Manila

5.2 Groundwater Sources

5.2.1 Aquifer Characteristics/Extend

The delineated surface water catchments contributing groundwater to Metro Manila aquifer constitute individual aquifer system where their groundwater discharges into Manila Bay and before reaching the sea, merge forming complex type of aquifer system. The extent of groundwater basin is delineated based on the surface water divides. The groundwater apparently intermixes/interflows due to stress created by the abstraction of multiple wells pumping simultaneously. Adding to the complexity is the landward movement of seawater from Manila Bay flowing into areas with significant decreases in aquifer pressures specifically at cones of depression (Valenzuela City, Pasig City and Paranaque City). The extend of groundwater basin is delineated with the main groundwater divides as the boundaries. These divides are usually determined from groundwater level contours. However, for Metro Manila the piezometric contours are significantly impaired due to excessive groundwater extraction therefore, the surface water divides in the delineation of the approximate extend of Metro Manila (Fig. 7).

In the eastern portion, particularly at Tagaytay area and vicinity, the aquifers are unconfined (Sandoval and Mamaril, 1970). The groundwater flows down gradient into the main confined aquifer. The shallow aquifers in the area are also unconfined which recharges the underlying main confined aquifer through leakages in the semi-confining layers (aquitard) of thickness in the range of 15-20 meters (Haman, 1998)

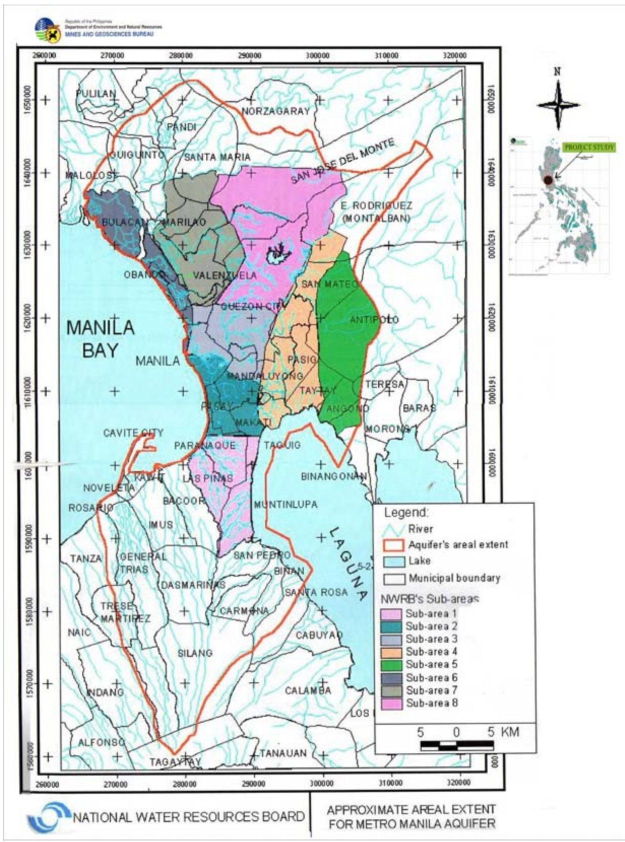


Fig. 7 Aquifer approx. areal extend

5.2.2 Aquifer Transmissivity

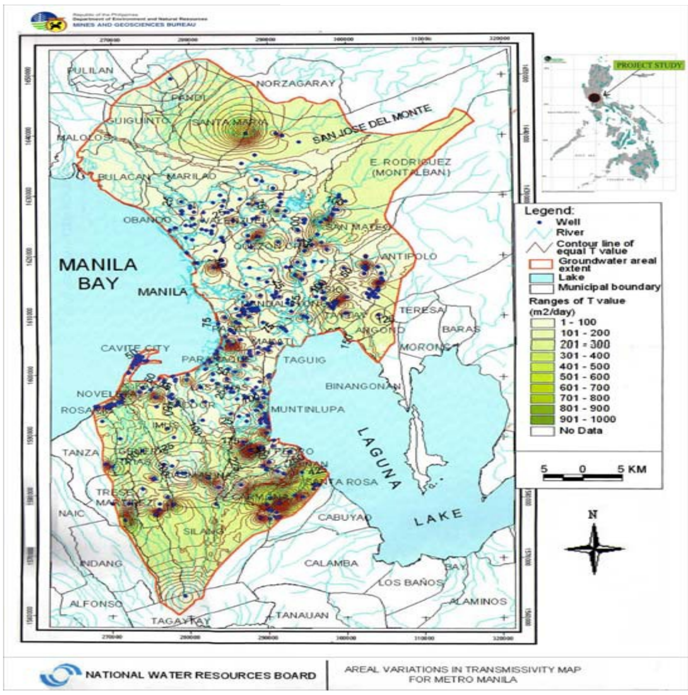


Fig 8 Transmissivity map

Transmissivity map for the whole Metro Manila was prepared in previous studies (Electrowatt/EGI, 1981) and constantly updated (MWSS, 1982 and JICA, 1998). The obtained values are incorporated to the calculated or estimated T-values of previous studies and plotted/contoured, the resulting Transmissivity Map is shown in Fig. 8. High transmissivity values, as high as 308 m²/day, are observed to exist in the area at the proximity of Constitutional Hill in Quezon City and similarly in the adjacent town of San Mateo, Rizal with values of 307m²/day. The upgradient municipality of Montalban nearer to San Mateo has also high T-values, up to 240 m²/day.In lower Marikina to Cainta, high values of transmissivities also exist to about 200 m²/day. In the southern areas, high T-values are observed adjacent to Laguna Lake, particularly at Muntinlupa where the Marikina Valley Fault System is located. The existence of ancillary faults and fractures adjacent the main fault accounts for the development of secondary permeability of the aquifers.

5.2.3 Storativity/Specific Yield

The ranges of storativities of confined aquifers and specific yields for unconfined aquifers for Metro Manila and suburbs as reported by Quiazon (1971) are as follows;

- Specific yields : 0.01 to 0.20 (unconfined aquifers)
- Storativities : 0.00001 to 0.009 (confined aquifers)

5.2.4 Groundwater Levels

The 1955 piezometric map indicates that in the northern part near Novaliches reservoir and at +60 contour in the groundwater divide, two separating groundwater flow directions exist. One is towards southeast direction to Marikina Valley and the other is towards the southwest direction to Pasig River near the sea. In the southern portion west of Muntinlupa, at +20 contour in the groundwater divide, two separating groundwater flows are also depicted by the groundwater level map. One direction of groundwater flow is towards the northeast to Laguna Lake and the other is towards the northwest to Manila Bay in Bacoor area. In the central portion at Laguna Lake shoreline, groundwater flow is towards the direction following the course of Pasig River to Manila Bay. Fig. 9 shows a piezometric map in 1955.

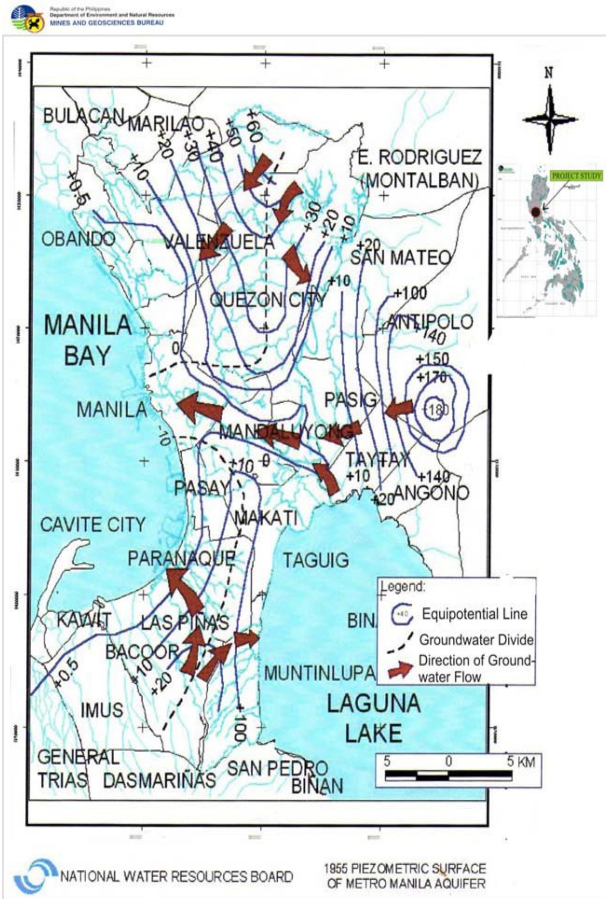


Fig. 9 A piezometric map in 1955

After 39 years since 1955, the groundwater flow pattern was significantly altered due to excessive withdrawal of groundwater in the aquifer. The adversely affected parts of the aquifer created cones of depression or decline groundwater level. This is depicted in Fig. 10 by the Piezometric Water level for Metro Manila. Three distinct cones of depressions are prominently seen within the roundwater abstraction areas, the Parañaque, Pasig and Valenzuela cones of depression. The 2004 groundwater level map depicts the worsened situation as increased groundwater abstraction resulted in deeper cones of depressions reaching 235 meters below ground level at Pilar Subdivision in Parañaque City (Fig. 11). In the Valenzuela city and vicinity (Marilao-Meycauayan-North Caloocan), two cones of depression appear with the deepest declined groundwater surface of more than 100mbsl in Marilao and in Meycauayan- Caloocan City. Small cone of depression is developed in Guiguinto area with the deepest declined groundwater surface of

80mbsl.Previous cone of depression in Pasig- Makati and vicinity enlarged with its aerial extend reaching Cainta and City of Marikina. Deepest declined groundwater surface is more than 80mbsl in Pasig-Makati area. Also previous cone of depression in Paranaque and vicinity with its aerial extend reaching Muntinlupa with the deepest decline is registered in northern Paranaque and Muntinlupa at 100mbsl.

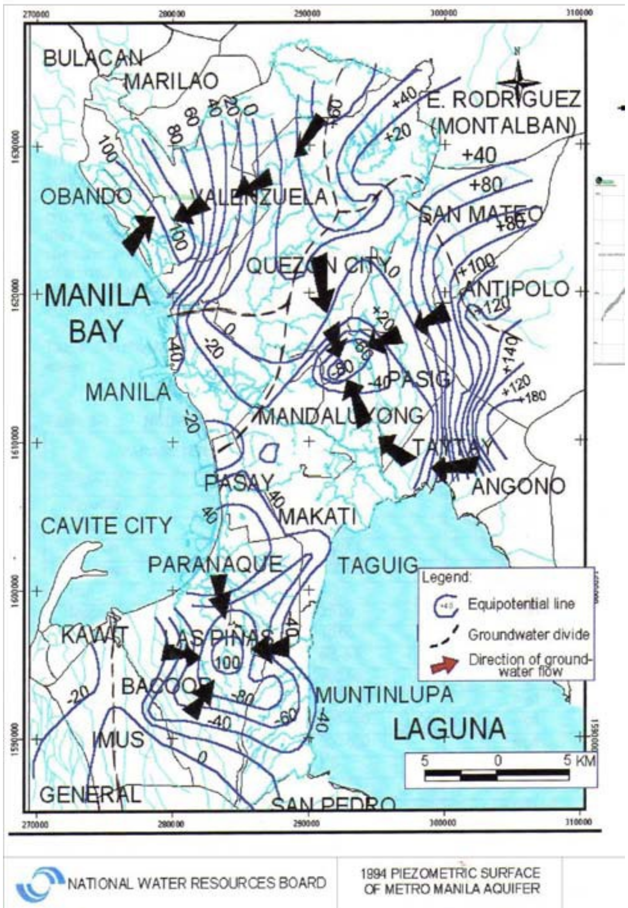


Fig. 10 A piezometric map in 1994

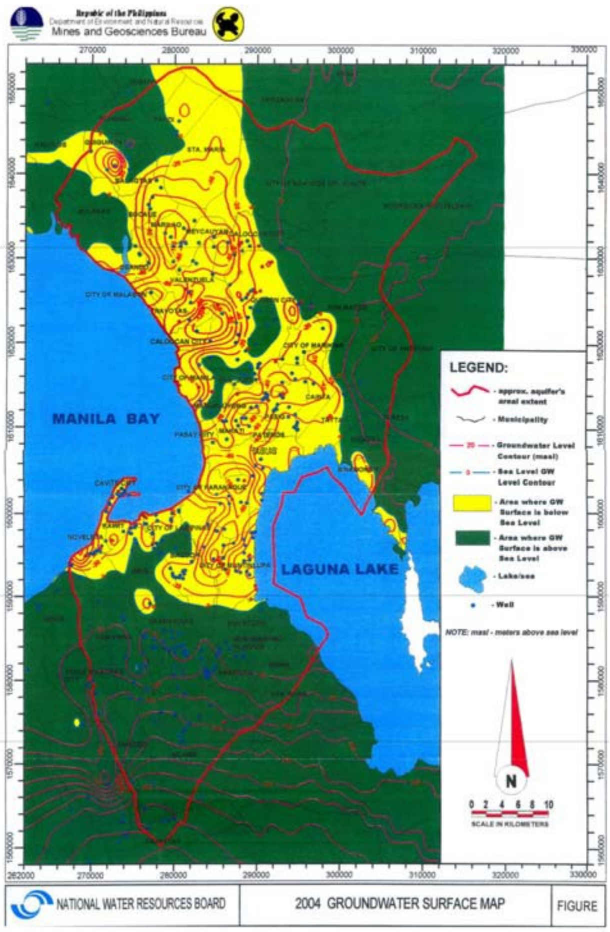


Fig. 11 A piezometric map in 2004

1994 – 2004 monitoring of groundwater level decline provides the 10-year groundwater decline suggesting that the Pasig-Taytay area shows the greatest groundwater surface decline recorded at more than 100m and 80mbgs.

5.2.5 Water Quality

Groundwater in Metro Manila aquifer deteriorates progressively as a result of the landward movement of seawater from Manila Bay into areas of significantly decreased in aquifer pressures particularly at cones of depression to replace the dewatered freshwater. Upconing of brackish groundwater and connate groundwater also take place in several places.

5.2.5.1 Total Hardness

Total hardness as $CaCO_3$ is an important chemical constituent to be considered water to be used in a particular industry. The total hardness of water samples within Metro Manila is plotted and contoured as shown in Fig. 12. Lower values of hardness ranging from 20 to 60 mg/l exist in the northwestern part of the study area, particularly in the municipalities of Balagtas, Bocaue, Marilao, Obando, Malabon, Navotas, Caloocan City and the lower part of Valenzuela. Lower hardness is also depicted in Paranaque, las Pinas, and part of Muntinlupa and in areas of Cavite City, Noveleta, and Kawit. Other parts of the study have higher hardness values ranging from 60 to over 300mg/l in San Jose del Monte and 60 to 180mg/l in Tagaytay area.

5.2.5.2 Electrical Conductivity (EC)

The electrical conductivity (EC), which gives indication of groundwater quality on salinity is the most mportant par ameter gathered during the fieldwork. The areas with EC values less than 2,000 microSiemens/cm is categorized as groundwater with low salinity; the areas with EC values from 2,000-5,000 microSiemens/cm is categorized as brackish groundwater of various uses; the areas with EC values >5,000 to <10,000 microSiemens/cm is categorized as brackish groundwater of limited use and groundwater with EC values >10,000 microSiemens/cm is categorized as saline and unusable groundwater. Fig. 13 shows the 2004 Salinity (EC) Map which depicts the salinity in Metro Manila. And the extend of landward movement of seawater from Manila Bay into areas of significantly deceased aquifer pressures, particularly at cones of depression to replace the dewatered freshwater.

For acidic water with pH lower than 7 may pose water quality problem on disinfection, corrosion control, water softening and higher treatment costs. The values of pH range from 6.5 to 8.5 as specified in the National Standards for Drinking Water (NSDW) predominates in the study area, except in some parts of Bulacan with higher pH of about 9, particularly in the municipalities of Marilao, Pandi, Guiguinto,Malolos and Bulacan. Lower pH (less than 6) exists in the area at Pasig, Taytay and Marikina and in San Mateo, Rizal. Fig. 13 shows the distribution and coverage of salinity deterioration in Metro Manila or study area.

Areas closer to the sea are the first to be affected by the landward movement of seawater flowing into areas of reduced aquifer pressures due to excessive groundwater withdrawals. Excessive pumping of groundwater results in upcoming of brackish or connate groundwater from underneath. It was suspected that the lowering of groundwater levels down to more than 60 meters below sea level in Cainta, Taytay, Pasig, and Taguig is due to over-extraction of groundwater. During periods when seawater is high particularly during high tides, seawater moves inland at the surface through rivers/streams like Pasig River. The Napindan structure built for purposes of blocking tidal inflow of seawater is believed to be not functioning effectively. Tidal inflow of seawater contributes to the existence of high salinity groundwater in Pasig and vicinity with electrical conductivity (EC) of groundwater reaching more than 3,000 microSiemens/cm.

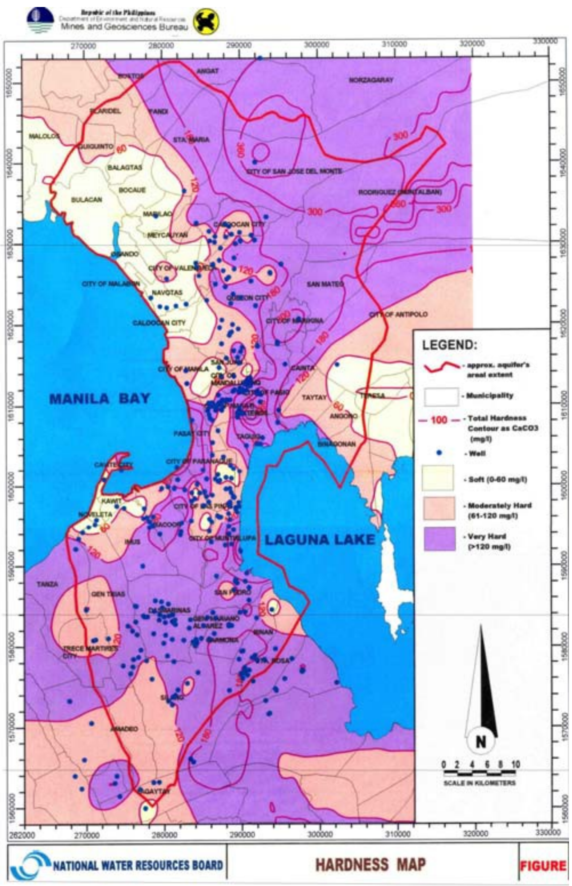


Fig.12 Hardness map

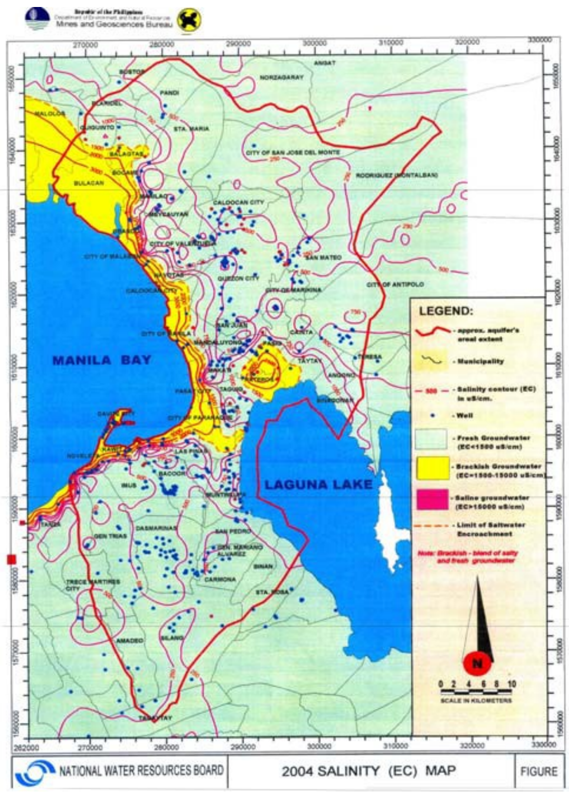


Fig 13 Salinity (EC) map

Industries discharging effluent on the ground surface, in rivers and lakes contaminate groundwater of the underlying aquifer. The Laguna Lake Development Authority (LLDA) has inventoried 336 industries and classified each according to their pollution potential. Large number of these industries is found along Marikina River, Pasig River, Laguna Lake and tributary rivers making use of these surface waters as disposal of their objectionable effluents. Polluted river and lake waters leak into the aquifer for which the groundwater is utilized for drinking by majority of existing drilled wells.

5.2.6 Groundwater Abstraction

The groundwater abstraction of MWSS wells accounts 3% of the total water consumption supplied by MWSS for Metro Manila. The present amount of groundwater withdrawal legally registered with the NWRB totals 12,823.53 liters/second. Unregistered wells drawing groundwater from the aquifer are considered as illegal wells. The amount of groundwater abstracted by illegal wells plus the amount drawn by permitees exceeding their granted amount is believed to be more than 60% of the total groundwater extraction of registered wells. Unregistered well drawing groundwater from the aquifer are considered as illegal wells. Fig.14 shows the density of permittees abstracting groundwater.

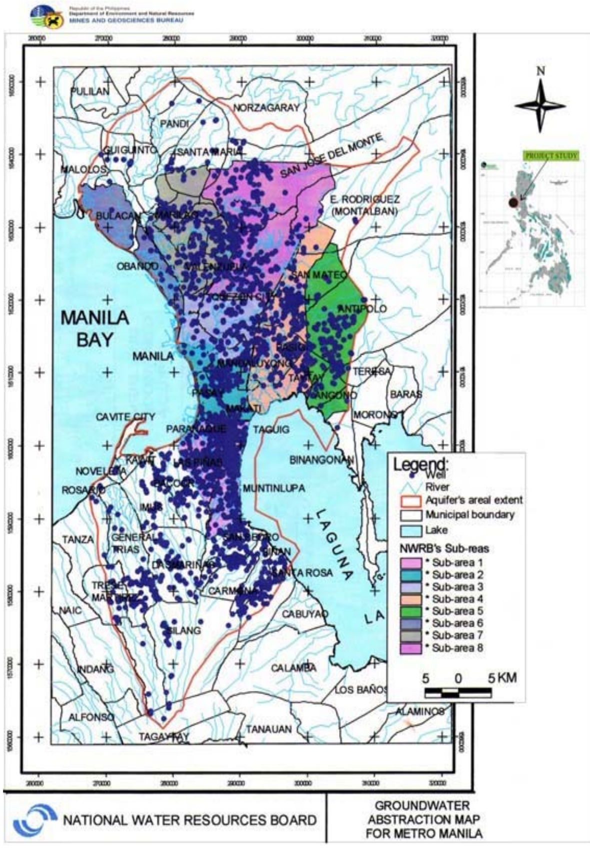


Fig 14 Legal abstracting groundwater permittee map

5.2.7 Groundwater Availability

The main confined aquifer of Metro Manila is replenished from several sources. Fig. 15 shows the different sources of aquifer replenishments.

a) Groundwater leakage inflow from the overlying shallow unconfined aquifer via aquitard.

b) Subsurface inflow of groundwater from upgradient (Tagaytay area and vicinity) unconfined aquifer;

c) Induced inflow of Laguna Lake; and

d) Subsurface inflow from upper portion of Marikina River catchment.

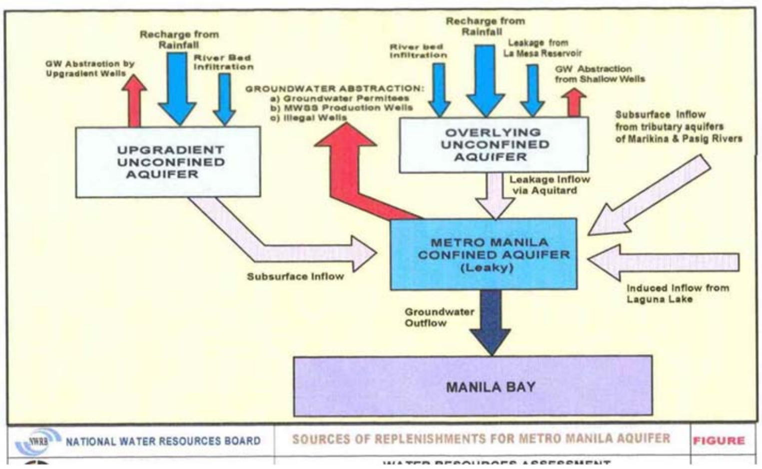


Fig. 15 Different sources of aquifer replenishment

6. Groundwater Resource Management

6.1 Resource Allocation

Safe yield is the extraction rate in the aquifer so that the groundwater contained in it could be used continuously ($t=\infty$) without drawing groundwater from its reserve/storage. Mining Yield is the extraction rate in the aquifer exceeding the safe yield limit. The amount of drawn groundwater in excess of the safe yield is mined from its reserve/storage annually until groundwater in the aquifer is totally exhausted.

Currently, issuance of groundwater permits for sub-area 1 is temporarily stopped pending the result of this assessment study. The estimated safe yield of 2,000 liters per second (NWRC & NHRC, 1983) is already exceeded. The present extraction rate for said sub-area totals 3,324.4 liters/second for which 15% of the estimated mining yield was already granted.

6.2 Resources Monitoring

6.2.1 Water Quality

There is no regular activity of continuous measurement of water quality parameters for Metro Manila aquifers to record time series data by NWRB or other entities. Measurement is done only when a certain project is undertaken and during the time when an individual/company applies for a water permit at NWRB to comply with the requirements of the application.

6.2.2 Water Levels

The government does not require permit to monitor water levels. Such undertaking should be incorporated as part of the activities in the maintenance of their waterworks systems is good engineering practice and should not only be encouraged but required to monitor water levels when possible. Water level sounding pipes should be integrated into well standard designs to enable water level monitoring.

6.2.3 Withdrawals

Abstraction rate by permit grantees is monitored by NWRB through its Monitoring and Enforcement Division only when verification of the granted amount is done. There is no activity of continuous measurement of well discharge to record historical data of pumpage. Permits should be required to submit a historical record of production and technical specification of pump installed.

6.3 Groundwater Resource Protection

Since the Implementing Rules and Regulation of the Water Code of the Philippines which declares that the State shall pursue a policy of economic growth in a manner consistent with the protection, preservation and revival of quality of the country’s freshwater, brackish and marine waters. Thus the protection of our water system that includes the sealing of abandoned wells by plugging or sealing of abandoned wells, proper location of refuse dumpsite, graveyard, septic tank and proper appropriation / allocation of groundwater.

7. Groundwater Modeling/Water Balance

Models or simulations may be used to estimate the hydraulic response of an aquifer, at complied conditions at some future point in time. The predictive simulations must be viewed as estimates, not certainties, to aid the decision-making process. The MODFLOW groundwater modeling software originally developed by McDonald and Harbaugh (1988) of the U.S. Geological Survey is used. The MODFLOW model is based on finite-difference method and designed for three-dimensional (3D) saturated groundwater flow.

One major task in groundwater modeling especially, 3-dimensional models, is the creation of the groundwater grid system based on the hydrogeological concept model. The grid file was prepared using Surfer graphic software over the study area. Having the same grid coordinate limits, this grid was then overlaid on the digitized geological maps to be able to assign geological codes at the surface. This particular grid system consists of 4,743 block-centered nodes (51 columns from west to east; 93 rows from south to north) with a square size of 1 km by 1 km. There are 2,350 active nodes in which 2, 182 nodes are land boundaries, 65 nodes represents Manila Bay boundary conditions and 103 nodes represent Laguna Lake boundary conditions. The remaining 2,393 nodes are inactive nodes, which are outside the physical boundary.

For the development of the aquifer geometry, the same grid was used and geologic codes were assigned to the grid cells based projections made from the surface geology and available subsurface eology. Geologically coded grid level maps, having the same grid limits, were prepared for zero (0) levation (mean low, low sea level) and every 30 meters above masl up to the highest known elevation and projected every 30 below sea level to elevation of -210 m.

The model finite-difference grid consists of 18 layers with thickness of 30 meters with 6 layers below mean low, low water (MLLW) sea level and 11 layers above MLLW. It may be noted that for the code maps of layers above MLLW, the blank areas are inactive nodes representing the above ground surface grids. In the coded maps for each layer, the finite-difference grid system has been classified into 10 types of soil/geologic characteristics. Each type of soil has a unique hydraulic conductivity, porosity and storage coefficient. The specific groundwater properties used in this study are discussed next.

Considering the given geology of the study area, the main sedimentary components are clay, silt, sand gravel, basaltic igneous rock (in varying degrees of fracturing) and minor limestone deposits. Based on the examined well logs of the Philippine Groundwater Database of NWRB, the components of sedimentary formations in the main aquifer present themselves as well as sorted and mixed textures. To facilitate simplicity in the description of the formations, terminologies pertaining to origin such as “tuff”, “tuffaceous”, “adobe” were treated as an equivalent of silt, based on the consultant’s experience in checking drillers log on-site and local description of adobe. Only textural terminologies pertaining to grain size using the Wentworth scale of sedimentary grain-size were adopted.

There are several boundary (including interior boundary) conditions that must be in the model. It is important to properly define these boundary conditions since they govern the groundwater flows. These are the rainfall boundary condition including evapotranspitation. Another major recharge to the groundwater system are the river leakages. There are 328 nodes with river boundary conditions. Another major discharge boundary conditions in the model are the pumping wells. There are a total of 2,206 registered pumping wells in the NWRB database. Two major head boundary conditions are specified in the model. These are Laguna Lake water levels and Manila Bay water levels. Another head boundary that being considered is the Novaliches Reservoir (lake leakage).

7.1 Model Calibration and Testing

Model calibration consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria. This requires that field conditions at a site are properly characterized. Lack of proper site characterization may result in a model that is calibrated to a set of conditions, which are not representative of actual field conditions. The calibration process typically involves calibrating to steady-state and transient conditions. With steady-state simulations, there are no observed changes in hydraulic head with time for the field conditions being modelled. Models may be calibrated without simulating steady-state flow conditions, but not without some difficulty. At a minimum, model calibration should include comparisons between model- simulated (computed) conditions and field (measured) conditions for the following data:

- Hydraulic head data;
- Groundwater-flow direction;
- Hydraulic-head gradient; and
- Water mass balance.

A calibrated model uses selected values of hydrogeologic parameters, sources and sinks and boundary conditions to match field conditions for selected calibration time periods (either steady-state or transient). However, the choice of the parameter values and boundary conditions used in the calibrated model is not unique, and other combinations of parameter values and boundary conditions may give very similar model results. History matching uses the calibrated model to reproduce a set of historic field conditions.

In the case of the Metro Manila model, there is only one area with observation wells, in Las Piñas, that have a hydrograph available. It would have been ideal to have had a period of monitoring, say three years prior to the start of this project, with many observation wells distributed around the study area for water table measurements as historical basis for the model verification.

Not withstanding the situation was the model would need some degree of calibration for its verity, the Metro Manila model could be calibrated using the transient method. Transient simulations involve the change in hydraulic head with time (e.g. aquifer test, an aquifer stressed by a well-filled, or a migrating contaminant plume). These simulations are needed to narrow the range of variability in model input data since there are numerous choices of model input data values which may result in similar steady-state simulations. Future measurements made from selected monitoring wells could be calibrated against the hydrographs of projected piezometric heads created using the Modflow that are presented in the later part of this chapter.

However, since the duration of this project is only 6 months, it cannot be done within the contract period. Thus, some recommendations are presented in the next Chapter 8 regarding the sustainability of the project, and only then can the calibration of the model be made.

7.2 Water Balance Study and Groundwater Simulation Scenarios

Four simulation scenarios were performed for Metro Manila. Under the four scenarios, all conditions indicate groundwater mining. Projections for 10-year and

20-year periods were made for the 4 scenarios as follows:

Scenario 1: Current (2004) levels of groundwater pumping rates (taken from water permits) including unregistered wells, which is assumed to be 60% of the existing registered wells. Table 5 below is an accounting of the water balance of the study area under the first scenario.

Table 5: Water budget for Scenario 1
Simulation Scenario 1- Existing Case (End 2004 Pumping Rate)

Parameter	End of 2004		End of 2015		End of 2025	
	Cumulative Volumes (m^3)	Rates For This Time Step (m^3/day)	Cumulative Volumes (m^3)	Rates For This Time Step (m^3/day)	Cumulative Volumes (m^3)	Rates For This Time Step (m^3/day)
IN:						
Storage	2,249,900,000	2,125,400	5,346,300,000	590,640	7,165,000,000	441,930
Constant Head	2,157,300,000	2,251,800	8,991,400,000	1,897,500	16,136,000,00	2,003,100
Wells	0	0	0	0	0	0
Recharge	76,285,000	104,500	457,710,000	104,500	839,140,000	104,500
River Leakage	30,526	40	167,550	36	299,250	36
TOTAL IN	4,483,500,000	4,481,700	14,796,000,00	2,592,700	24,140,000,00	2,549,500
OUT:						
Storage	2,009,500,000	1,357,900	2,664,500,000	31,492	2,718,600,000	9,588
Constant Head	549,030,000	446,010	676,210,000	3,171	681,110,000	422
Wells	1,860,900,000	2,548,700	11,156,000,00	2,545,700	20,446,000,00	2,544,800
Recharge	0	0	0	0	0	0
River Leakage	21,801	60	433,010	124	891,850	126
TOTAL OUT	4,419,500,000	4,352,700	14,498,000,00	2,580,400	23,847,000,00	2,554,900
IN - OUT	64,000,000	129,000	298,000,000	12,300	293,000,000	-5,400

At the present withdrawal rate, the Metro Manila aquifer would be depleted having a negative water balance estimated at -5,400 cu.m. per day. This could happen in less than 20 years, since, when the real mining rates started, cannot be determined. It should be noted that there are no records for illegal or unregistered wells.

Scenario 2: Pumping rates of Scenario 1, plus 230 new wells applicants, still pending for approval. Under the second scenario, the Metro Manila aquifer would be depleted having a negative water balance estimated at -6,500 cu.m. per day. This could happen in less than 20 years, since, when the real mining rates started, cannot be determined.

Table 6 Water budget for Scenario 2

Simulation Scenario 2 – Existing Case Plus 230 Wells

Parameter	End of 2004		End of 2015		End of 2025	
	Cumulative Volumes (m^3)	Rates For This Time Step (m^3/day)	Cumulative Volumes (m^3)	Rates For This Time Step (m^3/day)	Cumulative Volumes (m^3)	Rates For This Time Step (m^3/day)
IN:						
Storage	2,283,100,000	2,169,300	5,518,000,000	627,950	7,471,200,000	477,510
Constant Head	2,178,800,000	2,287,500	9,222,000,000	1,964,000	16,629,000,00	2,078,200
Wells	0	0	0	0	0	0
Recharge	76,285,000	104,500	457,710,000	104,500	839,140,000	104,500
River Leakage	30,505	40	167,780	37	299,830	36
TOTAL IN	4,538,300,000	4,561,300	15,198,000,00	2,697,100	24,940,000,00	2,660,300
OUT:						
Storage	1,982,600,000	1,325,200	2,584,000,000	25,441	2,630,800,000	8,948
Constant Head	548,570,000	445,560	675,350,000	3,056	680,080,000	418
Wells	1,943,000,000	2,661,200	11,649,000,00	2,658,200	21,350,000,00	2,657,300
Recharge	0	0	0	0	0	0
River Leakage	21,732	60	428,670	122	877,180	123
TOTAL OUT	4,474,200,000	4,432,000	14,909,000,00	2,686,800	24,662,000,00	2,666,800
IN - OUT	64,100,000	129,300	289,000,000	10,300	278,000,000	-6,500

Scenario 3: Pumping rates of Scenario 1, plus 461 new wells applicants, still pending for approval.

Table 7 Water budget for Scenario 3

Simulation Scenario 3 – Existing Case Plus 461 wells

Parameter	End of 2004		End of 2015		End of 2025	
	Cumulative Volumes (m^3)	Rates For This Time Step (m^3/day)	Cumulative Volumes (m^3)	Rates For This Time Step (m^3/day)	Cumulative Volumes (m^3)	Rates For This Time Step (m^3/day)
IN:						
Storage	2,310,800,000	2,206,800	5,657,900,000	655,440	7,709,800,000	502,830
Constant Head	2,198,000,000	2,319,300	9,415,100,000	2,019,100	17,036,000,00	2,139,300
Wells	0		0	0	0	0
Recharge	76,285,000	104,500	457,710,000	104,500	839,140,000	104,500
River Leakage	30,505	40	168,130	37	301,160	36
TOTAL IN	4,585,100,000	4,630,500	15,531,000,00	2,779,100	25,585,000,00	2,746,600
OUT:						
Storage	1,965,800,000	1,307,100	2,534,500,000	22,158	2,577,200,000	8,436
Constant Head	547,880,000	444,910	674,430,000	2,994	679,090,000	417
Wells	2,007,700,000	2,749,900	12,037,000,00	2,745,500	22,057,000,00	2,744,700
Recharge	0	0	0	0	0	0
River Leakage	21,528	59	423,520	120	863,840	121
TOTAL OUT	4,521,400,00	4,502,000	15,246,000,00	2,770,800	25,314,000,00	2,753,600
IN - OUT	63,700,000	128,500	285,000,000	8,300	271,000,000	-7,000

Under the third scenario, the Metro Manila aquifer would be depleted having a negative water balance estimated at -7,000 cu.m per day. This could happen in less than 20 years, since, when the real mining rates started, cannot be determined.

Scenario 4: Based on the projected withdrawal for the years 2015 and 2025 that was based on the historical increase in the number of wells. The projected increase in the number of wells permit was based on the historical data of NWRB records.

Table 8 Water budget for Scenario 4
Simulation Scenario 4 – Projected DEMAND FROM WELLS

Parameter	End of 2004		END OF 2015		END OF 2025	
	Cumulative Volumes (m^3)	Rates For This Time Step (m^3/day)	Cumulative Volumes (m^3)	Rates For This Time Step (m^3/day)	Cumulative Volumes (m^3)	Rates For This Time Step (m^3/day)
IN:						
Storage	2,342,400,000	2,238,800	6,238,400,000	915,590	11,016,000,00	1,290,600
Constant Head	2,244,900,000	2,422,000	10,450,000,00	2,484,400	21,491,000,00	3,365,200
Wells	0	0	0	0	0	0
Recharge	76,285,000	104,500	457,710,000	104,500	839,140,000	104,500
River Leakage	30,472	40	167,780	37	301,830	34
TOTAL IN	4,663,600,000	4,765,400	17,147,000,00	3,504,500	33,347,000,00	4,760,300
OUT:						
Storage	1,981,100,000	1,328,000	2,515,100,000	8,306	2,544,400,000	8,237
Constant Head	513,430,000	424,640	629,590,000	1,870	631,410,000	250
Wells	2,104,700,000	2,882,700	13,744,000,00	3,495,700	30,028,000,00	4,775,400
Recharge	0	0	0	0	0	0
River Leakage	21,906	60	424,090	118	844,700	112
TOTAL OUT	4,599,300,000	4,635,400	16,889,000,00	3,506,000	33,205,000,00	4,784,000
IN - OUT	64,300,000	130,000	258,000,000	-1,500	142,000,000	-23,700

Under the fourth scenario, the Metro Manila aquifer would be depleted having a negative water balance estimated at -1,500 cu.m per day by 2015. This could happen in less than 10 years, since, when the real mining rates started, cannot be determined.

A comparative water budget summary of IN (minus) OUT flow through the Metro Manila aquifer system under the different scenarios and periods are presented in Table 9 Water Balance Summary Table at the end of Section 7.

Table 9 Water balance summary table

Groundwater flow (000' m^3/day)	Existing case			Existing case plus 230 wells		
	2004	2015	2025	2004	2015	2025
TOTAL IN	4,481,700	2,592,700	2,549,500	4,561,300	2,697,100	2,660,300
TOTAL OUT	4,352,700	2,580,400	2,554,900	4,432,000	2,686,800	2,666,800
IN - OUT	129,000	12,300	-5,400	129,300	10,300	-6,500
Groundwater flow (000' m^3/day)	Existing case plus 461 wells			Projected demand from wells		
	2004	2015	2025	2004	2015	2025
TOTAL IN	4,630,500	2,779,100	2,746,600	4,765,400	3,504,500	4,760,300
TOTAL OUT	4,502,000	2,770,800	2,753,600	4,635,400	3,506,000	4,784,000
IN - OUT	128,500	8,300	-7,000	130,000	-1,500	-23,700

7. 3 Results of Simulations Runs and Simulated Hydrographs

Results of simulation runs using Modflow were produced to create data and binary files that was used to create map image of the predicted water level surface and plotted using Surfer to show depth and lateral changes of the groundwater piezometric head under all scenarios described above.

In general the simulated hydrographs show a slight increase in water levels that should be considered as a warm up period for the program. However, the graph towards the years 2015 and 2025 shows a general decline in predicted water levels.

7.4 Final Remarks

The generated groundwater model is an initial step to having a quantified evaluation of the available groundwater in the Metro Manila Aquifer. However, like any model, it should be updated to reflect changes that are in process in a dynamic aquifer system.

The 1955 groundwater piezometric map of Metro Manila depicted water levels at 0.53 meters above sea level. Ideally, in any well field, extraction rates should not exceed the recharge capacity of the aquifer. A common adverse condition when the withdrawal rates exceed the groundwater potential is the lowering of the piezometric head to levels below zero or sea level. The actual measured and simulated cones of depressions in the Metro Manila Aquifer suggest a worsening situation that only confirms conclusion of earlier studies (such as the 1991 JICA Study, 1994 UNDP-MWSS Study and the 1993 IDRC/NHRC).

Already, measured and simulated piezometric levels are critical in the range of -40 to -60 below sea level. The Model still has to establish what would be the maximum allowable level for the piezometric heads in the study area to which the decision makers in NWRB can use to decide as what permissible is. Such a question arises, since the alternative water sources (to replace well sources) to supply the needs of the metropolis still has to be developed and constructed. Should permitting for wells in the metropolis continue, how deep should we allow the piezometric head to lower?

Aside from the physical manifestations of the abused aquifer, we could expect changes in water quality to change or even deteriorate. There is no question as to whether it should become policy to allow water to deteriorate or up what permissible levels contamination could be allowed. This is another parameter of groundwater that the present model cannot address.

Hence, further studies and updating of the model should continue to establish what the physical and chemical manifestations are in the groundwater resource of the study area and how can the model be used as a tool to assist policymaking.

8. Conclusions and Recommendations

Based on the findings indicated above, the following are the conclusions and recommendations of the project.

8.1 Identified Critical Areas

Eight sites within the study area are considered in need of urgent attention. These include the cones of depression (dewatered portion of the aquifer due to over-extraction of groundwater that would induce saltwater intrusion due to landward advancement of seawater into cones of depression) shown in the 2004 piezometric level contour map of the study area and are shown in Fig. 16 as the cones of depression in: 1) Guiguinto, 2) Bocaue – Marilao, 3)Meycauyan – North Caloocan, 4) Navotas – Caloocan – West Quezon City, 5) Makati – Mandaluyong – Pasig – Pateros, 6) Parañaque – Pasay, and 7) Las Piñas – Muntinlupa. Considered also as critical area is the area of Dasmariñas in the Province of Cavite, where heavy groundwater abstraction is currently taking place.

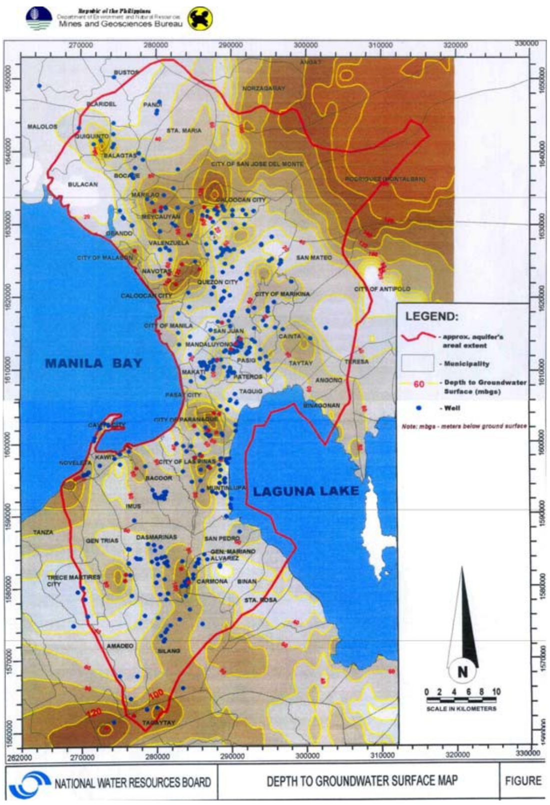


Fig. 16 Areas of groundwater concern

8.1.1 Recommendations of the monitoring wells

In response to the adverse conditions manifested by the seven major cones of depression, and the Dasmariñas area, which is considered a major abstraction zone, it is strongly recommended that drilling of monitoring wells (if abandoned wells suited for use as monitoring well is not available) for installation of data loggers to measure groundwater levels and electrical conductivities (EC) be implemented in these areas.

This would allow time series recording of groundwater level declines and recording level declines and recording of water quality deterioration. NWRB staff shall monitor and maintain the observation wells and the installed data loggers as shown in Table 10.

Table 10 The limits of the eight sites for monitoring area as follows:

Area	Location	Latitudes:	Longitudes
Area 1	Guiguinto	14° 50’to 14° 51	120° 53’to 120° 53’30
Area 2	Bocaue – Marilao	14° 44’30’’ to 14° 47’	120° 56’30’’ to 120° 58’
Area 3	Meycauyan – North Caloocan	14° 44’to 14° 4	120° 59’30’’ to 121° 01’

Area 4	Navotas – Caloocan	14° 39'30'' to 14° 41''	120° 59'to 121° 00'30''
Area 5	Makati – Mandaluyong - Pasig-Pateros	14° 33'30'' to 14° 34'30''	121° 02'to 121° 03'
Area 6	Parañaque – Pasay	14° 29'30'' to 14° 31'	121° 01'to 121° 02'30''
Area 7	Las Piñas – Muntinlupa	14° 24'30'' to 14° 26'	121° 00'to 121° 01'
Area 8	Dasmariñas	14° 19'to 120° 20'	120° 57'to 120° 59'

8.1.1.1 Criteria for the Selection of Monitoring Wells

- Deep wells should have known coordinates and were plotted on a scaled topographic map;
- Existing non-operational with known well design, having minimum depth of 200m;
- The deepwells should be within the cone of depressions identified;
- The well should have lithologic/electric log records and aquifer test data;
- There should be access (open holes or sounding pipes) for the water level monitoring probe;
- The wells should be granted access to NWRB staff by the owners.

8.1.1.2 Frequency of Monitoring

- Monitoring shall be made at least twice a month.

8.1.1.3 Parameters to be monitored

- EC (electrical conductivity)
- Water Levels
- Nitrate

8.1.1.4 Instrumentation for Monitoring

- Automatic data logger, capable of recording the three above mentioned parameters
- Data loggers 2002 price estimates were in the range of US$700 (each) and up, for a SOLINST Model 101 that could only measure only water level and EC. Additional parameters to be measured would mean costlier equipment; laptop computer to download data is not yet included.

8.1.1.5 New Observation Wells

For new observation wells, the same frequency of sampling and parameters to be monitored could be as stipulated in the said report.

The estimated cost for drilling and construction of each new well for 200 meters depth is P1, 611, 741 or about P8,060/meter of a completed well. Therefore, for the proposed 8 monitoring deep wells a total of about P12, 900, 000 should be allocated for drilling and construction of wells.

8.2 Groundwater Mining

The groundwater model having the worse scenario depicts that within 10 years, the decline of piezometric heads would accelerate to levels that would have irreversible adverse effects, such as:

1. Higher pumping cost due to lowered water levels, thus requiring higher energy.
2. Changes in water quality, through increased salinity by saltwater intrusion, or contaminants from near surface formations.
3. Reduction of porosity and permeability that result to ground subsidence
4. Overall, irreversible damage of the aquifer

It is now urgent that alternative sources of water should be developed and constructed to serve the growing demand, thus, allowing water users to divert sources from wells to surface water provided by the MWSS concessionaires.

It is apparent from the above observations that Metro Manila aquifer is now on its course to being depleted to meet the present water demand of the metropolis. If landward advancement of seawater becomes extensive, it will become extremely difficult to flush the intruding saline water back to the sea. It will take many years if sufficient quantities of freshwater (at a head that would be difficult to artificially induce) to force back to the sea the saline water that is intruded in the aquifer.

8.3 Recommendations

1. It is strongly recommended that alternative sources of water be developed (such as the Kaliwa or Kanan River water sources) and constructed within the next 10 years that would allow waterwell users to shift from groundwater to using surface water from the MWSS and its concessionaries.
2. New permits applicants should be given temporary short-term (10 year) permits to operate new well sources. While, existing water rights grantees should be given notice that all existing permits shall be revoked within 20 years from 2004. This should prevent the accelerated decline of the piezometric levels of the Metro Manila Aquifer expected to occur in 10 years, and at the same time encourage waterwell users to plan ahead for their eventual shift from groundwater source to surface water through MWSS concessionaries.
3. These should be supplemented by an information campaign that would educate the generate public and all groundwater users of the gravity of the situation and that measures are being undertaken to address the impending problem.

To save the aquifer from total depletion and degradation, a pre-feasibility study should be conducted for other mitigating measures such as artificially recharging the Metro Manila aquifer.

Figure 17 shows the following groundwater hydraulics between pumping and injection wells discharging and recharging in the same aquifer. It implies that with pumping so many million cubic meters (MCM) in the aquifer to create-100meters of drawdown, a corresponding +100 meters build-up can also be created by injecting the same quantity of recharge water in the same aquifer. It is believed that injection of recharge directly into the aquifer is the most suitable recharging technique for tuffaceous aquifer in Metro Manila.

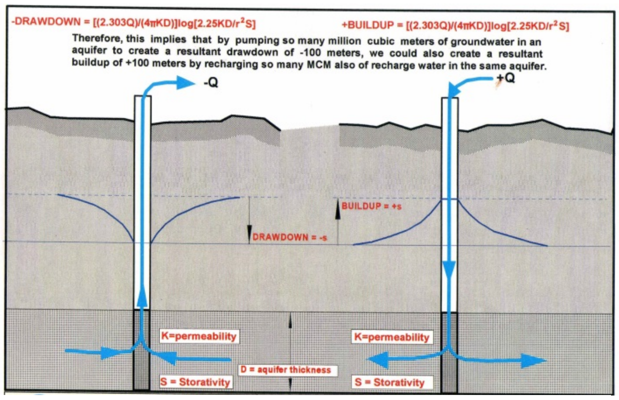


Fig. 17 A concept of pumping and injection wells.

One suggested focus of the pre-feasibility study is the construction of long horizontal infiltration galleries 30 to 50m from the lake shore (to allow filtering the objectionable constituents present in Laguna lake water) and parallel to Laguna Lake (Sta Rosa to Los Banos, Laguna), which would tap the groundwater from aquifer beneath the silty/clayey lake bed. Pumped groundwater from sump wells constructed at the ends and at intervals along the gallery could supply recharge wells (abandoned wells or newly drilled recharge wells) particularly at the cone of depression in Paranaque City and vicinity. Initially, short infiltration galleries could be tested to determine the yield per unit length and the quality of abstracted groundwater if it would meet the quality for recharge water. The plan and section of a low-maintenance cost infiltration gallery that could be used is shown in Figure 18.

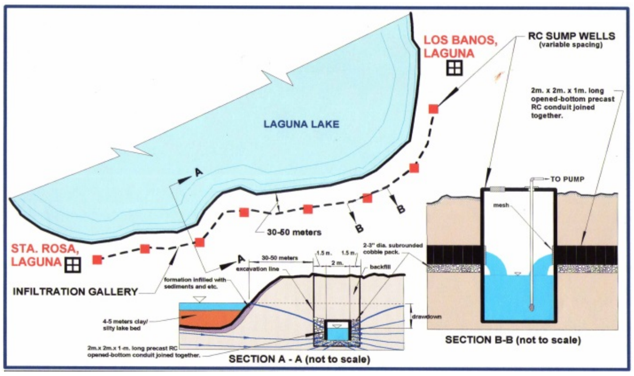


Fig. 18 A plan of an infiltration gallery.

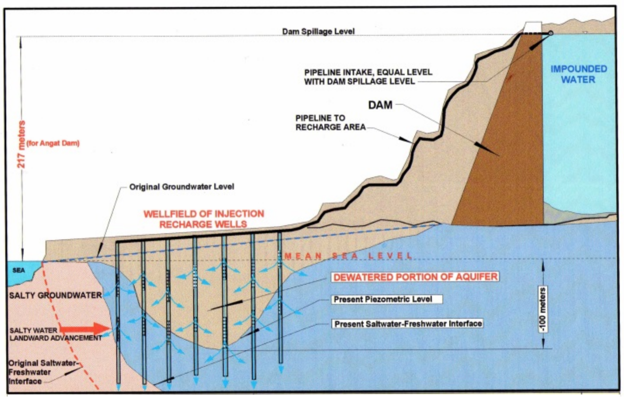


Fig. 19 The Angat dam and inject water flow.

Another suggested focus of the pre-feasibility study is to utilize untreated excess surface water overflows in dams, which are cleaner and fresher water coming from the mountains to artificially recharge the aquifer particularly at the cones of depression shown by piezometric level maps for depleted aquifers in highly urbanized cities adjacent to existing or future dams. Angat Dam for example, has a recorded total spillage of excess surface water of 234 MCM in 1995 alone. This excess water was spilled and wasted into the sea. This shows that we have surplus water during rainy seasons that can be tapped as a source for recharging the Metro Manila aquifer. The Angat dam was used as an example in Figure 19 which shows a 217m water pressure head to be used to inject water into the aquifer at the cone of depression in Valenzuela and vicinity.

References

JICA(2003): *The Study on Water Resources Development for Metro Manila in the republic of the Philippines* – 6 Volumes.

JICA(1998): *Master Plan on water Resource Management in the Republic of the Philippines* – 4 Volumes.

NWRC(1976): *Philippine Water Resource Summary Data*.

NWRC and NHRC(1983): *Groundwater Resource investigation for the Province of Rizal*.

NWRC：*Metro Manila groundwater Areas*

Haman, Bruno, Z(1996): On Sustainability of Withdrawal from Metro Manila Groundwater System and Availability of additional groundwater Resources, *Philwater International.*

PAGF(2002): *Strengthening Management of Groundwater Resource with Local Government Units.*

NWRC(1983): *Map of Metro Manila Groundwater A.*

JICA(1992): *Study for the Groundwater Development in Metro Manila.*

Sandoval and Mamaril(1970): *The hydrogeology of Central Luzon, Bureau of Mines*.

Ruser and Diomampo(1995): New Stratigraphic Information for Metro Manila and its Engineering Implication. *VIII Annual Geologic Convention, Geological Society of the Philippines*.

Corby *et at.,* (1951): Geology and Oil Possibilities of the Philippines, *Department of Agriculture and natural Resources.*

Electrowatt Eng’g Services/Eng’g Geoscience Inc., MWSS (1981): *Geologic Map of Metro Manila showing Fracture Patterns.*

IDRC/NHRC-UPRDFI/GRCMU(1993): *Water Resource Management Model for Metro Manila*.

Electrowatt Eng’g Services, LTD, Zurich (1983): *Groundwater Development Manila Water Supply Project II, Final Report.*

Lloyd, J.W. and Heathcote, J.A.: Natural Inorganic Hydrochemistry in relation to Groundwater. *Dept of Geological Sciences, University of Bermingham, UK.*

Quiazon, Hernando P.(1971): *Groundwater Situation in Manila and Suburbs*. Bureau of Mines, Manila.

McDonal and Harbaugh A. (1988): Modular Three-Dimensional Finite Difference Groundwater Model. *U.S. Geological Survey, Open File Report.*

NSO (1995): *Census of Population, Report No. 4, Population, land Area and Density, 1995, 1980, 1990 and 1995.*

LWUA/JICA: *Cavite Water Supply Development Study in the Republic of the Philippines*.

Application of Isotope Hydrology for Solving Nitrate Contamination in Groundwater in Northeastern Part of Thailand

Adisai Charuratna and Dawruang Sukarawat
Department of Groundwater Resources, Thailand

Abstract: As a result of provincially groundwater mapping in Northeastern region of Thailand during 1989-1997, more than 10 percent of investigated existing wells found that nitrate contents in groundwater exceeded unprecedentedly standard of drinking water or over 45 mg/l, particularly in 5 provinces –there are 20 provinces in this region. Principally, groundwater can be contaminated with nitrate by various sources in terms of human activities and natural processes. Northeastern terrain of Thailand is a high plain or so called "Khorat Plateau". Generally, geological units are mostly consisted of sandstone, shale and rock salts. In 2009, Department of Groundwater Resources (DGR) established a project to evaluate nitrate sources in groundwater by using principle of isotope technique. More than 100 water samples were analyzed in term of $\delta^{18}O$ and $\delta^{15}N$ as well as ^{14}C. Finally, nitrate contamination in this region can be definitely solved that leaching of domestic cattle wastes and septic systems from households are mainly caused by having suitable geological conditions.

Keywords: Isotope technique, $\delta^{18}O$ and $\delta^{15}N$, contamination

1. Introduction

Principally, nitrate contamination in groundwater is mostly associated with agricultural and human activities, particularly in shallow aquifers. High level of nitrate in blood from drinking groundwater can cause methemoglobinemia in infants or blue baby and can function as initiators of human carcinogenesis or cancer. World Health Organization (WHO) has limited an amount of nitrate for drinking water as 10 ppm nitrate-N or 50 ppm of NO_3^- Significantly, sources of nitrate are actually distributed to groundwater by percolating from septic systems, manure piles, waste water, fertilizers, natural precipitation, organic soils, etc. However, these sources can be reasonably identified by analyzing isotopic composition of NO_3^-($\delta^{18}O_{NO3}$ and $\delta^{15}N_{NO3}$) and can be discriminated schematic ranges of their values (Kendall, 1998).

The study area coverage a total of 59,768 km^2 (Fig. 1) is partly located in Northeast Thailand or Khorat Plateau. As a result of groundwater investigation during 1987-1997 for provincially hydrogeological mapping, about 10 percent of existing wells having nitrate contents in groundwater were obviously high exceeding 50 ppm (Table 1) whereas the other regions of Thailand were normally negligible amounts. Many people working in groundwater aspect were anxiously to know scientifically the cause of the major sources. In 2009, Bureau of Groundwater Conservation and Restoration under DGR established a project to study by using isotope techniques that water samples were analyzed by Thailand Institute of Nuclear Technology (TINT).In order to explain their sources, more than 100 water samples in the subdistricts from previous study that implied high nitrate potential were collected freezingly for isotropic analysis as $\delta^{18}O$ and $\delta^{15}N$ and some more practically for ^{14}C as water dating including 2D resistivity survey in some specific areas for geological identification.

The purpose of this study is to understand natural sources of nitrate leaching to groundwater through related geological units and their isotopic compositions in term of NO_3^-. Due to different environment process for sources of contaminants, an application of nitrate isotopes is a powerful tool to identify and to extend this study for such case of an experience.

2. Hydrogeological setting

In the Northeast or Khorat Plateau is mainly related with geological units so called "Khorat Group" that is made up entirely red beds of sedimentary sequence. These rock units as Mesozoic and Tertiary aged strata are generally formed topographic flat lying to low dipping of conglomerate, sandstone, siltstone, shale and rock salts. Hydrogeologically, the whole strata sequence is mainly categorized into 3 aquifers (Piancharoen, 1982) namely Lower Khorat Aquifer (Huai Hin Lat, Nam Phong and Phu Kradung Formations), Middle Khorat Aquifer (PhraWihan, Sao Khua and Phu Phan Formations) and Upper Khorat Aquifer (Khok Kruat, Mahasarakham and Phu Tok Formations).Particularly, Mahasarakham Formation is an outstanding of rock salts whereas Phu Tok Formation is obviously loess sediments. The rest of aquifers are sedimentary rocks deposited in shallow water. The almost of these aquifers is overlain by unconsolidated sediments of Quaternary age such as clay, sand and gravel. However, data recording system of provincial groundwater mappings is recently classified into aquifer names following each of Formations (Fig. 2). Phu Kradung and Phu Tok Aquifers are relatively good of groundwater potential both in quantity and quality from their geological structures and groundwater is very important for domestic uses in this region.

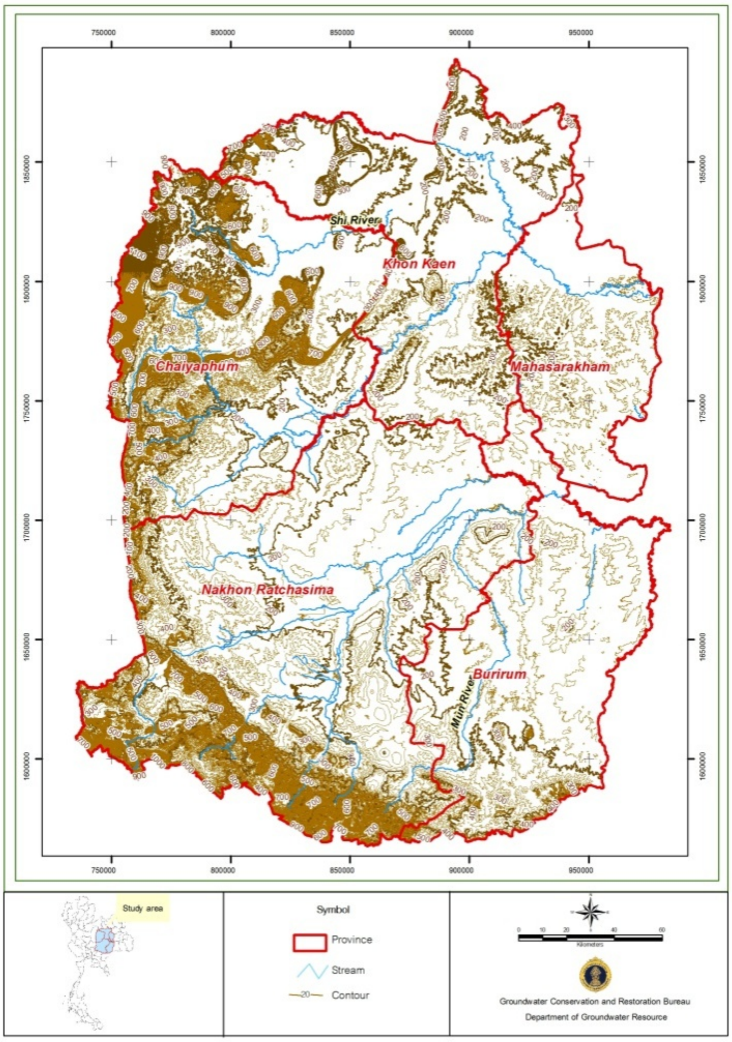


Fig.1 Study area

Table 1 Percent of wells found nitrate concentration more than 50 ppm

Provinces	Wells	Wells have nitrate Contents>50 ppm	Percent of wells
Mahasarakham	588	116	19
Khonkaen	1,061	192	18
Nakhonrachasima	1,074	152	14
Burirum	722	94	13
Chaiyaphum	1,043	122	11
Roiet	1,299	101	7.8
Udonthani & Nongbualamphu	1,253	80	6.5
Surin	1,055	64	6.1
Nakhonphanom	738	28	3.8
Sisaket	1,405	52	3.7
Sakonnakhon	935	33	3.5
Loei	807	24	2.9
Mukdahan	289	6	2.1
Ubunrachathani & Amnajcharoen	1,670	34	2
Nongkhai	n/d	n/d	n/d
Kalasin	n/d	n/d	n/d
Yasothon	n/d	n/d	n/d

In this paper, the study area coverage of 5 provinces namely Khon Kaen, Mahasarakham, Na Khon Rachasima, Chaiyaphum and Burirum located in southeast part of the Northeast region-a total of 20 provinces and almost having above mentioned aquifers but the problems of nitrate contamination are significantly occurred in Phu Kradung and Phu Tok Aquifers.

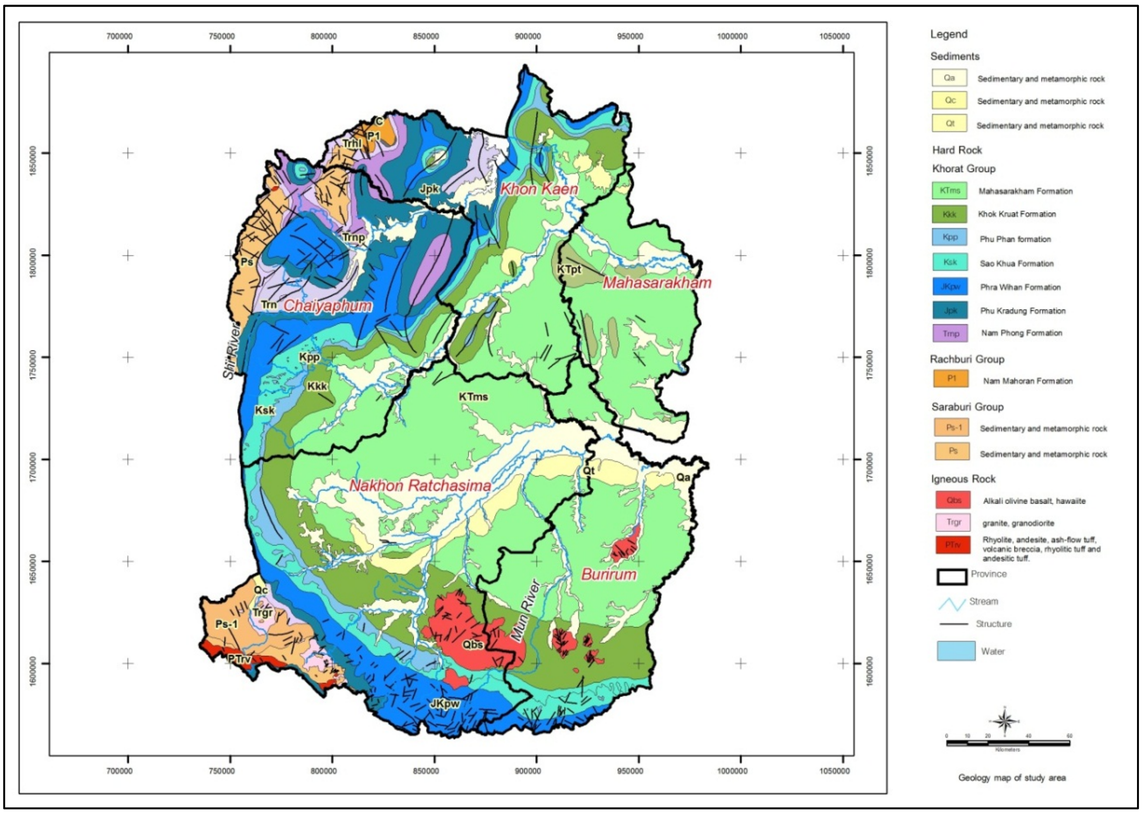


Fig. 2 Geological map showing each Formations in the study area

3. Methodology

According to the principal of nitrogen cycle, the sources of nitrate are derived through processes of nitrogen transformation both in biosphere - atmosphere and geosphere such as biological and synthetic fixations, mineralization, nitrification and denitrification. Generally, the sources of nitrate contamination in groundwater can be identified as synthetic and organic fertilizers, septic systems, waste water and manure that are related with agricultural and human activities. Hence, if any regions were found that there are high nitrate levels in groundwater more than usual standard, how to classify the sources originated. Although the nitrogen processes in nature as composition of NO_3^- are very complex but isotope technique is a powerful tool to discriminate satisfactorily their sources. This paper has followed the direction of nitrate isotopes (Kendall and Aravena, 2000) as a guideline to evaluate the sources by using the stable nitrogen and oxygen isotopes in term of NO_3^- in groundwater.

There are two stables isotopes of N – ^{14}N and ^{15}N where the average abundance of ^{15}N in air is constant with $^{15}N/^{14}N$ = 1/272. Nitrogen isotope ratios are reported in per mil (‰) relative to N_2 in atmospheric air and described as a term of δ or delta notation:

$$\delta^{15}N = \{[(^{15}N/^{14}N)_{Sample}/(^{15}N/^{14}N)_{Standard}]-1\}\times1000$$

δvalues are expressed as ‰ difference from the standard. ^{15}N values are reported relative to N_2 in air as well as stable oxygen isotopic composition are given in terms of $^{18}O/^{16}O$ where^{18}O defined similarly to above equation. The ^{18}O values of nitrate and other O-bearing materials are reported in ‰ relative to Vienna Standard Mean Ocean Water (VSMOW).

By using the concept of schematic of typical ranges of $\delta^{18}O$ and $\delta^{15}N$ values of nitrate (Kendall, 1998) shown in Fig. 3 to conclude that $\delta^{15}N$ values are fractionated from nature sources more or less closely to 0 ‰ where as $\delta^{18}O$ values are normally higher than 10 ‰. In contrast, $\delta^{15}N$ values through a multi-step oxidation process as nitrification or mineralization that means:

$$\text{Organic-N} \rightarrow NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$$

minimal and $\delta^{15}N$ in the soil nitrate relatively a few per mil are normally -5 to -35 ‰ whereas $\delta^{18}O$ values are -10 to +10 ‰. For synthetic fertilizers produced by the fixation of atmospheric N_2 as urea, ammonia nitrate and potassium nitrate, $\delta^{15}N$ values are in the range of -4 to 4 ‰ whereas $\delta^{18}O$ values are +18 to +22 ‰ due to be formed from atmospheric oxygen. In case of isotopic composition of nitrate from human or animal wastes are very important and frequently their leaching percolated into groundwater resources,$\delta^{15}N$ values are generally range of +10 to +20‰ and $\delta^{18}O$ values as similarity of nitrification process or -10 to +10 ‰. However, some researchers gave$\delta^{15}N$ values as +4.7 ± 5.4‰ for the soil nitrate produced from fertilizer and animal waste is average of +14.0 ± 8.8‰. In addition, nitrate residuals are persisting in anaerobic soils possibly reduced by denitrification into N_2 or N_2O gases and then diffuse into atmosphere. $\delta^{15}N$ values are increasing with proportional of decreasing nitrate concentrations.

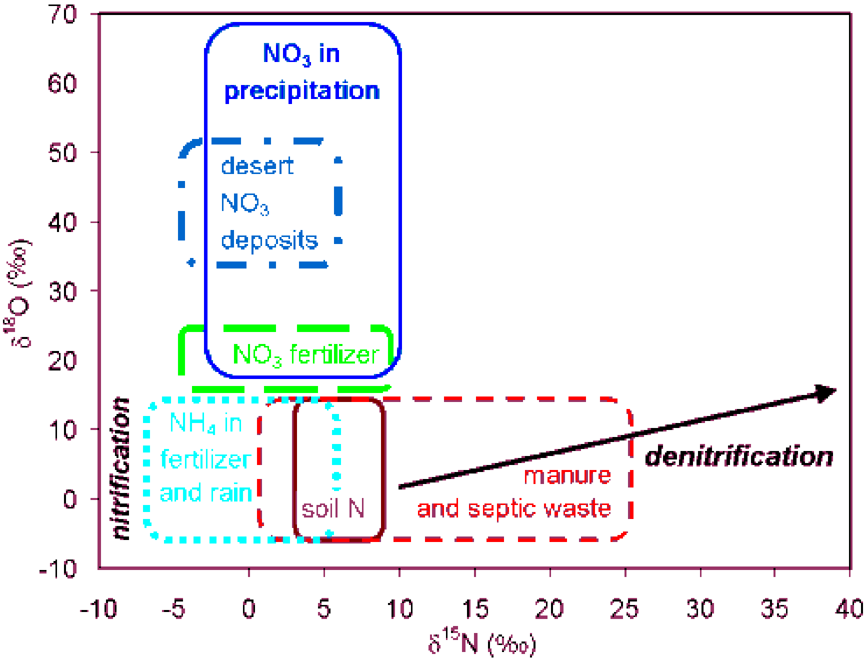


Fig. 3 Schematic ranges of nitrate isotopic compositions

and their identification (Kendall, 1998)

In the study areas, a total of 960 water samples were collected from shallow and deep wells about 12 to 79 meters in depth of 78 subdistricts (Fig.4) where the previous study indicated that nitrate concentrations were high for re-checking and re-analyzing. Results of their NO_3^- from any wells were still in high level exceeding 50 ppm, the re-water samplings were done in the way of isotopic method for nitrate compositions as a total of 81 samples including collected additional water for14C in age dating as a total of 51 samples. The isotopic water samples were analyzed by TINT while general chemical analysis was performed by DGR in order to understand their groundwater geochemistry. On the top of that, two communities namely Ban Non Thong and Ban Non Muang in Khon Kaen and Mahasarakham provinces were selected for geophysics survey by using 2D resistivity method in order to identify deeply hydrogeological units relative to Phu Kradung and Phu Tok Aquifers respectively.

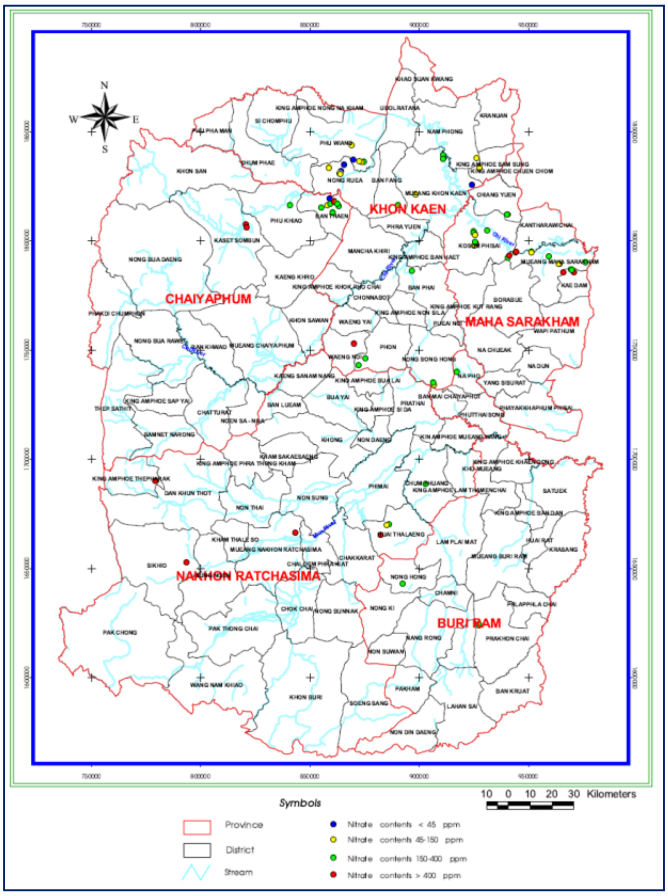


Fig. 4 A map of well location for water samplings and chemical analysis

4. Results and conclusion

The results of chemical and isotropic analysis have been shown in Table 2 and the schematic of typical ranges of $\delta^{18}O$ and $\delta^{15}N$ values of nitrate is presented in Fig. 5. $\delta^{15}N$ values of water samples in the study area ranged from +2.4‰ to +15.4 ‰ and $\delta^{18}O$ values ranged from +5.3‰ to +13.63‰. According to the diagram, all of values are fallen in mainly in the large zone of manure and septic waste, some values are inter-overlapping in the ranges of nitrogen soil and NH_4 in fertilizer and rain possibly including in term of denitrification that is identified by a line with slope of 1:2 ($\delta^{18}O$ and $\delta^{15}N$). In order to solve the sources of nitrate, each location has been evaluated case by case in the field. Unfortunately, some areas are ambiguously, particularly in causes of NH_4 fertilizer and natural organic soil. Prior to establish the project, some people understood that probably some minerals would be associated with rock salts like $NaNO_3$ or KNO_3 to be the sources of nitrate because of salty water common found in this region. Theoretically, both minerals are from the nature that $\delta^{18}O$ values must be much higher than in the table and $\delta^{15}N$ values have to be closely ± 0 as well. Obviously, the distinguished sources derived from local septic systems and domestic animals feeding. Traditionally, the lifestyles of people living in the Northeast are closely gathered with many families as a community and generally have their livelihood by feeding cattle and keeping them nearby or under their houses (Fig. 6). In addition, the unsuitable septic systems in densely population are the other significant sources supporting directly nitrate contamination. The effluents of animal waste or excretory waste are assumed to be NO_3^- concentration as 40 mg/l (Canter and Knox, 1986) that reasonably for general high nitrate concentration and average $\delta^{15}N$ is +8.9 ± 6.5 in this region similar to many concerned documentaries. $\delta^{18}O$ values are mostly less than +11.5 representing through process of nitrification.

Nevertheless, if the leaching and percolating processes are very important to conduct altered organic-N to water table or aquifers, the characteristics of soil profiles and water-bearing rocks must be in good conditions (Fig. 7). The results of 2D resistivity survey in two representing areas having high potential of nitrate contamination showed that the fractured shale or siltstone as aquifers are overlain by thin layer of loosely sand indicating high resistivity on the top layer – less than 6 meters (Figs. 8 and 9). The age dating of water samples by ^{14}C implied that they are young or recent water that NO_3^- concentration possibly attenuated in shallow aquifer but isotopic compositions are stable if not directly mixing with NO_3^--bearing water or soils.

It is concluded that almost evidences of nitrate contamination in groundwater derived from septic systems and domestic animal wastes in residential areas by considering plotted $\delta^{18}O$ and $\delta^{15}N$ values relative to their perspective situation in the field. In particular, the cattle pens are mostly located nearby domestic wells as well as several wells for water supplies are nearby households or toilets in temples. The littering from domestic animals year by year could be the cause of permanently contaminated soils and already further transformed by nitrification as nitrate in groundwater, denitrification as well. Thus, additional data of seasonal variation of nitrate isotopic composition and concentration are required to deeply explain in mechanism of nitrification, denitrication and even NH_4 fertilizer could possibly occurred. However, some areas having nitrate concentrations as high as hundreds of ppm are still used for water supplies by without any treatment systems.

Table2 Results of isotopic composition and chemical analysis

No.	Code	Well Number	Province	Depth (metre)	δN15 (‰)	δO18 (‰)	PMC	Age (Years, B.P.)	(mg/L)							
									NO_3	NO_2	Ca	Mg	Na	SO_4	Cl	HCO_3
1	N1	MJ1125	Chaiyaphum	30	13.47	11.3			760	4.3	230	120	300	100	590	299
2	N2	P52	Chaiyaphum	30	13.14	11.6			590	0.02	180	120	280	110	480	362
3	N3	D437	Chaiyaphum	30	12.3	10.24	110.58±2.32	Modern Carbon	210	0.01	180	50	200	26	440	320
4	N4	MJ1195	Chaiyaphum	18	12.4	12.1	76.30±2.29	2170±240	160	0.03	130	56	190	51	200	596
5	N5	D397	Chaiyaphum	36	5.6	9.7	94.25±2.18	480±190	44	0.01	220	86	260	33	570	571
6	N6	PW14337	Chaiyaphum	30	15.4	13.63			79	0.01	110	54	270	20	400	543
7	N7	MJ642	Chaiyaphum	30	6.1	7.7			400	0.01	190	65	400	10	780	342
8	N8	MJ778	Chaiyaphum	39	4.8	15.3	72.68±1.88	2560±210	400	0.01	180	97	230	28	460	338
9	N9	U893	Chaiyaphum	30	11.8	9.3			73	0.03	55	46	200	22	240	408
10	N10	D376	Chaiyaphum	30	7.1	5.4			490	0.03	170	100	300	29	670	145
11	N12	MJ901	Chaiyaphum	30	7.7	6.8			170	0.03	70	65	230	23	290	505
12	N13	MJ949	Chaiyaphum	30	11.2	12.1	111.30±2.57	Modern Carbon	240	0	160	83	310	171	480	489
13	N14	MJ1042	Chaiyaphum	42					< 0.9	0.01	45	42	410	620	110	582
14	N15	-	Chaiyaphum	-	7.5	8.3			170	0.21	62	64	380	270	360	476
15	N22	S350	Khonkaen	24	2.8	8.7			100	0.02	180	68	85	22	330	357
16	N26	S867	Khonkaen	30	3.4	12.7	100.35±2.64	Modern Carbon	78	0.03	24	10	15	3	67	15
17	N28	S1210	Khonkaen	48	2.63	5.6	88.41±2.02	990±180	220	0.03	150	55	270	10	510	406
18	N29	F482	Khonkaen	18	6.5	11.3	85.54±2.02	1250±190	290	0.04	120	48	250	140	440	569
19	N33	S822	Khonkaen	39	8.3	8.74	59.10±1.75	4220±240	210	0.05	340	39	910	1,600	720	533
20	N34	S892	Khonkaen	31.5	6.4	13.3	101.28±2.25	Modern Carbon	300	0.06	240	42	67	28	240	274
21	N36	DP484	Khonkaen	36	4.7	13.6			220	0.25	210	38	55	30	200	440
22	N37	F821	Khonkaen	27	4.4	12.7			40	0.29	140	18	63	30	99	468
23	N38	F1481	Khonkaen	30	3.6	9.5			110	4.1	210	31	41	32	210	460
24	N40	F1428	Khonkaen	30	9.3	10.2			78	0.22	140	26	49	32	100	446
25	N42	F527	Khonkaen	23	9.1	8.4	76.45±1.91	2160±200	100	0.09	210	33	41	44	210	411
26	N45		Khonkaen	36	9.7	10.5	64.67±1.78	3500±220	41	0.06	150	16	190	10	380	375
27	N46	PW18097	Khonkaen	41	7.1	8.9	101.63±9.48	Modern Carbon	180	0.06	140	25	43	42	180	140
28	N47	DP473	Khonkaen	38	7.7	9.2			240	3.4	500	30	460	290	1,300	240
29	N50	-	Khonkaen	27	8.4	11.1	94.67±2.06	440±170	150	0.07	50	34	200	84	220	335
30	N53	S663	Khonkaen	43.5	9.7	10.13	112.10±11.63	Modern Carbon	100	0.07	160	27	110	160	300	116
31	N56	F652	Khonkaen	24	15.4	11.6	84.41±6.87	1360±680	190	0.33	170	57	110	180	240	557
32	N56-1		Khonkaen	45	14.11	13.2			110	0.07	200	74	100	97	350	389
33	N56-2		Khonkaen						10	0.06	36	17	30	13	96	115
34	N56-3		Khonkaen		14.6	11.4			160	0.11	270	68	130	140	440	486
35	N57	F204	Khonkaen	35	13.7	11.9			45	0.29	120	18	76	51	83	473
36	N59	JJ1483	Khonkaen	12	4.4	11.3	93.58±2.04	530±180	150	1	160	28	92	56	120	473
37	N60	JJ1485	Khonkaen	45	3.6	11.5			59	0.2	230	40	210	60	480	632
38	N63	S626	Khonkaen	33	5.8	10.3	101.73±2.25	Modern Carbon	53	0.02	99	17	100	5	27	597
39	N64	S570	Khonkaen	18	7.4	10.46	101.00±2.20	Modern Carbon	350	0.07	190	42	250	120	440	264
40	N68	MY1030	Nakhonrachasima	45	13.4	11.7	113.45±3.27	Modern Carbon	440	0.12	180	69	610	220	600	794

No.	Code	Well Number	Province	Depth (metre)	δN15 (‰)	δO18 (‰)	PMC	Age (Years, B.P.)	(mg/L)							
									NO_3	NO_2	Ca	Mg	Na	SO_4	Cl	HCO_3
41	N69	MG412	Nakhonrachasima	24	8.7	11.2	82.71±2.10	1530±210	190	0.07	86	72	100	40	200	351
42	N70	NR298	Nakhonrachasima	36	2.7	10.4			610	0.07	230	100	130	11	370	303
43	N73	MY169	Nakhonrachasima	42	5.5	8.4	60.03±1.88	4100±250	92	0.07	83	10	220	34	280	332
44	N73-1	-	Nakhonrachasima		4.4	8.7			280	0.08	120	36	440	77	540	548
45	N74	MY741	Nakhonrachasima	36	2.3	5.1			1,700	0.07	1,100	160	450	980	1,400	284
46	N75	T756	Buriram	36	9.3	11.4	89.48±2.15	890±190	270	4.3	400	130	740	100	1,700	615
47	N76	AFD251399	Buriram	39.6	5.6	7.8	86.22±2.12	1190±200	190	0.13	120	24	440	120	660	304
48	N78	-	Mahasarakham	36	10.2	11.3	100.90±2.07	Modern Carbon	420	0.23	76	34	140	110	250	307
49	N79	D731	Mahasarakham	36	6.4	7.1	51.61±3.34	5310±530	170	0.23	67	21	44	9	110	103
50	N80	D1697	Mahasarakham	42	5.7	7.4			370	11	140	48	56	120	190	202
51	N81	X285	Mahasarakham	69	7.4	11.2	78.55±2.11	1940±220	240	0.44	100	17	61	44	120	146
52	N82-1	-	Mahasarakham	39	3.2	7.8	94.44±2.64	460±220	740	0.52	310	85	160	250	590	247
53	N83	PW9085	Mahasarakham	60.6	8.8	10.3	104.92±2.18	Modern Carbon	290	0.45	110	20	140	70	190	190
54	N86	D69	Mahasarakham	21	10.2	11.4	53.53±3.35	5020±520	250	0.3	150	52	1,400	1,600	1,100	171
55	N88	TX220	Mahasarakham	42	10.4	11.7	90.30±2.03	820±180	500	0.69	150	50	940	700	920	541
56	N89	PW19184	Mahasarakham	74	7.8	10.6	98.01±2.47	Modern Carbon	93	0.36	110	28	35	16	190	213
57	N90	L107	Mahasarakham	79.5	8.5	10.8	75.77±2.13	2230±230	450	8	270	46	59	6	220	456
58	N92		Mahasarakham		3.4	8.7	70.55±1.85	2800±210	91	0.22	130	30	45	21	120	417
59	N94	D889	Mahasarakham	51	10.5	11.4	94.36±2.05	470±170	170	0	140	25	45	10	140	325
60	N95	X330	Mahasarakham	39	10.2	11.8	105.27±2.34	Modern Carbon	310	0.14	120	45	74	75	210	204
61	N96	-	Mahasarakham	28	2.6	8.8	104.35±2.47	Modern Carbon	180	0.53	90	39	600	560	480	580
62	N98	_	Mahasarakham	24	9.6	11.5	104.22±2.89	Modern Carbon	240	0.2	410	82	730	1,500	760	253
63	N101	D763	Mahasarakham	18	3.7	8.3	92.20±2.33	650±200	350	0.32	130	34	260	130	430	132
64	N105	D820	Mahasarakham	30	11.4	10.6	87.98±2.13	1030±200	90	0.13	250	60	310	30	1,000	106
65	N106		Mahasarakham		11.7	11.3			200	0.19	240	54	110	27	330	382
66	N107	-	Mahasarakham	4.5	11.4	11.7	98.33±2.60	Modern Carbon	300	0.2	110	72	270	240	360	596
67	N108	L298	Mahasarakham	42	5.6	10.2	27.10±6.77	10490±2310	440	0.22	270	57	130	250	290	364
68	N109	D1549	Mahasarakham	27	2.3	8.4	97.87±2.17	Modern Carbon	67	0.27	240	52	130	23	520	408
69	N110	PW17884	Mahasarakham	19.8	2.7	8.9	103.50±2.49	Modern Carbon	530	0.3	220	73	100	42	420	151
70	N113	B2127	Mahasarakham	40	3.6	6.8	87.59±2.07	1060±190	240	0.24	90	35	280	80	490	106
71	N113-1		Mahasarakham		7.7	10.7			110	0.19	61	30	160	39	320	104
72	N114	L301	Mahasarakham	_	10.5	11.2	106.05±2.68	Modern Carbon	140	0.24	170	35	310	700	270	211
73	N115	L319	Mahasarakham	30	10.8	11.7	85.47±1.90	1260±180	110	0.24	220	38	300	850	240	215
74	N116	-	Mahasarakham	30	7.5	11.8	105.04±2.51	Modern Carbon	370	0.1	380	87	600	1,200	750	140
75	A2		Mahasarakham	25.00	5.2	7.3	102.66±2.15	Modern Carbon	120	0.86	160	76	560	820	660	468
76	A3		Mahasarakham	17.00	2.4	7.8			380	0.2	180	56	1,300	1100	1,500	574
77	A6		Mahasarakham		10.8	11.4			57	0.1	140	45	1,100	1,200	1,200	164
78	N117	MG661	Nakhonrachasima	54	2.6	5.6	84.80±1.94	1320±180	280	3.4	200	35	74	30	200	427
79	N118	MM100	Nakhonrachasima	18	2.9	7.3			110	0.05	140	13	58	47	120	261
80	N119	DCD9083	Nakhonrachasima	52.3	12.7	11.8			560	0.06	770	32	220	950	600	453
81	N121		Nakhonrachasima		2.5	5.3			450	0.07	320	99	610	57	1,400	203

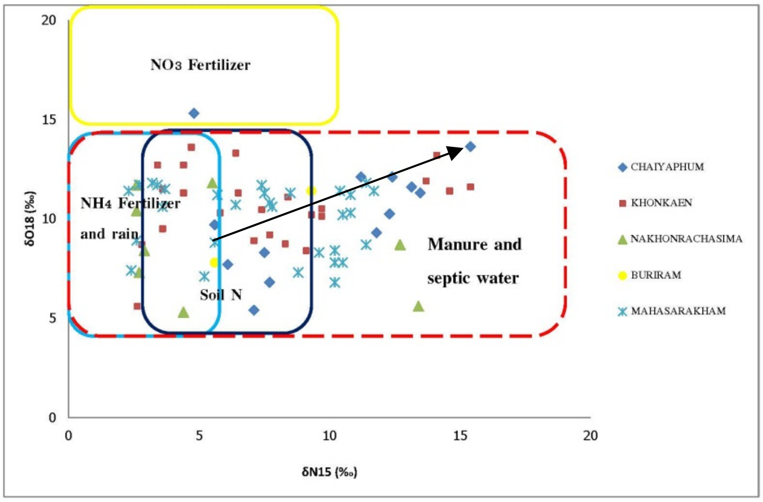


Fig. 5 Typical ranges of plotted δ^{18}O and δ^{15}N values of nitrate

Fig. 6 Domestic animal feeding nearby house

Fig.7 Fractured rocks of Phu Tok Aquifer

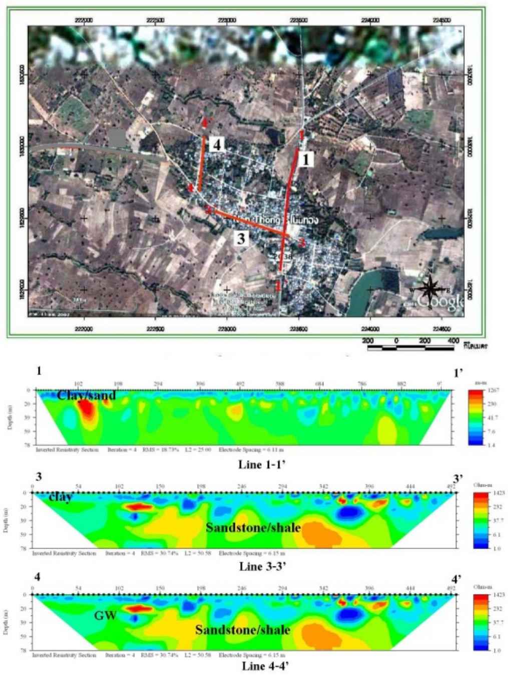


Fig.8 2D resistivity in Ban Non Thong,Khon Kaen

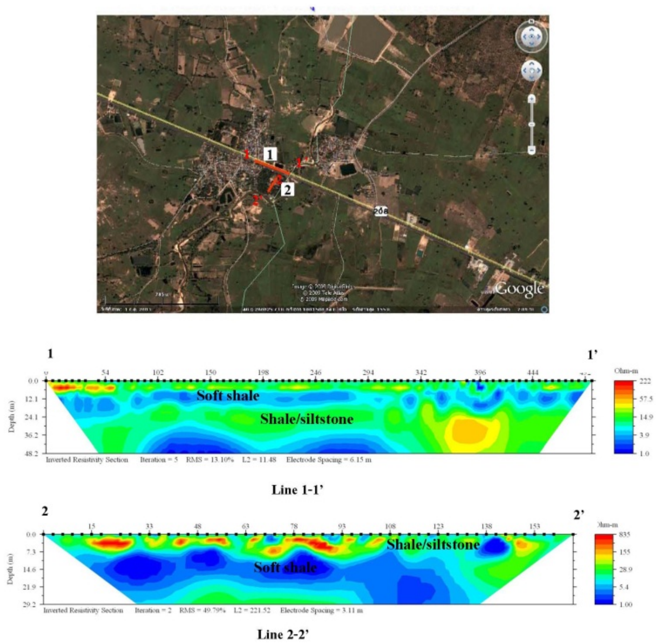


Fig.9 2D resistivity in Ban Non Muang Mahasarakham

References

Canter, L.W., Knox, R.C. (1986): *Septic Tank System Effluents on Groundwater Quality*. Lewis Publishers, Chelsea, MI.

Kendall, C. (1998): Tracing sources and cycling of nitrate in catchments. In *Isotope Tracers in Catchment Hydrology*, (eds. C. Kendall and J. J. McDonnell), pp. 519-576. Elsevier, Amsterdam.

Kendall, C., Aravena, R. (2000): Nitrate Isotopes in Groundwater Systems. *Environmental Tracers Subsurface Hydrology*, 261-298.

Piancharoen, C. (1982): Hydrogeology and Groundwater Resources of Thailand. Department of Mineral Resources, Ministry of Industry.

Seiler, R. L. (2005): Combined use of ^{15}N and ^{18}O of nitrate and ^{11}B to evaluate nitrate contamination in groundwater. *Applied Geochemistry*. **20**, 1626-1636.

Groundwater Resources in Timor-Leste

Francisco Xavier Pereira Sico
Ministry of Infrastructure

1. Background

1.1 Overview

The economy of Timor-Leste and the livelihood of its community are heavily dependent on groundwater resources that are sensitive to climate change (Barnett, J. *et al*., 2007). Threats to water and food security from variable rainfall, seawater intrusion into groundwater reserves, and groundwater contamination from solid waste and sewage disposal present serious challenges to vulnerable communities throughout the nation. Climate change, through changes in rainfall and temperature (potential evaporation), could cause longer periods of drought or more intense rainfall, which may result in insufficient groundwater recharge and reduced groundwater availability. Sea-level rise has the potential to drive seawater intrusion into freshwater aquifers, causing changes in groundwater flow and salinisation of water used for drinking and agriculture (Barnett, J. *et al*., 2007). These changes in groundwater flow can inturn exacerbate groundwater contamination from solid waste and sewage. Climate change is expected to affect the availability and quality of groundwater in Timor-Leste through changes in temperature, rainfall and sea level rise.

The current sustainability of groundwater use in Timor-Leste is largely unknown, as are the likely effects of climate change on both the quantity and quality of available groundwater resources. Seawater intrusion (resulting in degradation of groundwater quality) and reduced groundwater yields are both plausible consequences of climate change; however, it is not possible to quantify the effects of climate change on groundwater resources without first establishing a baseline understanding of how groundwater systems operate under current climate conditions. A more detailed understanding is needed of how pressures from climate change and groundwater pumping will influence the availability and quality of groundwater for management into the future.

An assessment of the groundwater resources likely to be affected by climate change is required immediately to enable the identification and prioritisation of adaptation options. To be most effective this should initially involve a characterisation of groundwater systems and their vulnerability to climate change impacts. This is followed by a participatory, capacity building program of knowledge transfer based on practical case studies to develop monitoring and assessment capabilities. Such an approach will support the Timor-Leste National Adaptation Programme of Action (NAPA) and will advance the science and current knowledge that underpins the management of integrated groundwater resources, a key threat identified in IPCC Fourth Assessment Report (IPCC, 2007) and by Barnett, *et al*. (2007).

To address some of these issues Geoscience Australia (GA) is undertaking a project ‘Assessment of Climate Change Impacts on Groundwater in East Timor’ in partnership with the Government of Timor–Leste’s National Directorate for Water Resource Management (DNGRA), other government agencies and existing programs of the Australian Agency for International Development (AusAID). The project is an Australian Government initiative under the Pacific Adaptation Strategy Assistance Program. This program is being managed by the Australian Government Department of Climate Change and Energy Efficiency (DCCEE) and is part of the International Climate Change Adaptation Initiative.

1.2 Objectives

The objectives of this project were:

(1) to provide support for development of the Timor-Leste NAPA through a review of existing information on groundwater in Timor-Leste;

(2) to develop skills and knowledge in DNGRA and other government agencies relevant for groundwater monitoring; and

(3) to produce a report on results from the project and provide a guide for assessment methods and continued use of groundwater monitoring equipment.

1.3 Description of the Study Area

1.3.1 Location

Timor-Leste forms the eastern half of Timor sitting adjacent to Indonesia and separated from Australia by the Timor Sea. The country is about 14,922 km^2 and includes the island of Atauro and the enclave of Oecussi (latitude 8° 00’ to 9° 30’ south and longitude 124° 00’ to 127° 30’ east; (Figure 1)(Asian Development Bank, 2004). The topography of the country is generally mountainous, characterized by rugged terrain and small narrow valleys (Figure 2). It has been suggested that as much as 44% of the country may have a slope more than 40%. Many of these mountains in the country are above 2,000 m elevation, with Mount Tata Mai Lau the highest at 2,963 m. The width of Timor-Leste ranges from 75-100 km. In the north-east, uplifted coral reef stretches along the coast, and is characterized by typical karst topography.

1.3.2 Climate

The climate of Timor-Leste is characterized by its Asian tropical monsoonal system mainly because of its topographic relief and the geographical location of the island.

In general, the climate of the Timor-Leste can be divided in two distinct seasons: the ‘w*et season’* starts around December to May-July depending on the region – the wettest month is January, February or May depending on the region; and the*‘dry season’* starts from June-July to October-November. September-October is generally the driest month depending on the region.

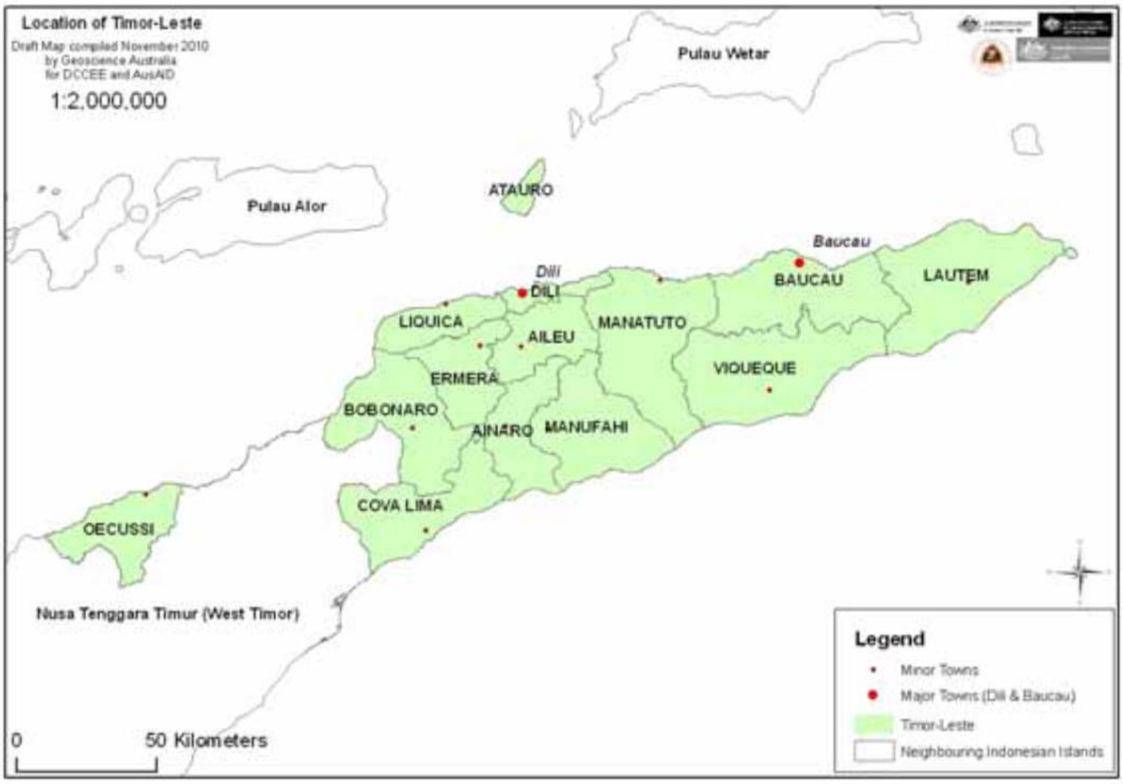


Fig. 1 Location of Timor-Leste

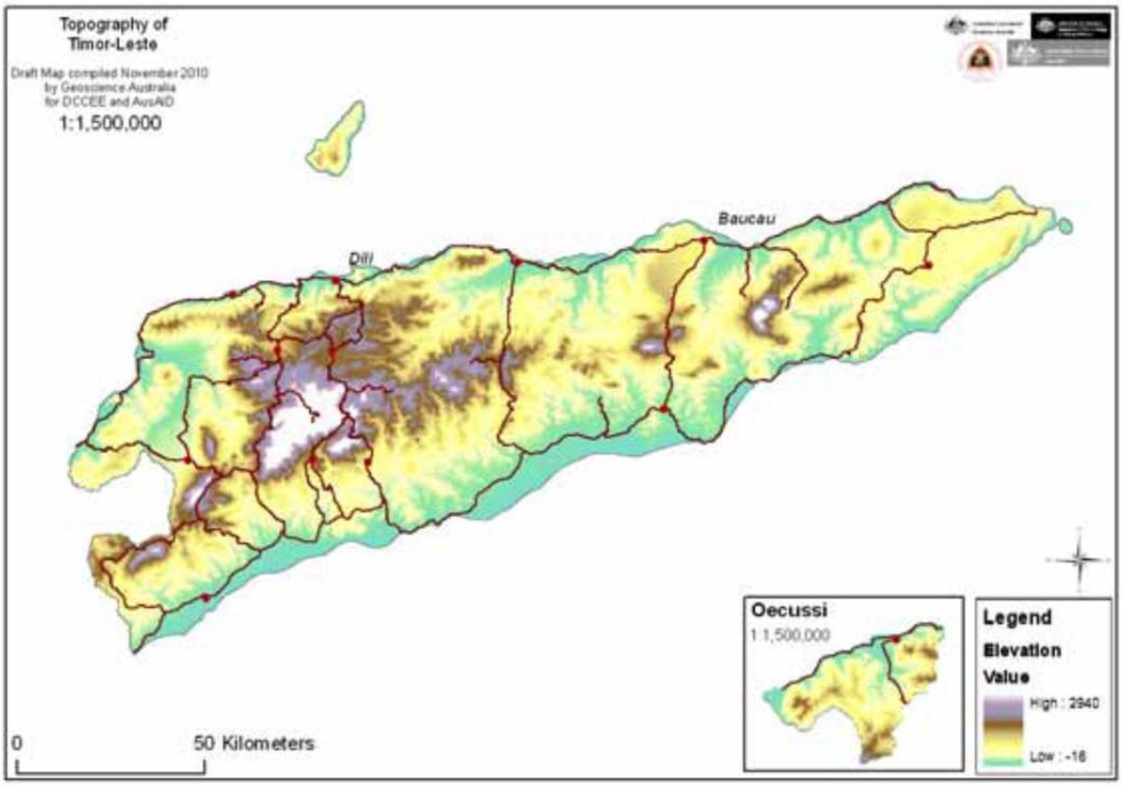


Fig. 2 Topography of Timor-Leste

1.3.3 Geology

The geology of Timor-Leste is complex both compositionally and tectonically as shown in Figure 3. Compositionally Timor-Leste contains a wide variety of rock types (igneous, metamorphic and sedimentary) with a range of textural (fine-grained and well sorted to large boulder conglomerates) and chemical (felsic to ultra-mafic) compositions. It is important to note, however, that volcanism is not a key feature of the geology in mainland Timor-Leste as in contrast to the surrounding islands. The tectonic history of Timor-Leste, which sits at the interface of the Eurasian and Australian Tectonic Plate boundaries, has received much attention and several tectonic evolution models exist. Geological work has been undertaken Pre-1975 before Indonesian occupation with foreign access (Audley-Charles) 1975-1999 during Indonesian occupation with limited foreign access; and Post-1999 with independence of Timor-Leste and foreign access once again possible. The detailed description of the geological features of the country relevant to groundwater are presented in the Hydrogeological report (Wallace, *et al*., 2010).

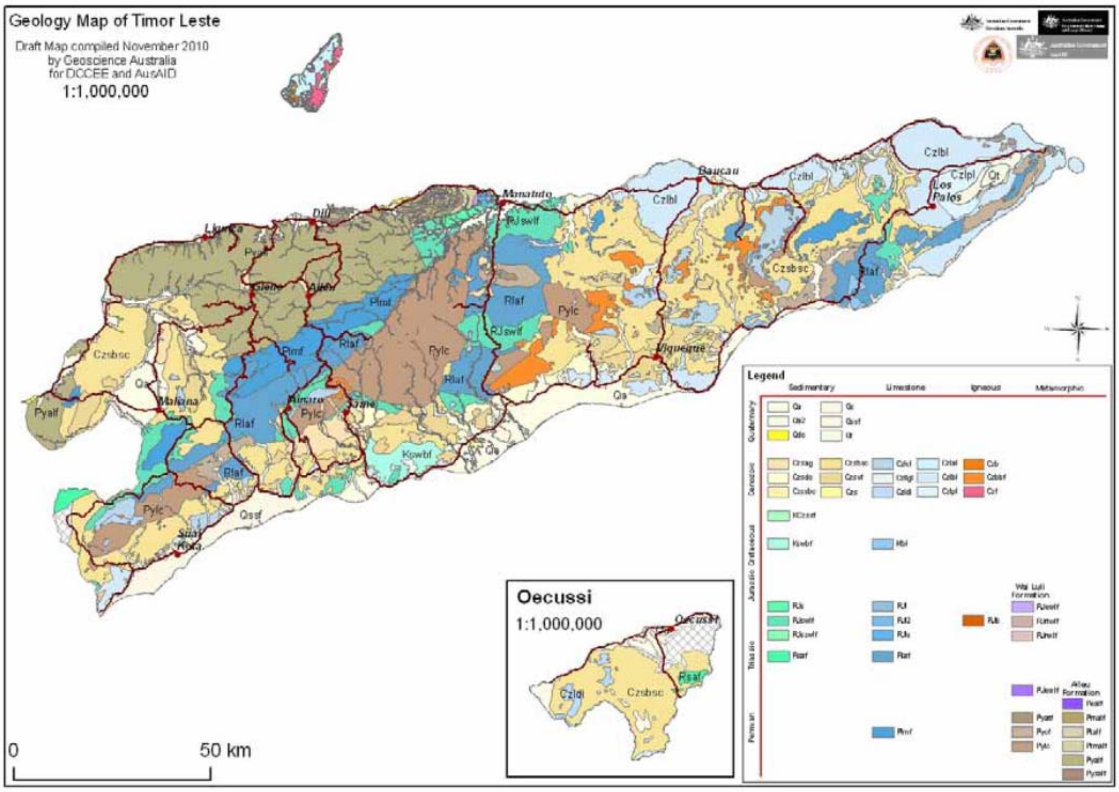


Fig. 3 Geology of Timor-Leste (Wallace, *et al.*, 2010)

1.3.4 Hydrogeology

Groundwater is a major water resource utilised in the Timor-Leste. The principal aquifer types can be divided into those with intergranular porosity, fissured porosity and localised flow (Figure 4). Intergranular porosity is assigned to rocks where groundwater flow will occur in pore spaces between sediment grains.

Fissured porosity has been given to rocks that are principally composed of limestone and known to have karst features. Localised flow is assigned to rocks where porosity is not pervasive but occurs along discreet zones within a unit. Localised flow is given to two principal rock types of fractured rocks, where porosity is restricted to fractures, and clay dominated rocks, where porosity is restricted to localised courser sedimentary horizons. The rock types that make up the three principal hydrological divisions are summarised individually in the hydrogeology report.

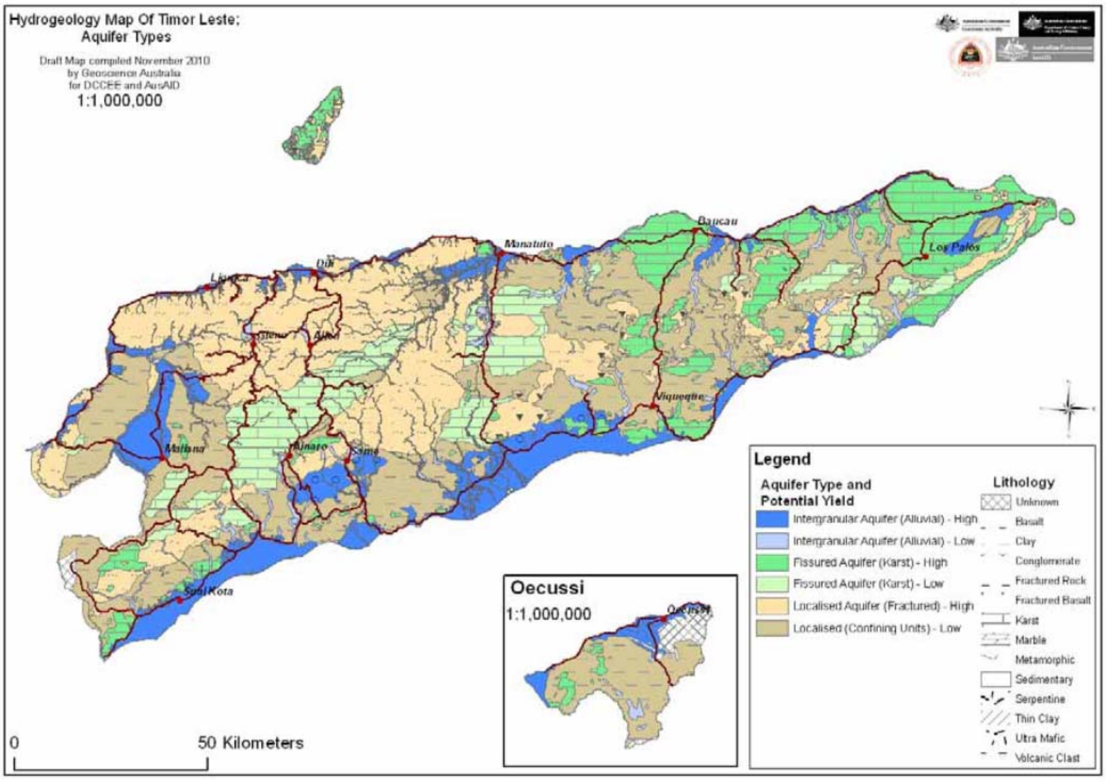


Fig.4 Hydrogeology map of Timor-Leste

2. Current Understanding of Groundwater Aquifer Systems in Timor-Leste

2.1 Groundwater

It is important to first define what is meant be the term ‘groundwater’. Groundwater is water stored below the ground in gaps and cracks in the rocks. These gaps and cracks are typically called porous rocks or fissured/fractured rocks. Groundwater is a vast resource which greatly exceeds the amount of water in rivers and lakes, both around the world and in Timor-Leste. The porous rocks and fissured/fractured rocks in which groundwater is stored and flows through are called aquifers. These aquifers typically consist of gravel, sand, limestone or fractured rocks. Groundwater may flow relatively evenly through an aquifer or may flow along localized preferential flow paths. The amount of even flow to localized flow within an aquifer will depend on the rock type. Some of the general properties of the typical aquifer types made of different types of rock are discussed in the following sections.

2.2 Groundwater Aquifers in Timor-Leste

Very little information is currently available for the quantity and quality of groundwater in Timor-Leste. No detailed national groundwater studies are available and few measurements have been made. Groundwater is likely to be found beneath most land in Timor-Leste, however the groundwater resources will be unevenly distributed and will vary in quality and quantity. A new hydrogeological map of Timor-Leste has been developed as part of this project and the descriptions of the various aquifers and their characteristics relevant to groundwater systems are presented in detail in the Hydrogeology report (Wallace, *et al.*, 2010). This hydrogeological mapping will be a valuable tool for managers, planners and groundwater users in better understanding groundwater systems in Timor-Leste. In Timor-Leste groundwater resources can be classified into three principle aquifer types: sedimentary porous rock aquifers with intergranular porosity associated with river valleys and coastal low lands; fissured aquifers of karst formations within limestone rocks; and rocks with localised flow comprised of fractured rocks and clay sediments, in alignment with international classifications (Figure 4).

The occurrence of groundwater is controlled by the geology of a region. The geology of Timor-Leste is diverse; therefore, there are different types of aquifers. These aquifer classifications are based on the physical storage properties of the rocks. To understand why certain rock types have been classified as a particular type of aquifer an understanding of the geology is necessary. Brief descriptions of the geology of the different aquifer types are presented below.

2.2.1 Sedimentary Aquifers (Intergranular Porosity)

Sedimentary aquifers can potentially hold large amounts of groundwater. Sedimentary aquifers are largely dominated by intergranular porosity. That is, groundwater within the sedimentary rocks flows between the sedimentary grains. The amount of porosity, or pore space, that exists between the sedimentary grains depends on a number of factors including how well-sorted the sediments are and the sediment grain-size. Generally, the more well-sorted the sediments the greater the porosity is. This is because, in well-sorted sediments, the pore spaces between grains are not taken up by smaller grains. Additionally, the smaller the grain-size the greater the porosity is. That is, well-sorted sand will generally have greater porosity than well-sorted gravel, but both will have high porosity if they are well-sorted. However, when the grain-size is smaller than silt, such as clays and mud, the porosity of the sediments is effectively clogged by the fine particles and groundwater cannot flow. This is known as low permeability (discussed further below in the Porosity and Permeability section). A homogeneous sedimentary aquifer will have consistent porosity throughout where as a heterogeneous sedimentary aquifer will have varied porosity at different locations. Likewise, sedimentary aquifers at different locations may have similar porosity or may be substantially different. Differences or similarities within aquifers, as well as between separate aquifers, are a result of how the sedimentary rock has formed. Below some of the typical sedimentary environments found in Timor-Leste are discussed.

All sedimentary rocks are formed from the weathering of older rocks and subsequent sediment deposition. Sedimentary materials may include particle sizes from clays to boulders and can be transported greater or smaller distances by gravity, wind, ice or water. Sedimentary rocks can be classified as those that form in: continental environments; at the boundary between continental and marine environments; and in marine environments.

Continental sediments include all sediments formed on cotenants by the action of water (alluvial, fluvial and lacustrine deposits), wind (eolian deposits), ice (glacial deposits) and gravity. Timor-Leste contains a number of alluvial, glacial and gravity style deposits. The alluvial sediments have developed well-sorted to poorly-sorted sediments in river valleys throughout the mountains and lowlands but are particularly prominent along the coast where large sedimentary alluvial deposits have formed broad flat plains, particularly on the south coast. Timor-Leste also contains a number of poorly-sorted sediments with large grain-sizes (conglomerates and boulder-conglomerates) that may have formed by gravity slides or glacial action. Many of the alluvial sediments of Timor-Leste have the potential to act as good aquifers.

Continental-marine boundary sediments, otherwise known as coastal sediments, develop where the land meets the sea at the interface of continental and marine environments. Coastal sediments largely develop by the action of water from a combination of rivers, waves and tide effects. The typical sedimentary formations in coastal environments produced from these effects are deltas, estuaries, lagoons, tidal flats and strandplains. Each of these coastal sediment formations may develop depending on the relative inputs from rivers, waves and tides. Many of these coastal sedimentary formations are present throughout the coast of Timor-Leste, particularly where rivers meet the ocean and along the south coast. These coastal formations often accumulate sediments which build up both vertically and horizontally. Like the alluvial sediments, which the coastal sediments are often associated with, the coastal sediments of Timor-Leste have the potential to be good aquifers.

Marine sediments range from those on relatively shallow continental shelf to deep ocean. The grainsize of marine sediments generally decreases from the sand sized grains near the coast to silts and clays of deeper marine environments. Carbonate rocks (limestone) often form in deep ocean environments and, in sub-tropical to tropical environments, can also form on the shallower continental shelf. Carbonate rocks are discussed in more detail in the next section. A range of marine sediments are present throughout Timor-Leste, exposed from under the ocean by the uplift of Timor. Many of the marine sediments in Timor-Leste are fine grained clays and are not likely to be good aquifers.

Sedimentary aquifers have the potential to store large amounts of groundwater. Many sedimentary aquifers are used around the world for their reliable groundwater resources. The groundwater storing capacity of sediments depends on the type of environment in which the sediments formed, as discussed above. In addition, the age of the sediments is important as over time the porosity of sediments can decrease due to filling of the pore space, discussed further below under the Porosity and Permeability section. An understanding of an aquifers sedimentary composition, structure, origin and history can allow for a more detailed assessment of the aquifers groundwater potential.

2.2.2 Limestone Karstic Aquifers (Fissured Porosity)

Limestone can contain large amounts of groundwater. These rocks are largely made out of carbonate minerals and for this reason limestone is also often called carbonate sediments or carbonate rocks. Limestone often forms in deep marine settings or near the coast as reefs. Some groundwater can move through cracks and around grains and rock fragments but the greatest amount of groundwater in carbonate rocks is stored in fissures (holes, gaps and caves) formed over time by the movement of groundwater itself. Limestone that has developed extensive fissures is described as 'karst' indicating the fissures are a prominent feature of the rock. Karst is an evolutionary feature formed in limestone by the dissolution of the carbonate rocks over time resulting in the gradual development of interconnected fissure systems of caves and smaller conduits. Initially, diffuse flow can dominate groundwater movement with flow through small fractures and porosity. Over time, a network of conduits begins to develop that carries an increasing proportion of the flow. In more mature karst systems there can be almost no diffuse flow and groundwater is largely channelled through the fissures. Sinkholes, large holes exposed at the grounds surface in limestone regions, are typical landform features of karst terrains. Sinkholes allow direct access for rainfall and runoff into groundwater systems and further enhance the formation and dominance of fissured groundwater flow.

Groundwater stored in karst aquifers is an important freshwater resource in Timor-Leste. Waters from karst aquifers supply water for a number of communities in both mountain and coastal areas. The groundwater from limestone areas, often the only source of freshwater, is generally of a very high quality and is suitable for direct drinking water. Karst aquifers in limestone regions can contain considerably more groundwater than fractured rock aquifers due to the dissolution of carbonate and enlargement of karst fissures. Many limestone regions in Timor-Leste show the development of classic karst features, such as the Baucau Limestone, where underground caves store and transmit large quantities of groundwater. The coral reef limestone features of the Baucau Limestone indicates that in some places it is strongly recrystallised, but elsewhere it remains highly porous. Thus, it is taken as having karst groundwater flow but also a proportion of porous flow. Other limestone regions, such as the mountainous area around Maubisse, have formed from uplift from the ocean floor rather than from the development of coastal reefs. These areas have also undergone differing amounts of heating (metamorphism) which may affect the way groundwater flows through these older limestones.

A common feature with the limestone regions is the presence of groundwater springs. Springs are a more common source of water in these areas rather than water extracted by pumping. These springs rely entirely on natural groundwater supply and therefore cannot be managed by changes in pumping rate. Karst aquifers are also renowned for having complex uneven groundwater flow paths. This means that, whilst groundwater is likely to be present in most limestone areas, the amount and flow rate may vary considerably. Determining the flow direction and discharge rates of karst systems is very a difficult, usually relying on local knowledge of karst features. Groundwater can also travel very quickly through the potentially large cave systems. In some areas changes to the amount of groundwater recharge can relatively quickly affect the amount of water coming out of some springs. Therefore, it is expected that the effects of climate change on groundwater vulnerability can be observed in particular at karst springs in Timor-Leste.

Groundwater Resources in Red River Delta

Nguyen Thi Ha
Centre for Water resources Monitoring and Forecast,Vietnam

1. General hydro-geological conditions of Red River Delta Plain

The Red River Delta Plain (RRDP) has a triangle shape, this is, the peak is in the Viet Tri and two sides open widely into seaward along the boundaries between bedrock and quaternary sediments. There are the Tam Dao-Yen Tu mountain from the north to north east, the Ba Vi - Vien Nam mountain from the west to south west, and the Bac Bo Gulf in the east. The study area has the following coordinates (Fig. 1):

From 19°56' to 21°21' N / From 106°17' to 107°58' E

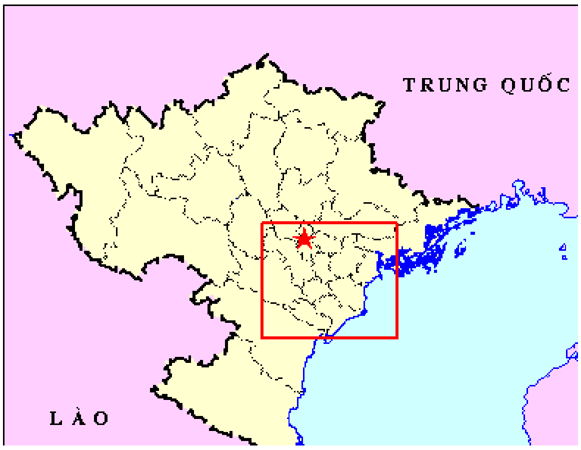


Fig. 1 Study area

The RRDP is one of important centres for culture, population, and economy of the country. The Plain is understood that the flat area is composed by the agglomerate of sediments from Hong - Thai Binh river system. The plain area beside 11 provinces is bounded by boundary between bedrock and Quaternary sediments. There are still parts of other provinces such as Phu Tho, Bac Giang and Quang Ning with 15,000 square kilometre.

In the RRDP the Quaternary sediments have thickness from some tens to more than 100m and the Neogene formation has thickness more than 10,000m. Because of this structure, hydrogeological conditions are very complex. Quaternary sediments can be divided into some water-bearing layers from the surface downward. The hydrogeological units in the Quaternary sediments were described as following:

1.1. Holocene aquifer (qh)

There are two water-bearing layers (WBL): qh1, qh2. The WBL qh2 is including Thai Binh sediment formation (Q23tb) with many different sources: alluvial, marine-alluvial, marine, bogy-marine, alluvial-bogy-marine and windy marine. It's distributed almost plain area: along the rivers from centre to the North West and covered the plain surface from centre to the South-East. The sediment contents are complex including sand, sandy clay, silty clay, silt which changed with depths and on area. Thickness of the sediment is from some tens to about 50m and most of them are ranges from 20m to 40m.

A Water-bearing layer (WBL) qh1 including the alluvial, marine sediment (amQ212-hh), bogy-lake sediments (lbQ21-2hh) distributed in Hai Hung, Hai Phong, Thai Binh, Nam Ha, where its only detected in wells. The sediment contents are fine sand, sandy silt, silty sand with vegetable remains, and the thickness is from 15m- 20m.

The qh aquifer is the moderate water-bearing which may be satisfied in a medium or small scale for water supply.

TDS and groundwater chemical contents are complex change in the aquifer. In general, the TDS is increasing from some ten percent to more than 3 g/l from the top of the delta to the sea and from the edge to the centre. It is recharged by rain, irrigation and seasonal river water. The aquifer is discharged by evaporation and vegetable dispersion for underneath aquifers.

1.2. Confine aquifer - middle - upper Pleistocene sediments (qp)

The aquifer is cropped out in the edge such as Chi Linh, Dong Trieu, Hiep Hoa, Viet Yen, Lam Thao, and Co Tiet. In the centre zone, it is completely covered as detected in wells. The sediments are consisted of alluvial-marine sediment amQ12-3hn), alluvial sediment (aQ12-3), pluvial- alluvial (apQ12-3) and bottom of the Vinh Phuc formation.

Lithological contents are two parts: the upper part is including sand and gravel, meanwhile the lower is cobbles with gravels sandwiched by clay and sandy clay lens. The aquifer thickness is some tens to 85m, increasing from West North to South East and from edge to the centre.

This is a confined aquifer, the water-bearing characters fairly homogeneous. It is divided into two parts: the upper part is including sand and gravel, and the lower is cobbles with gravels sandwiched by clay and sandy clay lens.

In the cropped out area, specific capacity (SC) of wells are only 0.2-0.5l/sm. The rest is divided in two layers which are detailed studying Ha noi as follows: well SC is 0.9-4.9 l/sm and transitivity (T=Km) 120 m2/d-400 m2/d. The other area which is studied in the lower layer or for all aquifer, has small SC in the edge (0.1-0.2 l/sm to very huge values more than 10 l/sm (in the centre). T values are from 50-100 to 2,000-3,000 m2/d. TDS is increased from 0.5 to more than 3 g/l in West North – South East direction. The TDS 1 g/l line from the centre to Diem Dein commune whereas in the two edge areas it is spreading into onshore: to Hai Duong, Bac Ninh in the East, to Phu Ly in the West. In Hai Phong existed 2 fresh water (FW) lens in salted water area. In Hai Hau Nghia Hung the FW area developed from the West, North- West (Viet Tri) to some districts of Thai Binh (Hung Ha). In the plain centre the FW area spread out to Hung Yen along the Luoc river via Thai Binh to Hai Phong in the Vinh Linh fault. The FW narrow stripe from Thai Binh to Hai Phong has relation to mineral water in Neogene formation which is specified by bicarbonate content. The groundwater chemical type changes from bicarbonate to bicarbonate- chloride, chloride - bicarbonate to chloride types.

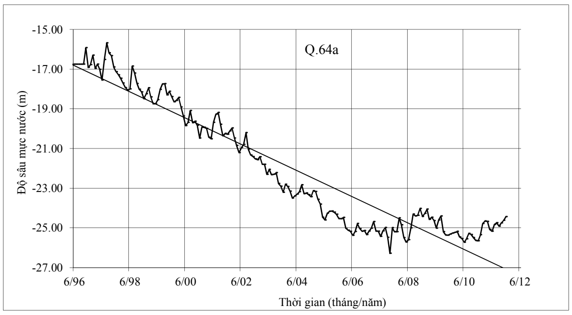
The aquifer is recharged by rain water, river water, and the upper and the lower aquifers. It is discharged to rivers, (seasoning) sea, water exploitation and the lower aquifers

Between upper- middle Pleistocene (qp) and Holocene aquifer is an aquitard upper Pleistocene - Vinh Phuc formation. This layer is discontinuous contribution forming “hydrogeology windows” leading to strongly exchange groundwater between aquifers

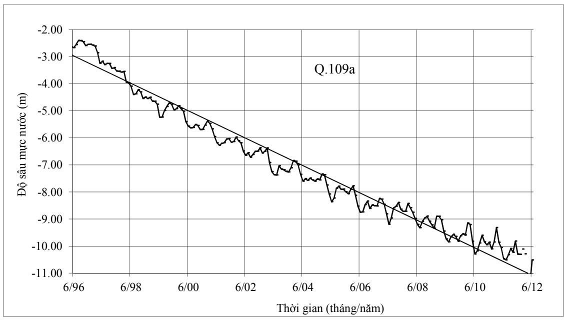
Wherever it is contributed often forming exchanges groundwater of qh and qp aquifers leading to mixed groundwater contents of two aquifers. Wherever its continuous forming different groundwater chemical type which typified by TDS, Cl- and Na+ contents. Qp aquifer is fresh, but qh aquifer is salty.

2. Water level declining in the Red River Delta

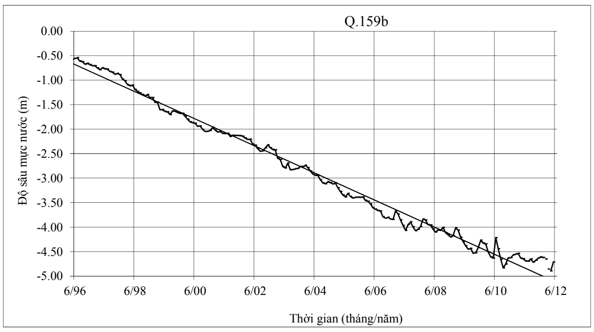
In some strong water extraction, the water level decreases with time (see Figure 2, Table 2). At some monitoring points the water level was lowered almost to permitted water level like Mai Dich, Cau Giay District, Ha Noi. In some places such as the Hai Hau, Nam Dinh Truc Ninh, Quynh-Pacific, the water level is still in safe level, but due to complexivity hydro-geochemical conditions of aquifer, attention should be paid to avoid intrusion salinity caused by water extraction. Water resource management agencies need to pay attention to appropriate solutions.



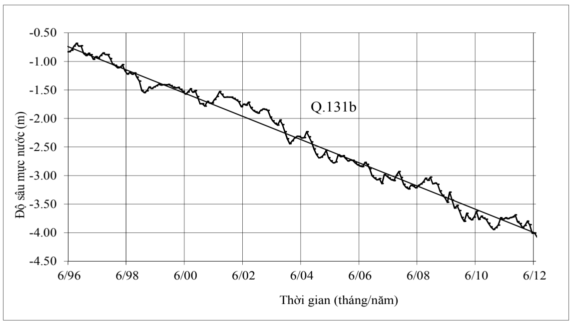
Hanoi



Nam Dinh



Thai Binh



Hai Duong

Fig.2 Water decling in some areas of Red River Delta

3. Forecast for water level in the Red River Delta

Based on the water level in long term we have drawn graph and estimated water level by using statistic method. The results of estimation are presented in the Table 1.

Table1. Estimation of water level in a strong extraction area, qp1 aquifer

Well	Hmin 1995 (m)	Hmin 6/2012 (m)	Comparison with Hcp, (%)	Estimated water level, (m) December 2012	Hcp (m)	Location
Q64a	16.66	24.36	38.06	25.06	64.00	Hanoi
Q109a	2.19	11.45	22.90	11.19	50.00	Nam Dinh
Q159b	0.52	4.90	9.79	4.96	50.00	Thai Binh
Q131b	1.26	4.01	8.02	4.05	50.00	Hai Duong

4. Groundwater quality in the Red River Delta Plain

4.1. Upper Holocene aquifer (qh2)

The analysed results from 33 water samples in dry season 2012 showed that average TDS value is 3,092mg/l. There are 11 samples having TDS higher than standard limitation (SL). The maximam value is 22,246 mg/l in well Q.111 (Hai Ly - Hai Hau - Nam Dinh); The Minimum value is 235 mg/l in well Q.115 (Ho town - Thuan Thanh - Bac Ninh).

The analysed results from 25 water samples in dry season 2012 showed that all sample having ammonia higher than SL (>0.1mg/l in N). There are 8 very high samples, 4 high samples. The average ammonia value is 71 time higher than SL. The maximum value is 44.18 mg/l in well Q.111 (Hai Ly - Hai Hau - Nam Dinh).

4.2. Lower Pleistocene aquifer (qp1)

The analysed results from 49 water samples in dry season 2012 showed that average TDS value is 756mg/l.

There are 20 samples in 40 samples having maganese higher than SL. There are 6 samples in 40 samples having arsenic higher than SL. The maximum value is 0.4 mg/l in well Q.58a (Hoai Duc- Ha Noi), 8 time higher than SL; The other trace elements having values lower than SL.

The analysed results from 44 water samples in dry season 2012 showed that all sample having ammonia higher than SL. There are 13 very high samples and 6 high samples. The average ammonia value is

73.2 time higher than SL. The maximum value is 44.18 mg/l in well Q.111 (Hai Ly - Hai Hau - Nam Dinh).