MINISTRY OF INDUSTRY, MINES AND ENERGY
SIEM REAP WATER SUPPLY AUTHORITY
THE KINGDOM OF CAMBODIA

THE PREPARATORY STUDY ON THE SIEM REAP WATER SUPPLY EXPANSION PROJECT IN THE KINGDOM OF CAMBODIA

FINAL REPORT 2

VOLUME II

MAIN REPORT

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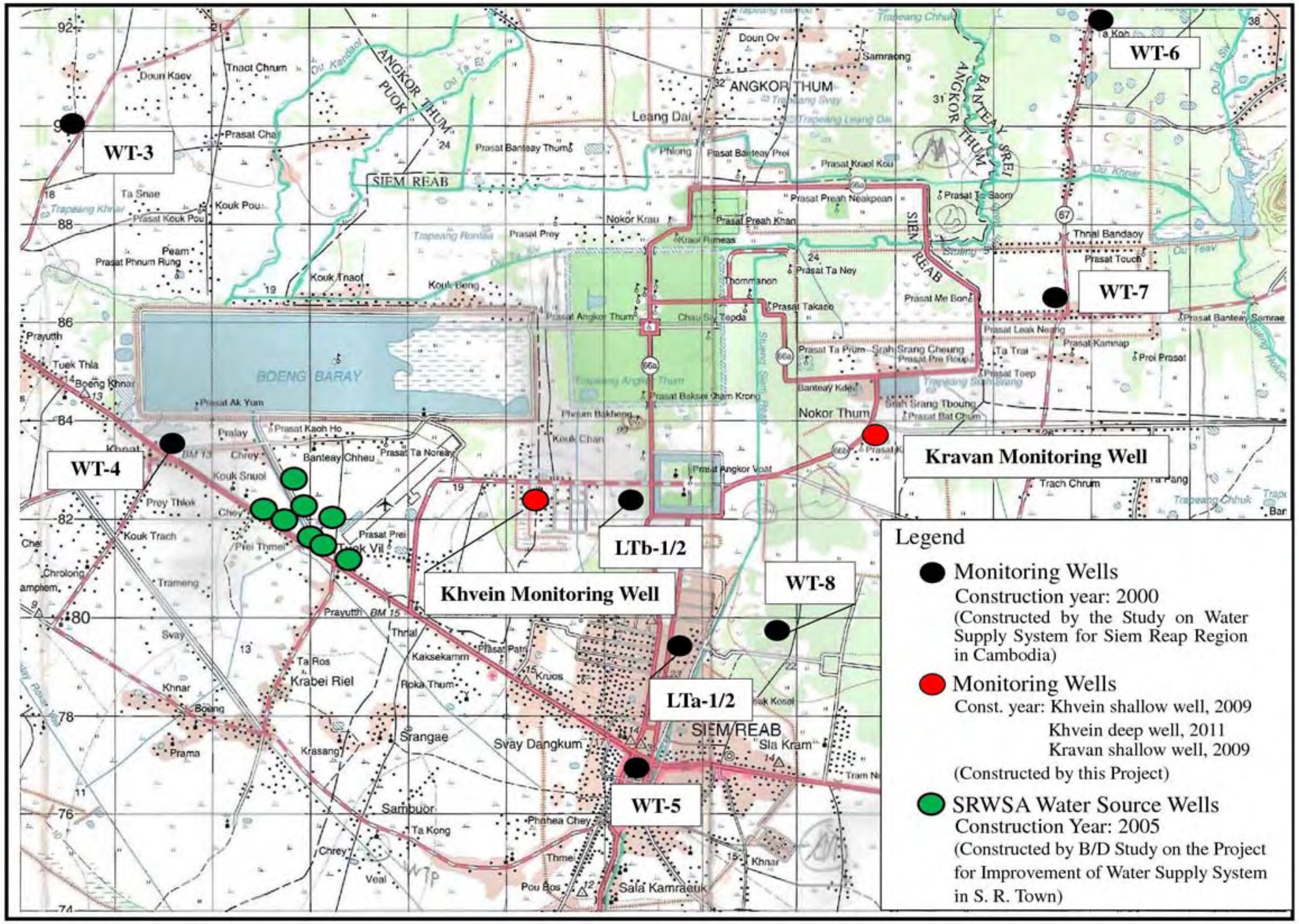

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EXECUTIVE SUMMARY

1. Background of the Project

1.1 Authorization

The Preparatory Study on The Siem Reap Water Supply Expansion Project is in pursuance to the Scope of Work, signed on 29th January 2009, between the Ministry of Industry, Mines and Energy (MIME), the Siem Reap Water Supply Authority (SRWSA), and Japan International Cooperation Agency (JICA).

The Study started in May 2009, and completed in August 2011. During the approximately 28-month period, the Study Team will undertake the study in close cooperation with the MIME and SRWSA counterpart officials. This Final Report presents the results of the activities in the field of groundwater study.

1.2 Objective of the Study

The objectives of the Study are:

1) To select new water sources(s) for an efficient and sustainable water supply system in Siem Reap;
2) To conduct surveys of existing wells and assess the potential yield of groundwater
3) To identify an urgent water supply expansion project to satisfy the estimated water demand for Siem Reap up to a selected target year of the Project;
4) To conduct a feasibility study for the proposed water supply expansion project, provided that the Project is to be implemented under finance by the Japan's ODA loan;
5) To formulate a long-term water supply development plan up to year 2030; and
6) To pursue technology transfer to the Cambodian counterpart during the course of the Study.

1.3 Study Area

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.

1.4 Target Year

The year 2030 has been set as the target year for the proposed long-term water supply development plan, as agreed by and between the JICA mission and Cambodian side in January 2009.

1.5 Methodology of the Study and Component of Final Report 2

The methodology envisaged by the Team in their Inception Report was kept through the study. Since the Study was conducted in three phases, Final Report 1 (water supply planning) and Final

Report 2 (groundwater study) were prepared in the course of the Study.

In the field of groundwater study, Phase 1 included basic study such as well inventory survey, electric sounding, water use awareness survey, and basic examination on possibility of groundwater development by computer simulation. Phase 2 was mainly formed by preparation of facility development plans and the feasibility study in the field of water supply. Phase 3 was conducted based on basic information from Phase 1.

- Phase 1 — Basic Study on Structure of Groundwater Basin, Well Inventory, and Basic Examination on Possibility of Groundwater Development by Computer Simulation
- Phase 2 — Preparation of facility development plans and the feasibility study
- Phase 3 — Study on groundwater use and assessment

1.6 Contents of Final Report 2

This Final Report 2 deals with the results of the study for Phase 1 and 3.

2. Survey Results for Groundwater Sources

2.1 Geophysical Survey

A Vertical Electrical Sounding (VES) was conducted in the zone along the shore of Tonle Sap lake extending 30 km on the east and west side of Phnon Kraom hill. 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 results of the study (2000), the geophysical survey data of this study were analyzed and the analyzed geological structures are shown in Table 2.2.

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 (May 1997) 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 sedimentary rocks.	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 are the major aquifers. The geophysical survey data of this study were analyzed by reference to the survey results of the above study (2000).

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 as outlined in the right table.

Outline of the Inventory Survey

Survey period	July 22 to August 29, 2009
Survey method	• Interview with structured questionnaire • On-site measurement
Major survey items	1. Basic information of the site 2. Basic information of the water supply system 3. Well Structure and water use 4. Water use awareness 5. Water quality
No. of survey targets	Total 280

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.

Average Number of Wells and Depth of Wells

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

(Note) * 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. It was estimated based on pump capacity, tank volume, and operational hours of pumps. The results are summarized in the following table.

Estimated Daily Average Water Use Amount by Category (m^3/day/establishment)

Category	Hotel	Guest house	Restaurant	Factory	Other
Rainy Season Mean	30.35	4.62	8.89	39.00	8.89
Dry Season Mean	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.

Ratio of Awareness on 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.

The information for the 280 surveyed establishments have been converted to a MS-Access database and handed over to SRWSA.

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.

Summary of Estimated Present Groundwater Use Amount in Siem Reap

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 in 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	

The data for monthly average O/M cost and installation cost of water supply facilities obtained in the inventory survey were used to estimate the unit water production cost (US$ per one cubic meter of water) for each category. The result is shown below. The figures are also larger than the current water tariff of public water supply system.

Water Production Cost of Groundwater Users

Category	Hotel	Guest House	Restaurant	Factory	Other
Average unit water production cost* (US$)	0.781 – 0.815	0.802 – 0.835	0.734 – 0.745	0.446 – 0.460	1.028 – 1.048

(Note): Production cost* : production cost range was calculated by estimation that major repair cost of main facilities correspond to 30-35 % of construction cost.

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 Phnon Kraom as in the table below.

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	1600**	0.3	0.1	1.5
East	5.43	48	1.21	0	0.18
West	5.60	83	2.08	0	0.15
Phnon Kraom	4.90	518	0.45	0.17	0.15

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

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.

2.5 Survey Result of Core Sample

Under this study, a monitoring well (shallow well) was constructed in the premise of Kravan primary school on October 2009 and two monitoring wells (shallow and deep wells) were constructed in Khvein primary school on October 2009 and May 2011, respectively.

At the same time, in the same locations as the monitoring wells, a core boring of 80 m in depth were conducted at each site on October 2009 and the observation survey for the core samples was followed on January 2011. In addition, in the observation survey, core samples which JSA (Japanese Government Team for Safeguarding Angkor) carried out in the yards of Angkor ruins (Angkor Wat and Bayon shrine) in 1995 were also observed as reference samples.

The survey results were different from accepted concept on geological structures in Siem Reap area based on the study results of "the Study on Water Supply System for Siem Reap Region in Cambodia (2000)", namely, geological structures that Quaternary formations of Alluvium and Diluvium were underlain by claystone (equivalent formations of Tertiary). Claystone in the core samples by this observation survey was not observed.

According to the above study (2000), in Siem Reap area, geological structures are made up of 4 ones: Alluvium and Diluvium are distributed in the depth of ground surface to about 30 m to 50 m and are underlain by Tertiary formations with layer thickness of about 40 to 50 m, and basement rocks of sandstone, siltstone, shale, and tuffaceous breccias of Upper Jurassic, andesite, basaltic intrusive rocks, and diorite of Late Mesozoic to Tertiary are distributed in the depth of about 70 m to 80 m.

However, the observation of the core samples in both sites of Khvein and Kravan led to the following results: (1) In the depth around 40 m, change of formation facies which clearly divide between Diluvium and Tertiary formations together with the boundary of both formations cannot be recognized and it can be deemed to be consecutive formations. (2) Formations equivalent to Tertiary formations does not exist in core samples as a result of core observation. These facts are also observed in the core samples of Angkor ruins by JSA.

3. Current Status of Groundwater Use

3.1 Present Status of Groundwater Monitoring

In the Study Area, 10 monitoring wells were constructed under the Study on Water Supply System for Siem Reap Region in Cambodia (2000). SRWSA has collected the monitoring data every month. Manual measurement of groundwater level has been conducted once a month to confirm the reliability of monitoring systems since July 2007.

However, Activities done by SRWSA so far is not necessarily enough in reference to recommendations made in the Basic Design Study (report) on the Project for Improvement of Water Supply System in Siem Reap Town in the Kingdom of Cambodia (2003). As shown in "Chapter 3, Table 3.2 Existing Monitoring Wells, Reliability of Monitoring Data, and Necessity of Calibration", equipment of many monitoring wells normally does not function and needs its calibration. SRWSA should take proper measures such as restoring of mal-functioned monitoring equipment to improve this situation as described in chapter 6, conclusion

Under this study, a monitoring well (shallow well) was constructed in the premise of Kravan primary school on October 2009 and 2 monitoring wells (shallow and deep wells) were constructed in Khvein primary school on October 2009 and May 2011, respectively.

3.2 Private Wells

Current status of groundwater use by private wells distributed in Siem Reap area was examined by using well inventory information and monitoring well data.

- Tapped aquifers and withdrawal volume of groundwater
  Private wells pumping up more than 10 m^3/day and owned by large establishments are concentrated in the city center areas. Those private wells with a pumping capacity of more than 10 m^3/day extract 96 % of the total amount of groundwater usage (5,786 m^3/day) surveyed by well inventory survey. The extracting volume of groundwater by private wells is 5,554 m^3/day in the dry season. These private wells mainly extract groundwater from Diluvium formation distributed in the depths of 20 m to 50 m and partially from Tertiary formation distributed in depth of 60 m to 70 m.

- Influence of pumping up
  Influence of pumping up by the private wells was examined by using WT-5, and LTb-1 and LTb-2 well data collected on the same day on 7 to 9 January 2008. The automatic monitoring data include low reliability ones in some period due to malfunction of monitoring equipment. Reliability of the data was confirmed by comparison between automatic and manual measuring data and only data with high reliability were used for data analysis.

  The WT-5 well is located in the center of the city and it monitors groundwater level of Tertiary formation. The monitoring data of WT-5 well with the lowering of groundwater level of 3 to 6 cm indicates the influence of pumping of groundwater by private wells in the Tertiary formation in Siem Reap City area. It also suggest that its pumping have not an influence LTb-1 monitoring site (due to no fluctuation of groundwater level), tapped to the same Tertiary formation, where is located apart 5 km from WT-5 monitoring well.

The screens of LTb-2 are set in the Diluvium formation. In the same day, the lowering of groundwater level of LTb-2 was larger than that of WT-5 because extracting volume of groundwater from the Diluvium formation by private wells shall be much larger than that of the Tertiary formation.

3.3 SRWSA Production Wells

- Tapped aquifers and withdrawal volume of groundwater

  Eight (8) SRWSA wells intakes groundwater from aquifers distributed in the lower part of Alluvium and main portions of Diluvium. The current water supply amount is recorded to be over 9,000 m^3/day

- Influence of pumping up

  Influence of pumping of the SRWSA production wells was examined by using WT-4 and Khvein shallow wells' data.

  Monitoring data was collected on January 8 and 9, 2008. Operating condition of the SRWSA production wells was fully operated on January 9 and was halted to pump up for 4 hours during the mid-night time on January 8. Under these different operating conditions, fluctuation of groundwater level in WT-4 monitoring well was compared. If pumping up of SRWSA wells causes some influence to groundwater level of WT-4, depression of cone shape in groundwater level by pumping up shall expand and influence to monitoring water level located in far place from pumping wells and cause lowering of groundwater level. As a result, WT-4 monitoring well located 2.6 km away from and in Northwest of SRWSA production wells, the influence of pumping by SRWSA wells was not detected. The same tendency was confirmed on the monitored data of December 14-16, 2007.

  By using similar method applied to WT-4 well to check influence of pumping of SRWSA production wells, monitoring data of Khvein shallow well were examined. Screens of SRWSA wells and Khvein shallow well are set up in the same aquifer. The examination was conducted for 4 days from May 7 to 10, 2010. As a result, it can be concluded that SRWSA production wells do not have an influence against environment of the Khvein monitoring shallow well which is located 4.1 km away from and in Northeast of the SRWSA wells.

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 precipitation, 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.

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 levels 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.

Comparison of Water Level in Rainy Season in Town Area

Time	Sept_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 (m)	5.12	3.51	3.1	3	3.26	2.9	2.32
Minimum (m)	0.2	0.1	0	0.3	0.23	-0.28	-0.41

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 (m)	7.4	5	5.1	4.6	4.81
Minimum (m)	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 86,300 m^3/day in 2030, about one sixth of the groundwater recharge amount of 516,000 m^3/day. However, 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 plans is 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 west-east direction and 46.5 km in 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 2.2 Geological and hydrological characteristics of 2-1 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) assumes 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 (lake) 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 m^3/day: (SRWSA wells' extraction volume = 9,000 m^3/day) + (private wells' extraction volume)}

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

Scenario 4: Taken KTC project into consideration and then expending groundwater supply capability by an amount of 43,000 m^3/day.

{Total withdrawal volume = 52,000 m^3/day: (SRWSA wells' extraction volume = 9,000 m^3/day) + (Groundwater development volume by new wells 4,300 m^3/day)}

Scenario 5: Also taken KTC project into consideration, but the expanding amount is set following maximum water demand to be 60,000 m$^{3/}$day.

{Total withdrawal volume = 69,000 m^3/day: (SRWSA wells' extraction volume = 9,000 m^3/day) + (Groundwater development volume by new wells 60,000 m^3/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 m^3/day.

{Total withdrawal volume = 39,000 m^3/day: (SRWSA wells' extraction volume = 9,000 m^3/day) + (Groundwater development volume by new wells 30,000 m^3/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 m^3/day)

5.7 Simulation Results

1) Groundwater level

Five (5) provisional observation 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.

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 5.21.
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.

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	8.2
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 5.21.

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

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	2.82	0.45

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

3) Evaluation of all considerable plans

The simulation results reveal that potential land subsidence would occur in all water supply expansion plans. The following table summarizes the amount of groundwater production and the potential land subsidence amount in the main heritage sites.

Effect Evaluation of All Considerable Scenarios

Scenario	PA (m^3/d)	LD_ANW	LD_WB	Bakong	Risk Level
Scenario 3	77,250	6.25	9.24	72.96	1
Scenario 2	0	5.67	5.1	2.3	2
Scenario 5	60,250	4.52	8.28	46.44	3
Scenario 4	43,060	3.65	7.06	31.64	4
Scenario 6	30,000	3.65	5.84	2.82	5
Scenario 7	0	1.15	4.19	0.45	6

(Note) PA: production amount from new wells (well locations are shown in Figure 5.16). Existing production amount of SRWSA wells is not included in the figure.
LD_ANW: potential land subsidence (mm) under the Angkor Wat heritage site.
LD_WB: potential land subsidence (mm) under the West Baray heritage site.
Bakong: potential land subsidence (mm) under the Bakong heritage site.
Risk Level: the primary standard for risk level setting is the magnitude of the effect to the most important heritage, Angkor Wat; while the second standard setting is the effect to the second most

important heritage, West Baray.

The scenario 7 has the smallest effect to the heritages. However the effect is not zero. Therefore, it is indispensible to examine if the scenario 7 is really an adaptable plan or not.

The effect on Angkor Wat is 1.15 mm. It is nearly unimaginable to cause inspectable uneven settlement by this amount of land subsidence. Therefore, it can be considered as safe for Angkor Wat and other heritages, such as Angkor Thom, which is further than Angkor Wat from the existing SRWSA well sites.

The effect for West Baray might reach a magnitude of 4.19 mm. Considering the structure of the heritage West Baray, it was created mainly using clay, which has almost the highest plasticity among construction materials. On the hand, the groundwater drawdown is not a suddenly occurring event, but a gradually changing process. For a clay created work on a scale of several km^2 like West Baray, the plasticity is more than enough to compensate for land subsidence on a magnitude not more than 4.19 mm in a period of several months. Therefore, not only the deformation would not be detected, because 4.19 mm is too small to be perceived by humans in a work with the size of West Baray, but also no breaks or cracks could be predicated from the viewpoint of experience and geotechnical engineering. Therefore, the effect on heritage of West Baray form the scenario 7 can also be considered sufficiently small as to be ignored.

The potential land subsidence including both shallow aquifer and deep aquifer for Bakong is as small as 0.45 mm, smaller than the effect to the Angkor Wat and West Baray. Therefore, the effect of scenario 7 to Bakong heritage group can be considered as within safe limits.

6. Conclusion and Recommendation

6.1 Conclusion

Survey 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.

(1) 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 groundwater of about 5,786 m^3/day in the dry season. In addition, SRWSA pumps up groundwater of about 9,000 m^3/day for water supply and ordinary houses use groundwater of about

24,000 m^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) for water supply planning year 2030 were prepared and reviewed.

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 Scenario 5	To use irrigation canal water from West Baray reservoir for water supply and diminish a part of groundwater development volume (Withdrawal volume including SRWSA production wells: 52,000 m^3/day – 69,000 m^3/day)
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.

Groundwater development as future water sources for the above scenarios was planned to construct new production wells in the area of more than 10 m in elevation and about 4 - 5 km in south of National Road No.6 with width of about 30 km in East – Northwest direction (Well locations are shown in Figure 5.16).

The simulation results revealed that potential drawdown of groundwater level and land subsidence to world heritage would occur in all scenarios in a dry year of 50 return years. Especially, of these scenarios, scenario 3 which used groundwater as the only source for water supply resulted in the largest land subsidence and the highest risk. Subsequently, scenario 2 which continued groundwater use by the present amount had secondary higher risk. Furthermore, scenarios 4 to 6 also did not recommend having impact to world heritage. Of these scenarios, scenario 7 which utilized lake water of Tonle Sap as future source for water supply had the lowest risk.

For these results, to use lake water of Tonle Sap as alternative water sources without new groundwater development in Siem Reap area for future water demand was concluded to be reasonable.

(2) Enforcement of Monitoring System

Since Angkor Wat ruins which are important world heritage are formed by architectural structures with only piling stones without cements, they are very weaken against land subsidence. Thus, to conserve ruins from drawdown of groundwater level and land subsidence which may be caused by over-pumping of groundwater in the city area in the future is very important. In Siem Reap area, 9 monitoring wells for groundwater levels at 8 sites and 4 observation wells for land subsidence at 2 sites has been constructed and they monitor groundwater levels and land subsidence. However, it was revealed by this study that a part of these facilities normally did not function and their monitoring data had not high reliability. Operating conditions and necessity of calibration of monitoring equipment in each monitoring wells are shown in Chapter 3. SRWSA which manages these monitoring wells presently collects and keeps the data as routine works. They should be able to collect high reliable data by restoring malfunction monitoring equipment.

In Siem Reap area, in addition to SRWSA, Monitoring of groundwater levels by APSARA is conducted. Though DOWRAM presently does not have any groundwater monitoring system, they own position to conduct study and research on water resources utilization of the area. At present, there is no linkage among these organizations. In the future, to conserve important world heritage in Siem Reap area, it is necessary to enforcement groundwater monitoring systems by creating their linkage.

6.2 Recommendation

(1) In a dry year of 50 return years, groundwater simulation results revealed that potential land subsidence to world heritage would occur, not only scenario 3 which used groundwater as the only source for water supply but also scenario 2 which continued groundwater use by the present amount. To improve these situations, it is hoped that new water supply system which is supplied by lake water of Tonle Sap as water source is completed as soon as possible.

(2) If new water supply system which is supplied by lake water of Tonle Sap is completed in the future, the ban of pumping by private large establishments' wells should be conducted. For this purpose, ordinances and regulations by Siem Reap Province and APSARA should be

enforced together with campaign to enhance residence's awareness.

(3) SRWSA generally collects monitoring data of groundwater levels and land subsidence once a month from monitoring wells and also conducts manual measurement of groundwater level to check data reliability at the same time. However, collected data of manual measurement often lack for mismatch of collecting time. SRWSA should keep and conduct thoroughly setting manners for data collection.

(4) SRWSA should check reliability of auto monitoring data by comparison between manual measurement and auto monitoring data. It is necessary to compare and put manual measurement and auto monitoring data at the same observation day/time in the same table and to check the difference of groundwater levels and correlation by drawing on graph.

(5) SRWSA immediately should restore mal-function monitoring equipment. Present conditions of each monitoring wells are described in "Chapter 3, 3-1 Current Status of Groundwater Monitoring."

(6) SRWSA should builds up mechanism and structure for sharing and putting each monitoring data to practical use with APSARA and DOWRAM.

FINAL REPORT 2

THE PREPARATORY STUDY ON
THE SIEM REAP WATER SUPPLY EXPANSION PROJECT
IN THE KINGDOM OF CAMBODIA

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ABBREVIATIONS

AMSL	Above Mean Sea Level
ANT	Angkor Thom
ANW	Angkor Wat
BOT	Build Operate Transfer
CA	Concession Agreement
D/D	Detailed Design
DOWRAM	Department of Water Resources and Meteorology
DWL	Dynamic Water Level
EC	Electric Current
EIA	Environmental Impact Assessment
EIRR	Economic Internal Rate of Return
E/N	Exchange of Notes
FIRR	Financial Internal Rate of Return
GDP	Gross Domestic Product
GPS	Global Positioning System
GW	Groundwater
I/P	Implementation Program
JICA	Japan International Cooperation Agency
JPY	Japanese Yen
L/A	Loan Agreement
L/s	Liter per second
MIME	Ministry of Industry, Mines and Energy
MOWRAM	Ministry of Water Resources and Meteorology
M/P	Master Plan
NPV	Net Present Value
ODA	Official Development Assistance
O&M	Operation and Maintenance
PS	Pumping Station
PVC	Polyvinyl Chloride
SAPROF	Special Assistance for Project Formation
SRWSA	Siem Reap Water Supply Authority
STEP	Special Terms for Economic Partnership
SWL	Static Water Level
TOR	Terms of Reference
UTM	Universal Transverse Mercator
VES	Vertical Electric Sounding
WB	West Baray
WL	Water Level
WMO	World Meteorological Organization

Chapter 1.
Background of the Project

Chapter 1. Background of the Project

1-1 Authorization

The Preparatory Study on The Siem Reap Water Supply Expansion Project is in pursuance to the Scope of Work, signed on 29th January 2009, between the Ministry of Industry, Mines and Energy (MIME), the Siem Reap Water Supply Authority (SRWSA), and Japan International Cooperation Agency (JICA).

The Study started in May 2009, and completed in August 2011. During the approximately 28-month period, the Study Team will undertake the study in close cooperation with the MIME and SRWSA counterpart officials.

This Final Report presents the results of the activities in the field of groundwater study, based on an agreement for the scope of works for Feasibility Study confirmed in the Board Meeting held on January 22, 2010. It also presents the evaluation of findings, the recommendation and conclusion in the field of the groundwater study

1-2 Objective of the Study

The objectives of the Study are:

1) To select new water sources(s) for an efficient and sustainable water supply system in Siem Reap;

2) To conduct surveys of existing wells and assess the potential yield of groundwater

3) To identify an urgent water supply expansion project to satisfy the estimated water demand for Siem Reap up to a selected target year of the Project;

4) To conduct a feasibility study for the proposed water supply expansion project, provided that the Project is to be implemented under finance by the Japan's ODA loan;

5) To formulate a long-term water supply development plan up to year 2030; and

6) To pursue technology transfer to the Cambodian counterpart during the course of the Study.

1-3 Study Area

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.

1-4 Target Year

The year 2030 has been set as the target year for the proposed long-term water supply development plan, as agreed by and between the JICA mission and Cambodian side in January 2009.

1-5 Methodology of the Study and Component of Final Report 2

The methodology envisaged by the Study Team in their Inception Report has been maintained. Since the Study has been conducted in three phases, Final Report 1 (water supply planning) and Final Report 2 (groundwater study) were prepared in the course of the Study.

In the field of groundwater study, Phase 1 includes basic study such as well inventory survey, electric sounding, water use awareness survey, and basic examination on possibility of groundwater development by computer simulation. Phase 2 is mainly formed by preparation of facility development plans and the feasibility study in the field of water supply. Phase 3 is conducted based on basic information from Phase 1.

Phase 1 Basic Study on Structure of Groundwater Basin, Well Inventory, and Basic Examination on Possibility of Groundwater Development by Computer Simulation

Phase 2 Preparation of Facility Development Plans and the Feasibility Study

Phase 3 Study on Groundwater Use and Assessment.

1-6 Contents of Final Report 2

This Final Report 2 deals with the results of the study for Phase 1 and 3.

Chapter 2.
Survey Results for Groundwater Sources

Chapter 2. Survey Results for Groundwater Sources

2-1 Geophysical Survey

2-1-1 Background and Outline

The use of groundwater in the plain area along the shore of Tonle Sap Lake located to the west of Phnon Kroam hill was proposed by the preliminary study team as a possible alternative source for water supply to the city of Siem Reap. Some geological surveys had already been conducted and had clarified the underground geology of the urban and suburban areas of Siem Reap city prior to the preliminary study. However, there has been little geological information available on the zone along the shore of Tonle Sap Lake. For this reason, a resistively sounding survey to investigate the underground geology was first planned for this zone. Later, the study team (of this study), had a discussion with SRWSA staff at the beginning of the study in July 2009 and decided to extend the target area for the survey to the east of Phnon Kraom hill, in consideration of their request.

The entire survey area, as a result, extended about 30 km on both western and eastern sides of Phnon Kraom hill along the shore of Tonle Sap Lake. The survey primarily aimed at determining the position of the bedrock in the area and attempted to discern different types of aquifers overlying the bedrock. The surveyed points are shown in Figure 2.1 along with the locations of the resistivity survey points of the Study on Water Supply System for Siem Reap Region in Cambodia (2000). The outline of the survey is summarized below:

Table 2.1 Outline of the Geophysical Survey

Survey period	July 13 to 30, 2009
Type of sounding	Vertical resistivity sounding (VES)
No. of survey points	53
Electrode array	Schlumberger
Target depth	150 m

The survey points were arranged at intersections of crude grid lines to cover the area as uniformly as possible. However, since the survey was conducted in the middle of the rainy season, most of the surveyed sites had to be located in a small piece of dry land in an inundated terrain.

2-1-2 Results

The survey results were analyzed together with existing borehole geological log data to distinguish aquifers and the bedrock. The sounding data for each survey point was interpreted using a computer program for inversion analysis. 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 of over 100 sounding points and geological log data from eight test boreholes. 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 results of the study (2000), the geophysical survey data of this study were analyzed and the analyzed geological structures are shown in Table 2.2 and the results of the analysis (resistivity curve fitting with a layered model) is given in the Supporting Report.

Table 2.2 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: 1.87-1.67 x 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 sedimentary rocks.	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 Reaap area were formed by 4 ones and the layer 1 and 2 above are the major aquifers.

The only available geological log data for the surveyed area is of the test well drilling work carried out in 2000 at the south-eastern foot of Phnon Kraom hill, some 300 m to the south of VES 53. Bedrock was struck at depths of 27 to 43 m from the ground at this site. Based on the analysis results and in consideration of horizontal geological continuity, several cross-sections of resistivity structure of the surveyed area were prepared and presented as Figure 2.2 –Figure 2.10. The interpreted geological section that cuts across the entire Siem Reap is given in Figure 2-11 along with some hydrogeological information.

(1) Bedrock

The analysis revealed that the depth to the bedrock is likely to be 50 to 80 m below ground level, except around Phnon Kraom hill where the bedrock is exposed and forms the hill. The drilling logs mentioned above show that the bedrock is located deeper than 30 m, a few hundreds of meters away from the hill. This suggests that this topographic rise of the bedrock is limited to this point. The resistivity of the bedrock itself is highly variable due to that fact that it consists of different type of layered rocks and that they steeply dip southeast with a strike of 60 degrees bearing. Bedrock of high resistivity values is found on the western side of Phnon Kraom hill around VES 010 and VES 22. These rocks have resistivity values of more than 1000 ohm-m and interpreted as impermeable rocks such as siliceous acidic tuff and fresh crystalline diorite.

(2) Overlying Layers

There are three overlying layers above the bedrock. The first layer from the ground is alluvial deposits made up of alternation of thin layers of sand, silt, and clay. It is possible that more fine-grained sediments are deposited in the surveyed area in comparison with the area surveyed in the Study on Water Supply System for Siem Reap Region in Cambodia (2000), since the surveyed area is located downstream and its topography is very gentle. The thickness of this layer is variable, ranging from 10 to 25 m, and the resistivity values range from 5 to 1,000 Ohm-m.

The second layer consists of sandy deposits characterized by relatively higher resistivity values as compared to the third layer underneath. The thickness ranges from 5 to 35 m and the resistivity values are generally between 30 to 500 Ohm-m.

The third layer is characterized by low resistivity values of normally less than 100 ohm-m. The layer is much thicker than the overlying two layers and the thickness ranges from 10 to 55 m.

It should be noted that the geological information available in the surveyed area to date is very limited. Thus the interpretation above primarily counted on the resistivity sounding data. It is very likely that geological and, thus, hydrogeological characteristics of the layers differ further upstream in the Seam Reap town area: coarser sediment and higher permeability. It is recommended that several drilling cores be taken to confirm this interpretation.

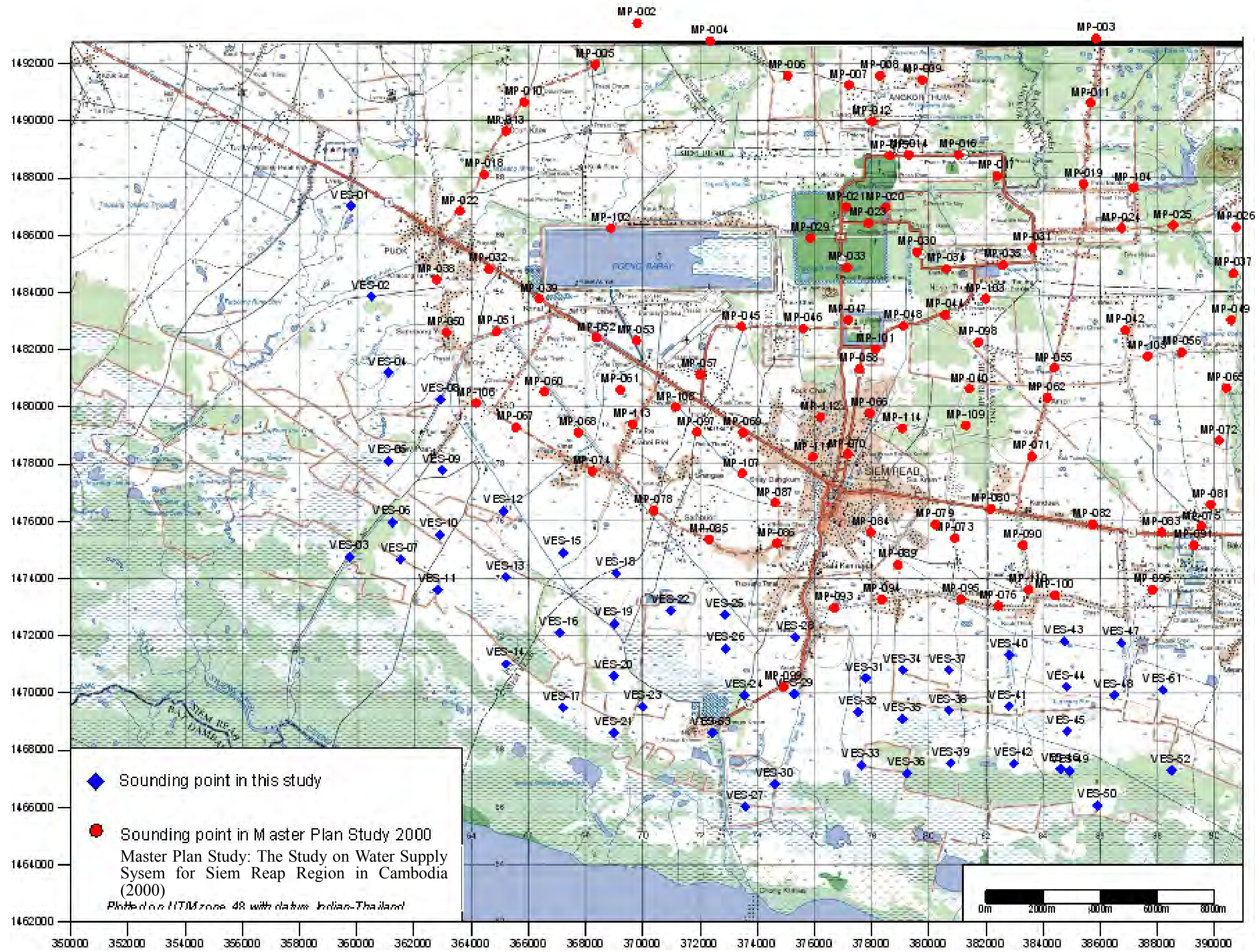


Figure 2.1 Location of Resistivity Sounding Points

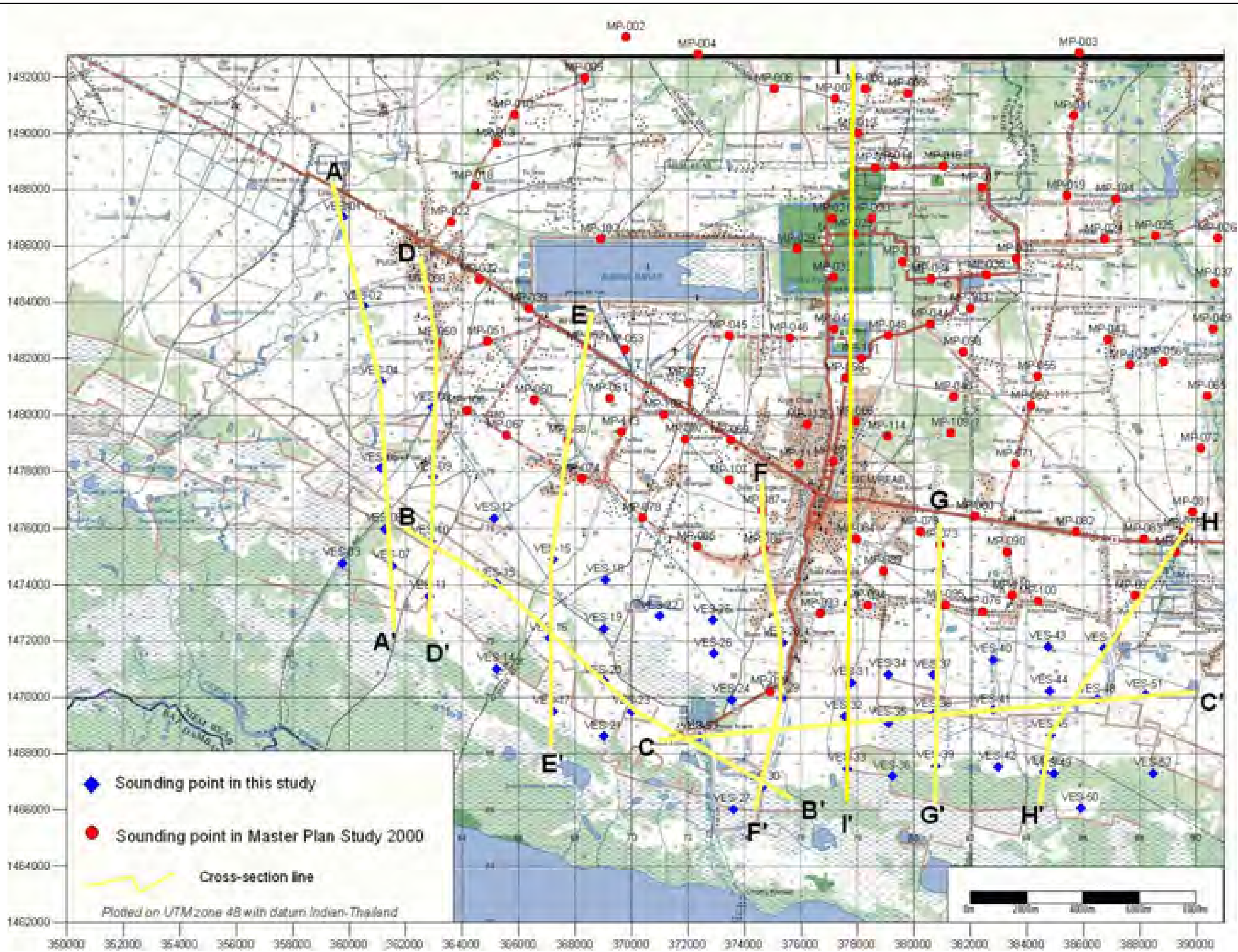


Figure 2.2 Location of Resistivity Cross-Sections

(Note, Master Plan 2000: the Study on Water Supply System for Siem Reap Region in Cambodia (2000))

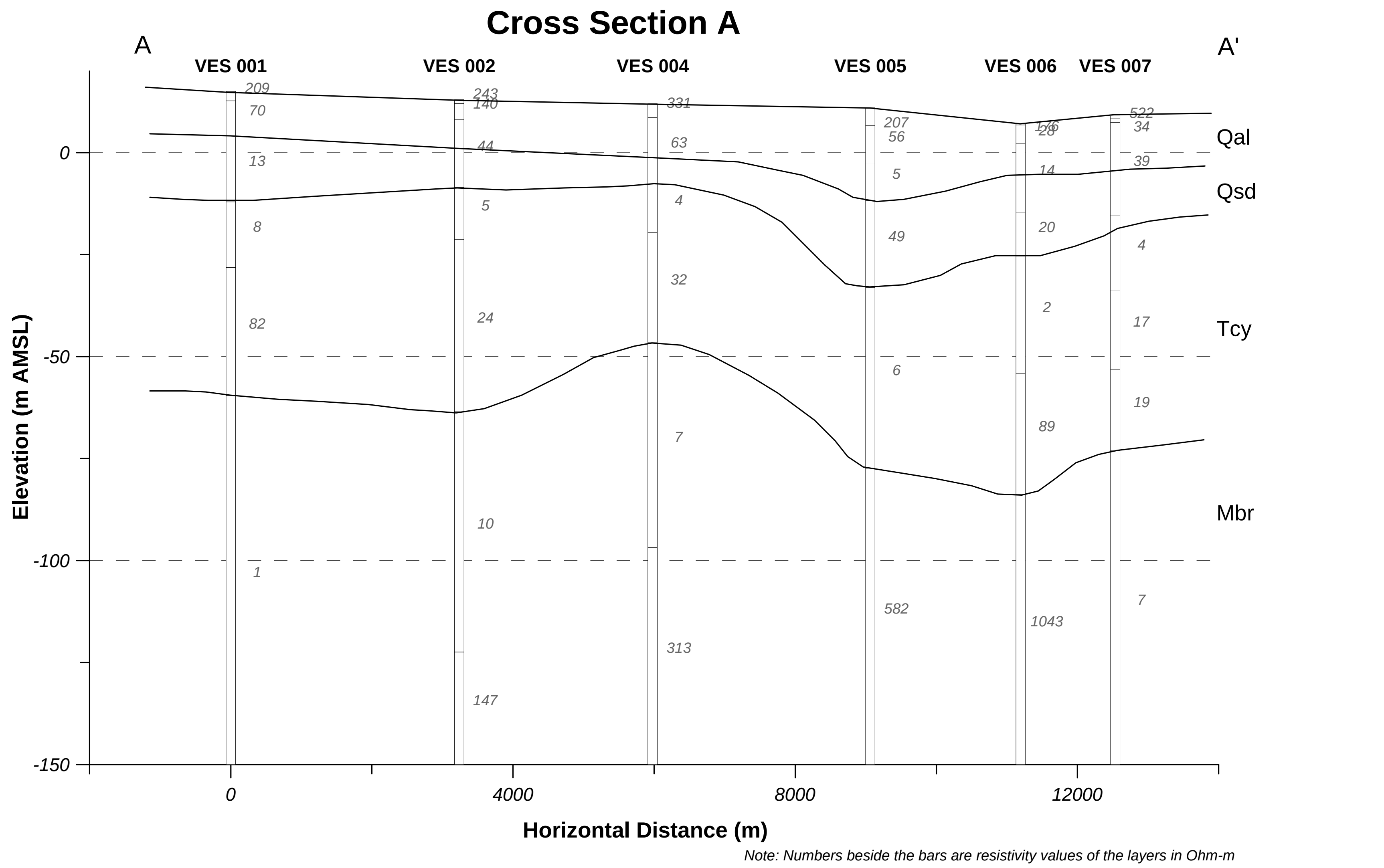


Figure 2.3 Cross-sectional View of the Layered Structure in the Surveyed Area (1/8)

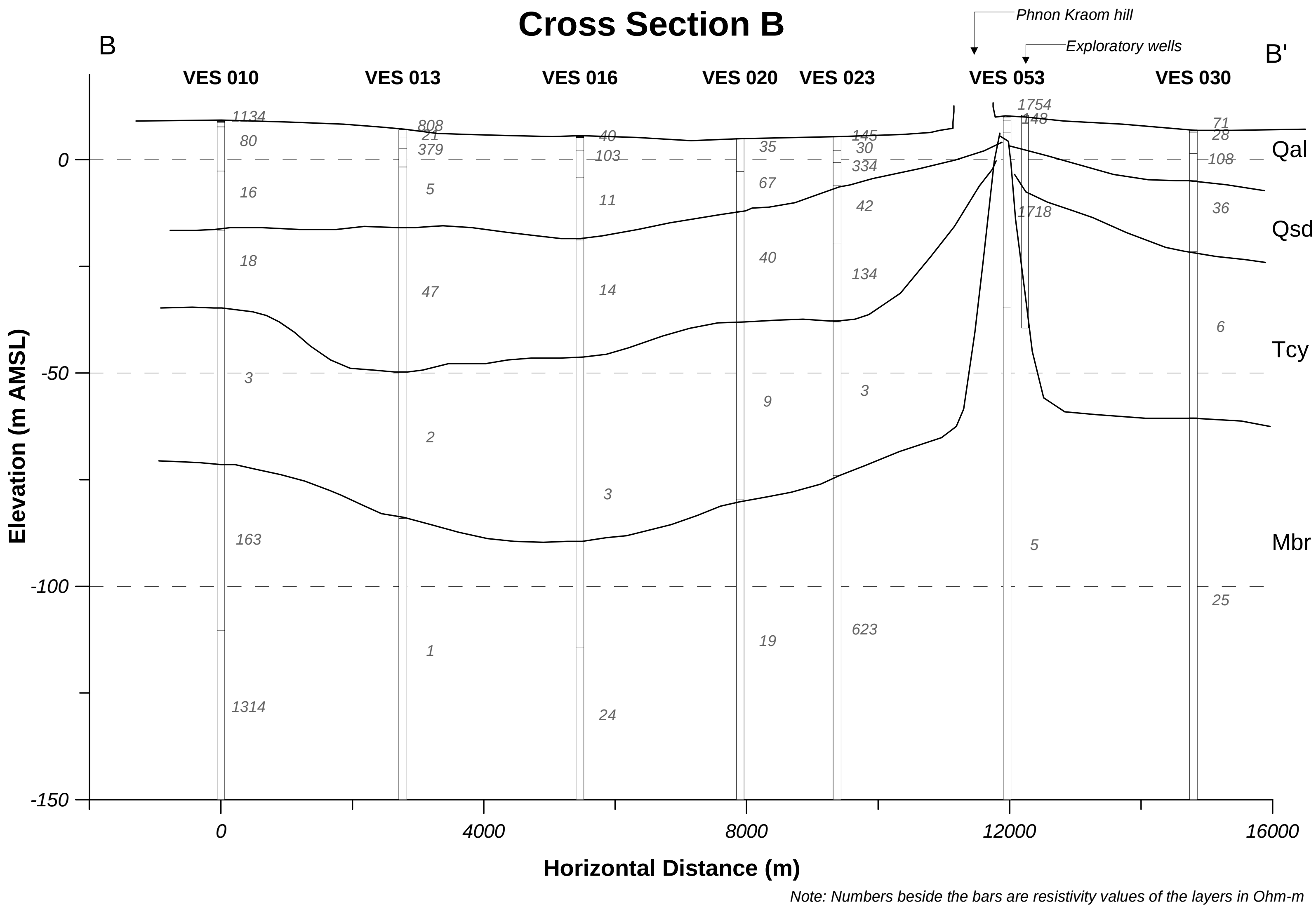


Figure 2.4 Cross-sectional View of the Layered Structure in the Surveyed Area (2/8)

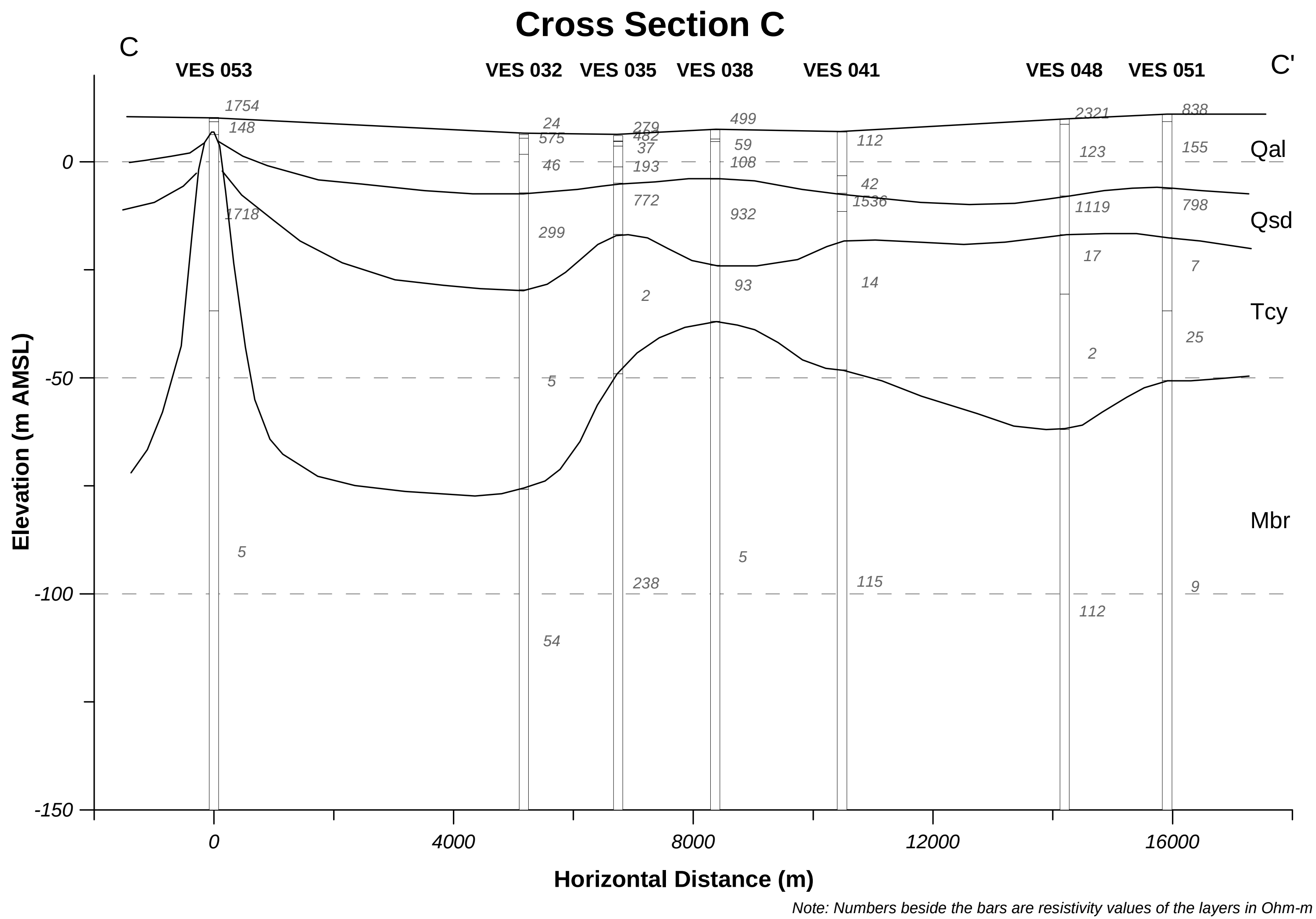


Figure 2.5 Cross-sectional View of the Layered Structure in the Surveyed Area (3/8)

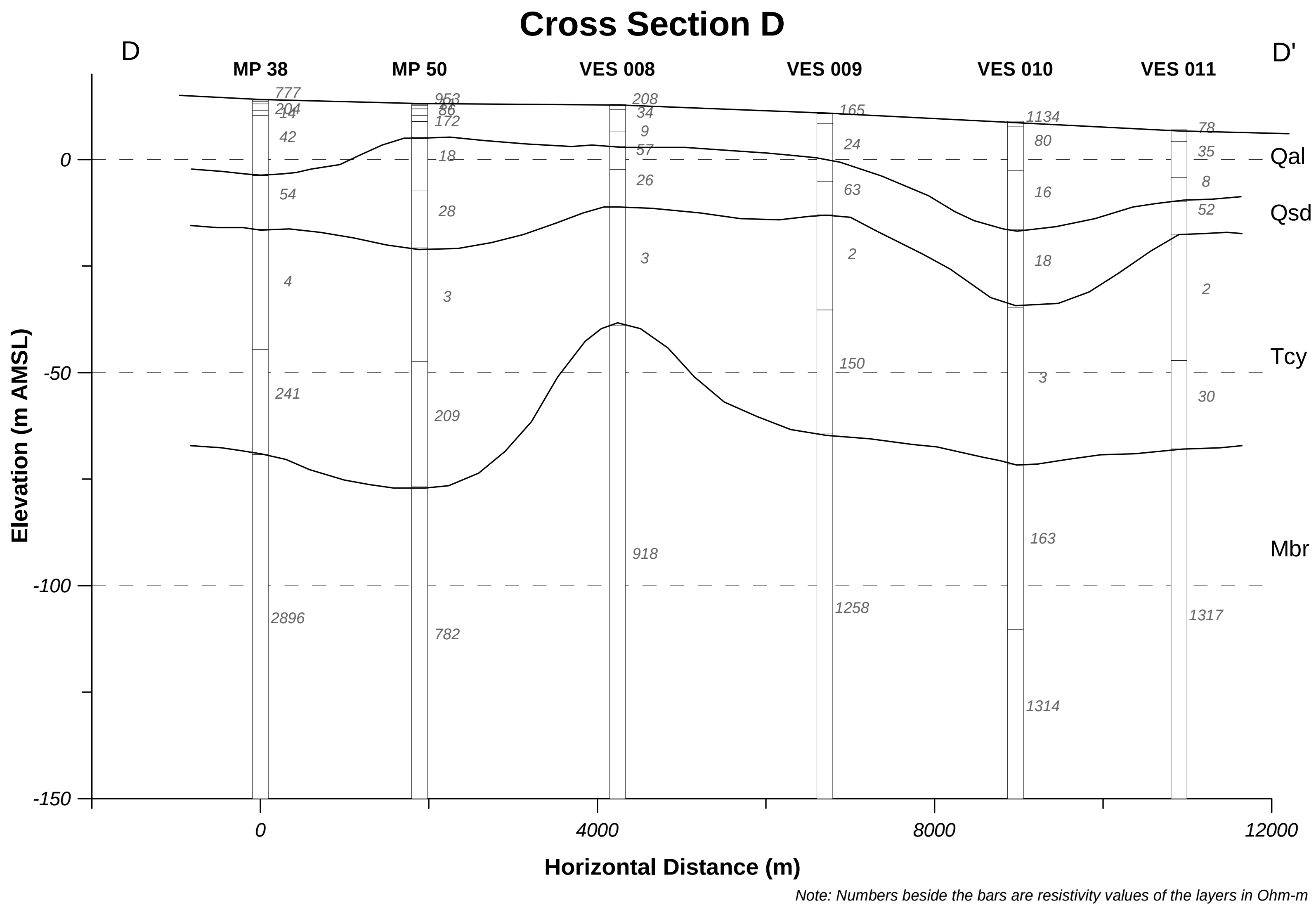


Figure 2.6 Cross-sectional View of the Layered Structure in the Surveyed Area (4/8)

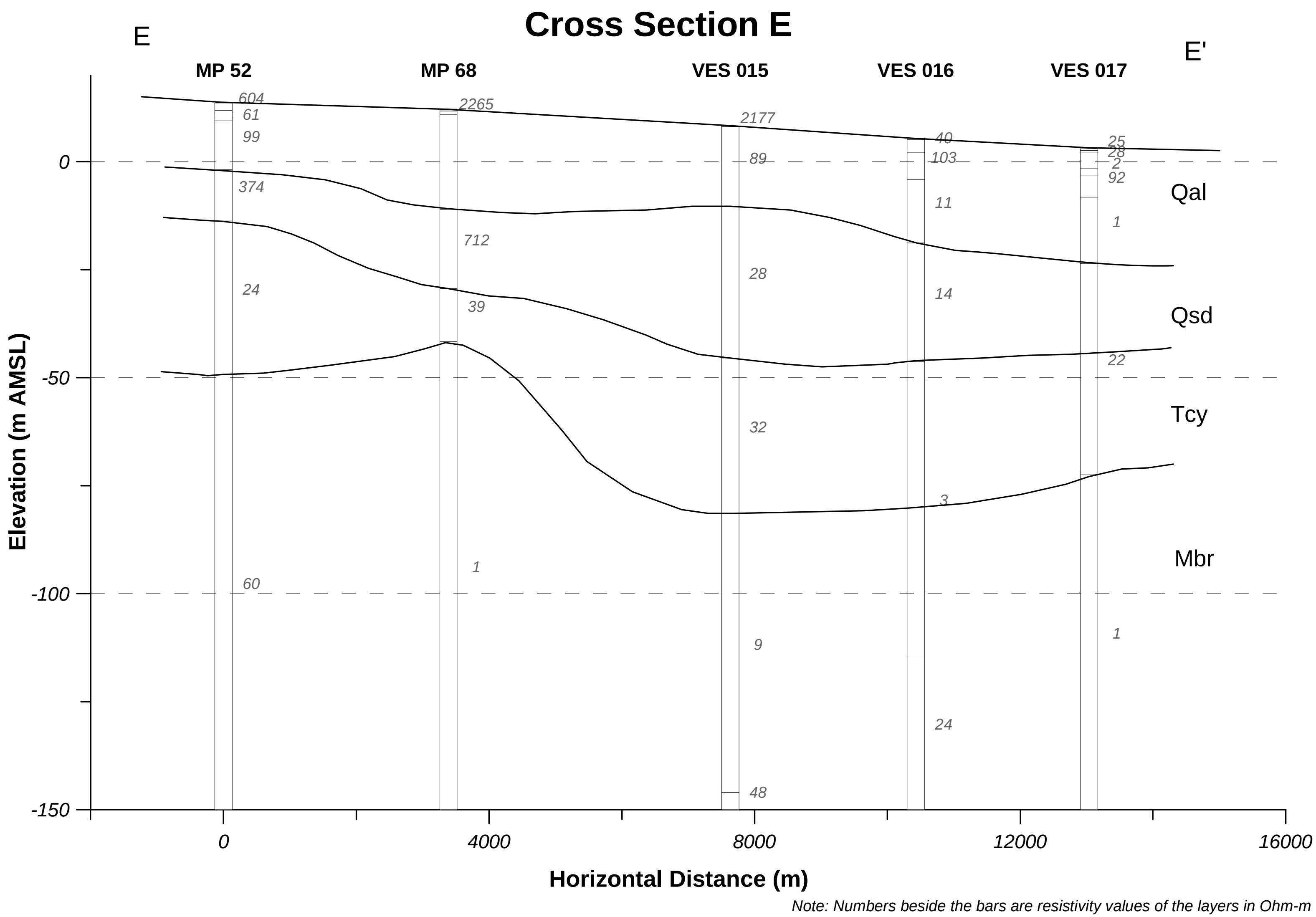


Figure 2.7 Cross-sectional View of the Layered Structure in the Surveyed Area (5/8)

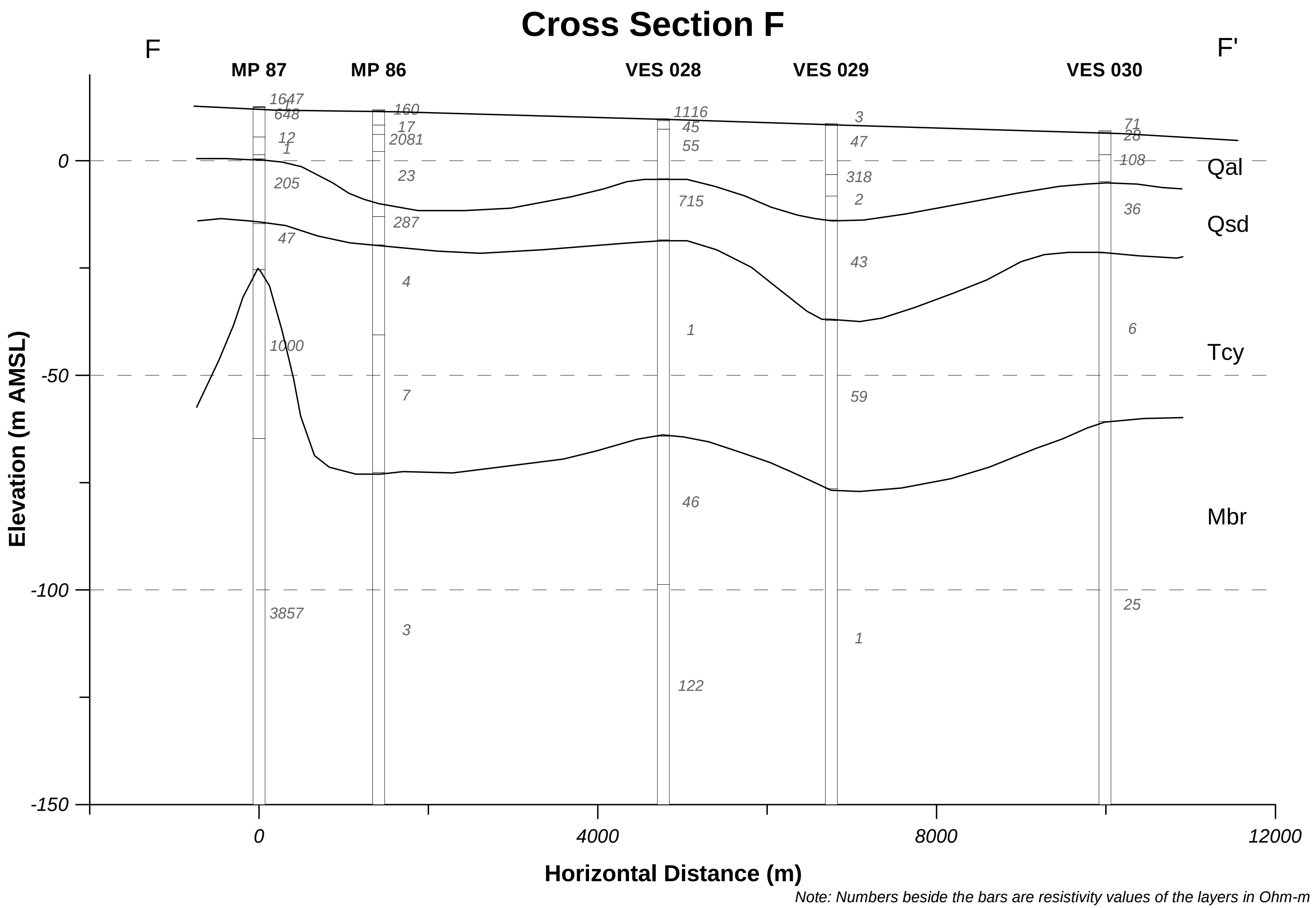


Figure 2.8 Cross-sectional View of the Layered Structure in the Surveyed Area (6/8)

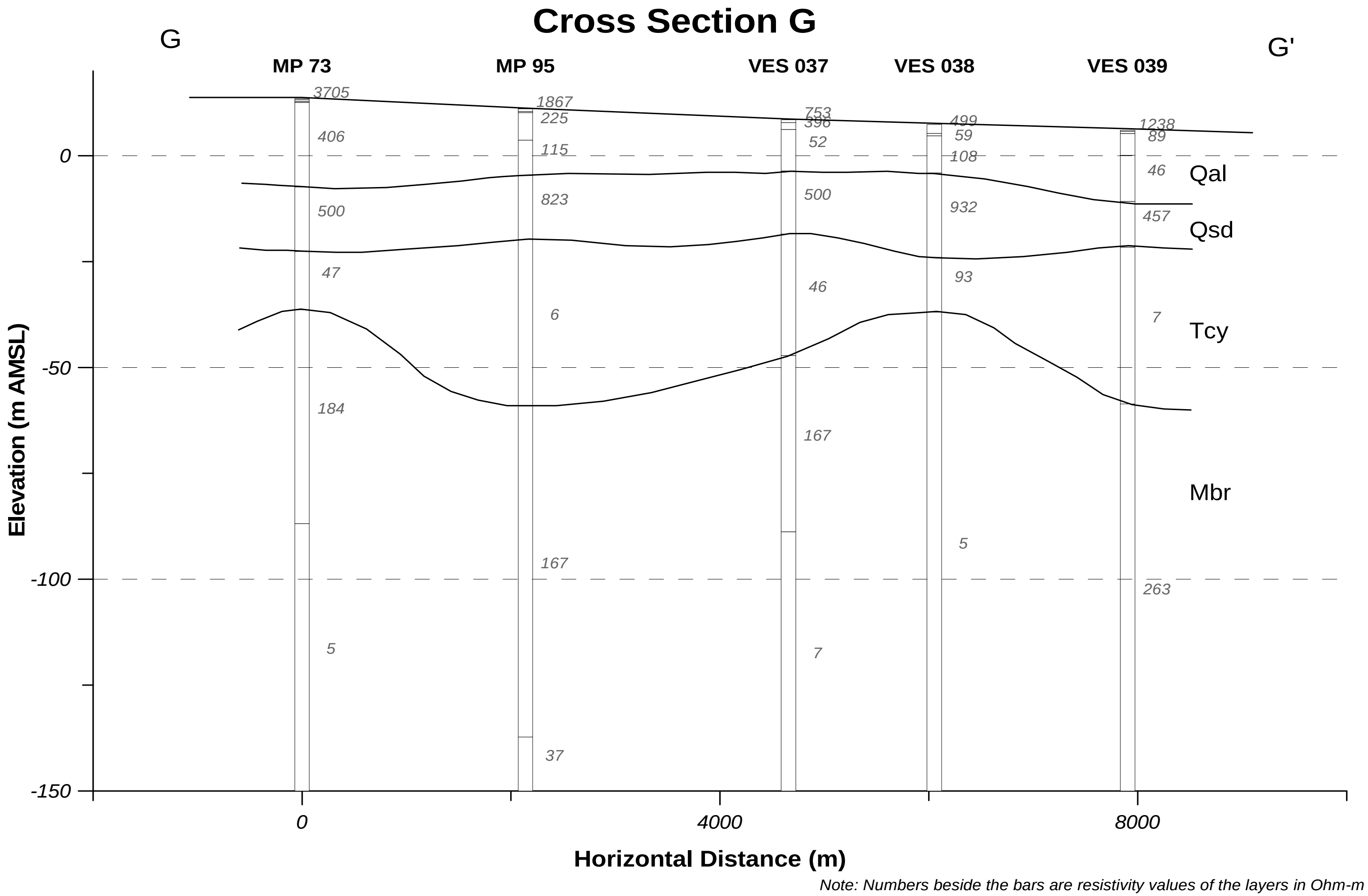


Figure 2.9 Cross-sectional View of the Layered Structure in the Surveyed Area (7/8)

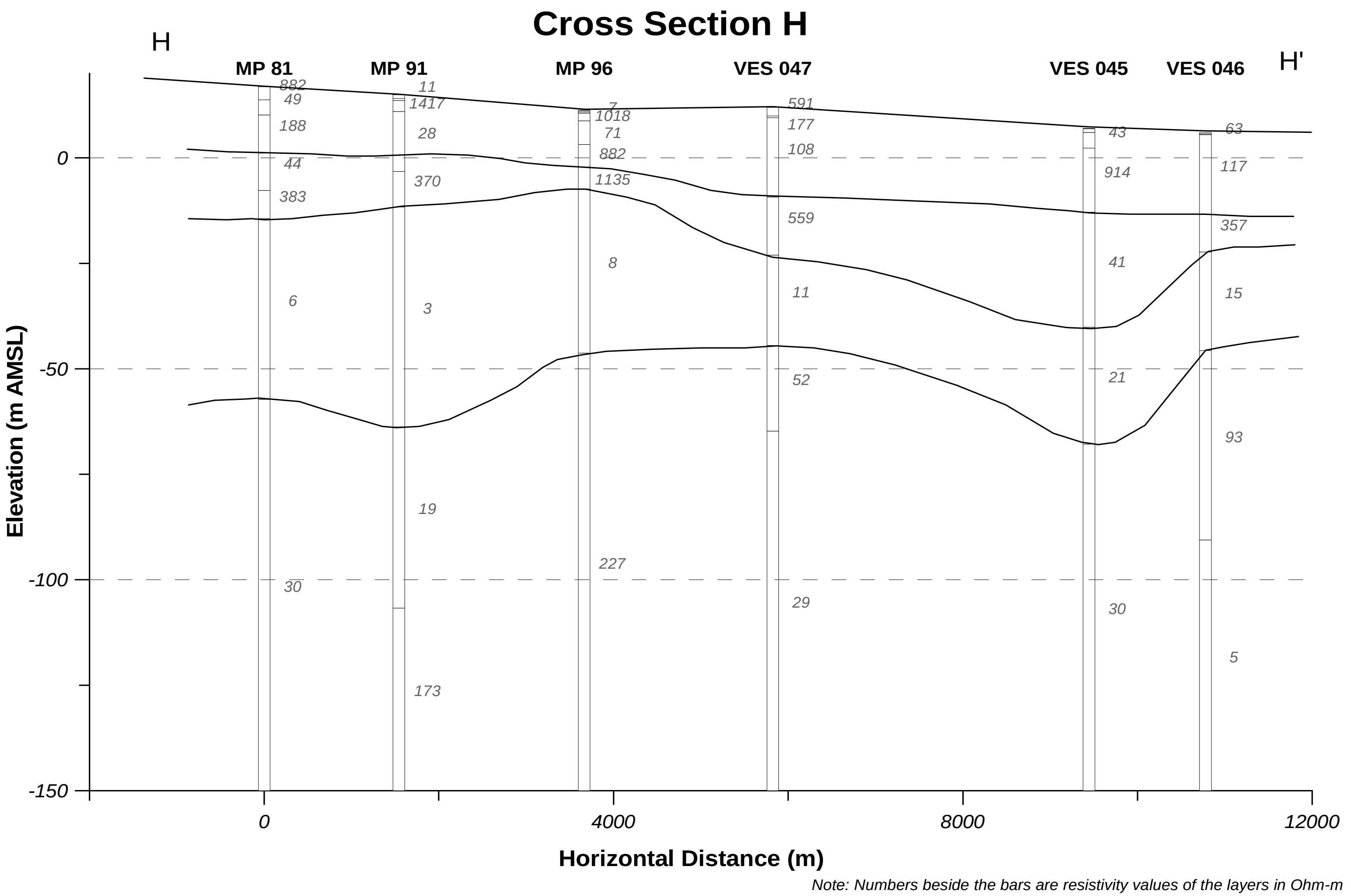
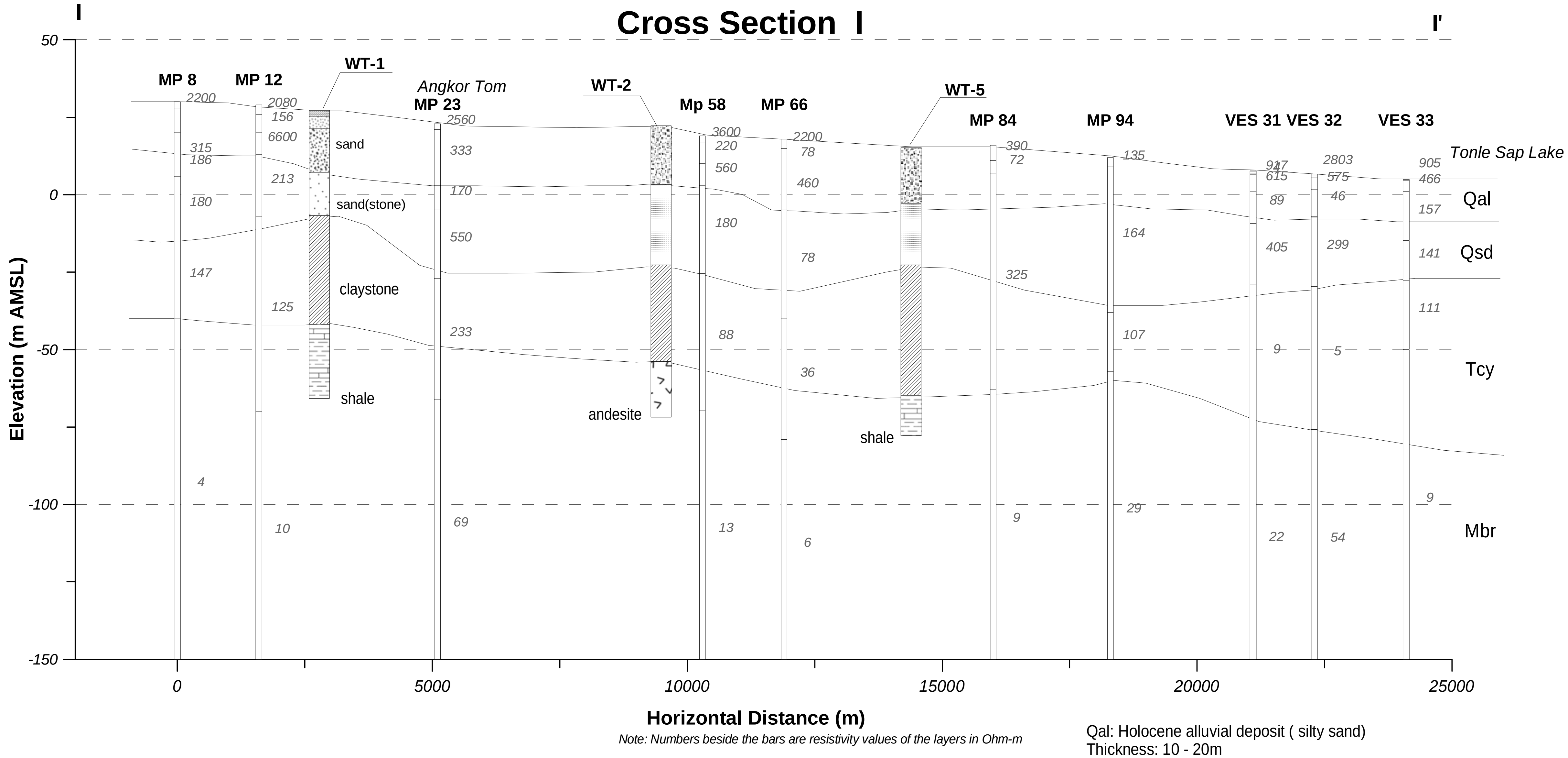


Figure 2.10 Cross-sectional View of the Layered Structure in the Surveyed Area (8/8)



Qal: Holocene alluvial deposit (silty sand)
Thickness: 10 - 20m
Aquifer (K = 1.9 - 1.7 x 10^{-2} cm/sec)

Qsd: Plistocene deposits (silt-clay with coase sand and gravel at the bottom)
Thickness: 10 - 30m
Aquifer (K = 1.9 - 1.7 x 10^{-2} cm/sec)

Tcy: Pliocene sediment (sandy clay stone)
Thickness: 20 - 50m
Aquiclude - aquifer

Mbr: Mesozoic bedrock(shale, tuff, andesite)
Thickness: unknown

Figure 2.11 N-S Cross-Sectional View of the Interpreted Geology and Hydrogeology in Siem Reap

2-2 Well Inventory Survey

2-2-1 Background and Outline

(1) Background

This survey was conducted for the purpose of assessing the influence of lowering of groundwater table on the cultural remains in Siem Reap, and also to obtain basic data for groundwater use and demand estimation. The survey targets are large consumers of groundwater such as hotels, restaurants and schools, and an interview survey was conducted using a structured questionnaire. Since this survey and the water use awareness survey share the same survey targets and items to ask, these two surveys were conducted together.

Table 2.3 Outline of the Inventory Survey

Survey period	July 22 to August 29, 2009
Survey method	• Interview with structured questionnaire • On-site measurement
Major survey items	1. Basic information of the site 2. Basic information of the water supply system 3. Well Structure and water use 4. Water use awareness 5. Water quality
No. of survey targets	Total 280

The outline of the survey is summarized above and the location of surveyed establishments is shown in Figure 2.12.

Table 2.4 Surveyed Establishments by Category

Establishment	Detail	Q'ty	Total
Hotel		75	190
Guesthouse		115	
Restaurant		40	40
Factory/Manufacturer		10	10
Other	Car wash	31	40
	School	4	
	Entertainment	4	
	Clinic	1	
Total			280

(2) Survey Target

The survey targets are mainly large commercial and public establishments that have a groundwater drawing system (borehole with a motor pump). The survey was sub-contracted to a local consulting firm and a total of 280 establishments were surveyed as shown in Table 2.4.

The survey targets were selected based on the list of hotels/guesthouses and restaurants registered under the Ministry of Tourism (December 2008) and on some other data that was available. In principle, larger water users were preferentially selected as survey targets within each category. It turned out, at the beginning of the survey, that many hotels and guest houses were already connected to the public water supply and had stopped using groundwater. Thus, these hotels were excluded from the survey. The study team obtained a list of customers from SRWSA, in which a total of 314 establishments are registered (61 hotels, 43 guest houses, 190 restaurants).

(3) Survey Method

The survey was conducted by two teams that are made up of two interviewers. The teams visited the person responsible, generally the manager or the owner, at each establishment and conducted an interview with a questionnaire form. The questionnaire form was first prepared by the study team and field tested and modified before it was actually used for the survey. The teams also conducted measurement of water levels in wells and checked the quality of water using a field test kit and portable pH and EC meters. The copy of survey sheets used for the work is attached in the Supporting Report.

(4) Survey Contents

The questions in the survey sheets are grouped into five sections. The following is the description of purposes and contents of each of the sections.

Section 1 (Basic information of the site): this section is about basic information of the establishment that is surveyed. Its type, size, name and contact number etc. are surveyed through interview with the owner or the manager.

Survey Items	Name of establishment, GPS data, Elevations, etc.

Section 2 (Basic information of the water supply system): this section is about basic information of the water supply system of the surveyed establishment. Type, use, capacity of the system etc. are asked and also installation/construction date is confirmed through interview and actual site inspection.

Survey Items	Water source type, Purpose of use, No. of wells, Pump type, With/without of treatment system, etc.

Section 3 (Well inventory): this section is about the structure, operation and performance of the boreholes (with a pump) that are the main water source of water supply in Siem Reap. When the establishment has several wells, they are named A, B, and C and separately surveyed. The questions will provide vital data on groundwater use by the establishments. Questions about operation and construction cost of the water supply system, and also a question on “ease of switching to public water supply system” are asked in this section, in order to help assess the possibility of shifting to the public water supply in future.

Survey Items	Well depth, Casing diameter, Screen depth, Pumping rate, SWL, DWL, Operating hours, Total O & M cost, etc.

Section 4 (Water use awareness survey): is mostly about the social aspects of groundwater use. The questions are designed to reveal the awareness of the users of negative groundwater issues caused by excessive groundwater pumping and their intention to switch to the public water supply system.

Survey Items	Satisfaction (Amount, Quality), No. of O & M person, Technical problems, etc.

Section 5 (Water quality test): is about the quality of water from the water supply system of the surveyed establishments. The water samples are taken either directly from the well or from the reservoir tank to check if there are any quality problems (above standard items). This section will provide data on natural groundwater conditions and also is expected to find any water quality issues that may prompt users to shift to the use of public water supply system.

Survey Items	EC, pH, Fe, Mn

The list of questions along with the explanation for each question given to the survey team is attached as Table 2.2.1, 2.2.2, 2.2.4 and Figure 2.2 in the Supporting Report.

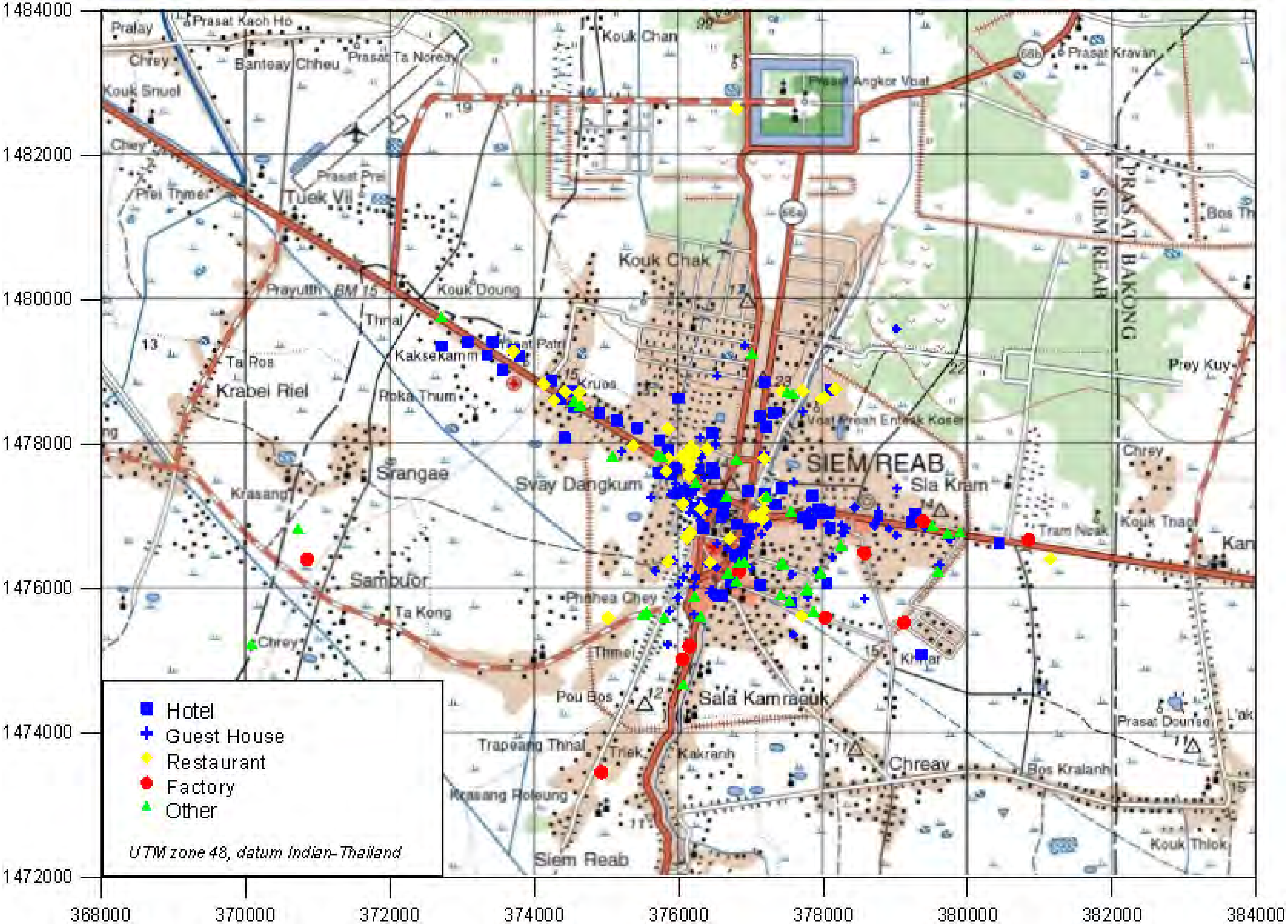


Figure 2.12 Location of Surveyed Establishments

2-2-2 Results

The following sections give detailed explanation of major finings extracted from the result of the analysis of the survey data. A more comprehensive list of findings is also presented as Table 2.15.

(1) Water Supply Facilities and Water Use

The water source for all the surveyed establishments has been found to be boreholes (tube wells) of at least 20 m deep. Approximately 15 % of the hotels and guest houses have more than two wells and the same ratio for restaurants and factories is approximately 23 % and 50 % respectively. Most establishments under category "Other" use only one well. A substantial proportion (around 35 %) of hotels, guest houses, and restaurants are also connected to the public water supply system. They generally use the public water supply as a backup or for specific purposes and thus the use of public water supply by these establishments is limited.

Table 2.5 Average Number of Wells and Depth of Wells

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

(Note) * depth of the main well (“well A” in the survey sheet) if there are more than 2 wells.

The depth of the wells ranges from 20 to 80 m and the average depth for hotels and factories are around 45 m and around 30 m for the other types of establishments. Few wells are equipped with a water meter or an observation pipe (only about 4 % of the total). On the other hand, the use of water treatment is common in hotels and factories and over 90 % have water treatment facilities. The most commonly used treatment is sand filtration and it accounts for 40 to 60% of all the treatment facilities for all categories. At most establishments, the water is pumped up by an automatically operated ground pump to an elevated water tank and then distributed by gravity.

As anticipated somewhat, it was found difficult for the interviewees to provide any reliable information on the amount of water they use every day. Therefore, in most of the cases the surveyors had to estimate the amount of daily water use based on the capacity of the pump, the size of reservoir tank, and the operation hours of the pump. The results are summarized in the following table.

Table 2.6 Estimated Daily Average Water Use Amount by Category (m^3/day/establishment)

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

The water consumption is higher during the dry season and lower in the rainy season for all the categories except for “Other” due to extra consumption to cope with increased number of tourists. The reason for the decreased water use amount under “Other” is that most of the surveyed establishments are car wash places and cars become dirty less often during the dry season.

The survey team obtained information about the location of screen casings at 49 establishments across the categories. According to this data, boreholes are screened at no shallower than 16 m and the average length of the screen casing is 9.6 m. The distribution of the screen location is illustrated in Figure 2.13. Most of the wells (80 – 90 %) were constructed after the year 2000 at the time the buildings were constructed.

For pumping groundwater, a ground pump of around one (1) Kw capacity is commonly used for guest houses and restaurants and those of four (4) Kw capacities for hotels and factories. The pumps are generally automatically operated by the water level sensor in the reservoir tanks. Submersible pumps are only used at large hotels (36 %) and some factories (30 %). The prevalence of use of ground pumps suggests that the water table is generally high and rarely goes down below 10 m in the surveyed area.

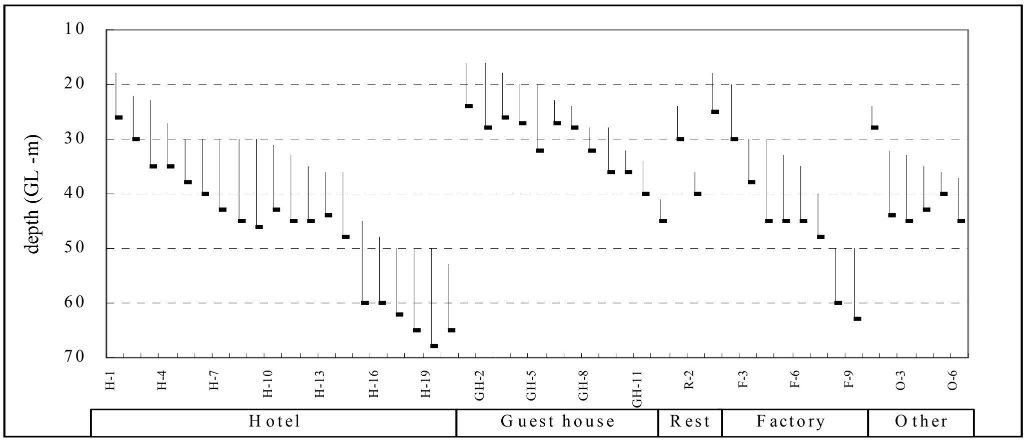


Figure 2.13 Distribution of Well Screen Location by Category

Static water levels of the wells were measured at majority of hotels (92 %) and Factories (80 %) either through the opening between the casing pipe and the pump riser pipe or using the observation pipe. The result of the measurement at “well A”, the main well, is summarized in the table below.

Table 2.7 Measured Static Water Level of Main Well by Category

(GL-m)

	Min	Max	Mean	Mode	STD
Hotel (Borehole A = 69)	1.30	2.90	1.76	1.60	0.34
Guesthouse (Borehole A = 27)	1.35	2.20	1.68	1.60	0.22
Restaurant (Borehole A = 5)	0.85	1.90	1.50	NA	0.43
Factory/Manufacturer (Borehole A = 8)	1.50	2.30	1.73	1.60	0.25
Others (Borehole A = 19)	1.40	2.20	1.78	1.80	0.24

(Note) STD: standard deviation

The static water levels measured during the survey range between 0.85 m and 2.9 m and the average for each category is quite uniform, being around 1.7 m. The static water level for the dry season was only obtained at two hotels where they keep the record. The data shows that the water level is about 1.5 m deeper at both sites in dry season. The dynamic water level was found difficult to measure properly due to the limitation of pump operation time that is automatically controlled. Thus the measurements were done at about 40 % of the establishments across the category and typically after 15 to 20 min of pump operation. The results are summarized in the table below.

Table 2.8 Measured Dynamic Water Levels (GL - m^{-})

Category	Hotel	Guest house	Restaurant	Factory	Other
Rainy Season Mean	6.2	5.82	3.37	7.14	7.24

(2) Water Use Awareness

Section 4 of the survey is designed to understand the perception of the interviewees on the groundwater use and to find out their intention to connect to the public water supply system in the future. The survey revealed that the majority of the hotels, guest houses, and restaurants are aware of the possible negative effect (lowering of groundwater level and occurrence risk of land subsidence) of groundwater withdrawal on the environment. On the other hand, establishments under the other two categories are not quite aware of this issue. This is perhaps due to the effect of the environmental education designed for these tourist related businesses.

Table 2.9 Ratio of Awareness on 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 water supply system when it becomes available and can supply enough water volume. The main reason is to cut down the operational cost of current groundwater pumping system. Although it was assumed that the public water supply will provide stable and good quality water at a reasonable cost, some respondents raised concern about the service interruption. Also, many establishments are not satisfied with the quality of water they use, and expect that they will receive water of better quality from the public supply system.

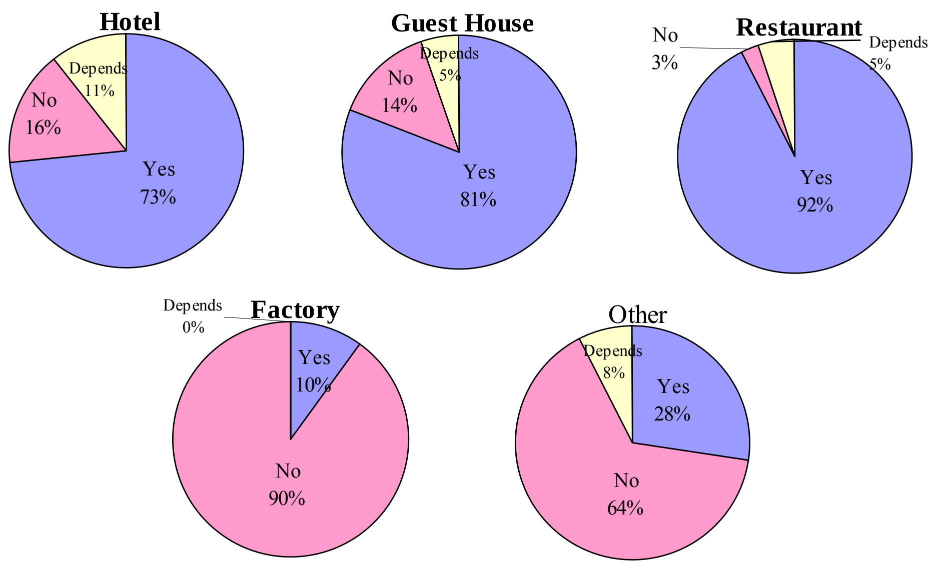


Figure 2.14 Ratio of Intention of Connection by Establishment Type

As can be seen from Figure 2.14, there is a contrasting difference in the responses between Hotel/Guest house/Restaurants and the other two categories. More than 70% intends to connect to the public water supply system for the first group, but the situation is the opposite with the latter group. Of those that answered "depends" for intention of connection, two raised usability and the other 16 raised "cost" as the condition.

Many of those who answered "Yes" to this question mentioned that they expect cleaner water from the public water supply system. They also mentioned environmental-friendliness of that option. It seems that those establishments (hotels, guest houses, restaurants) that heavily depend on tourism are much more conscious of the groundwater issues that might eventually affect tourism.

(3) Water Quality

The following items of water quality were tested at each establishment using field test kit and potable meters.

Table 2.10 Items of Analysis and Method

Item	pH	EC	Fe	Mn
Method	Portable pH meter	Portable EC meter	Pack test	Pack test

The water samples were taken mostly from the reservoir tanks before any treatment and some were taken directly from the wells. Thus the samples are considered to represent the groundwater at the site. pH and EC are the most basic indicators of water quality and Iron (Fe) and Manganese (Mn) were tested because of the reported high concentration of these items in the groundwater in past studies.

The overall variation of water quality with depth of well is not great. However, as can be seen in the following figure, the shallow groundwater is characterized by 1) higher iron and manganese contents, 2) higher EC values, and 3) lower pH values. The quality of groundwater from deeper wells tends to be relatively better in these respects.

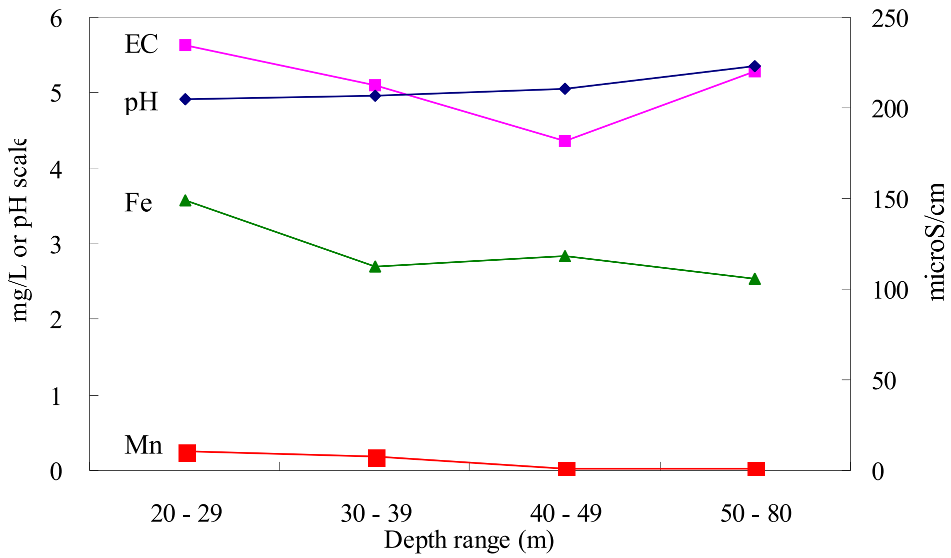


Figure 2.15 Quality of Water by Well Depth

Shallow well users are mostly small establishments that cannot afford expensive water treatment facilities. Thus, they suffer from the water with high iron concentration. This can be also demonstrated in other questions about satisfaction with water quality, where only 38 % of the guest houses and 15 % of restaurants answered that they are satisfied, as opposed to 88 % satisfaction ratio by hotels. These small establishments are considered highly motivated to switch to the public water supply system when it is in place.

(4) Database Construction

The information for the 280 surveyed establishments have been converted to a MS-Access database and handed over to SRWSA. The specification of the database is summarized below.

Table 2.11 Summary of the Database

Title	Well Inventory of Large Groundwater Consumers
Software	MS-Access
Record number	280 records in text and number
Contents	11 tables corresponding to each section in the questionnaire except for section 4 (water use awareness survey)
Query	9 default queries
Language and units	English and metric system
Positional information	The data comes with GPS coordinates for each record and can be integrated into a GIS

The structure of the tables and list of queries are given in the Supporting Report.

(5) Important Findings from the Inventory Data

1) Present groundwater use amount

The total amount of daily groundwater use in Siem Reap at present (year 2009) can be estimated using the data obtained in the well inventory survey. Since the groundwater is used by the large commercial and public establishments surveyed in the well inventory survey and also by smaller establishments and ordinary houses (domestic users), the total amount is the sum of water use amount by the two main groups of users. In this report, the following set of data and conditions were adopted to estimate the daily groundwater use amount for both dry and wet seasons.

Table 2.12 Summary of Estimated Present Groundwater Use Amount in Siem Reap

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 in 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 (see table 2-6). - 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 , 0.120 m^3/day/capita for dry season
Total	29,216	35,213	

(Note) It should be noted that the figures for the total groundwater consumption calculated here are those of the collective consumption by domestic users, commercial users, and tourists regardless of the types of supply facilities. In other words, the groundwater consumption by SRWSA customers is also included.

2) Cost of operation and maintenance (O/M) for groundwater supply facilities

In the inventory survey, the cost of operating and maintaining various types of water supply facilities of each establishment was roughly estimated by the interviewers by using the information they obtained during the site visits. The monthly operation and maintenance cost estimated here consists of labor cost and energy cost in addition to other regular running costs such as the cost for chlorine (disinfectant) and minor repair costs. The obtained data for monthly average O/M cost and installation cost of water supply facilities were used to estimate the unit water production cost (US$ per one cubic meter of water) for each category of the five establishments. Since the total cost of unit water production over a long period (15 years) is considered, major repair cost was included in the calculation. The following two cases of different ratios of major repair cost were evaluated.

Case A : Major repair cost is 30 % of the total installation cost, 3 times over 15 years

Case B : Major repair cost is 35 % of the total installation cost, 3 times over 15 years

The results are shown in the tables below along with the average water use amounts, the O/M cost, facilities installation cost obtained in the survey, and the calculated major repair cost for the category. The unit water production costs are shown in the bottom (row F).

Table 2.13 Summary of Water Production Cost of Groundwater Users (Case A)

	Category	Hotel	Guest house	Restaurant	Factory	Other
A)	Average water use in WS (m^3/day)	30.35	4.62	8.89	39.00	8.89
B)	Average water use in DS (m^3/day)	47.27	5.65	9.91	85.4	8.51
C)	Average O/M cost (US$/month)	413	59	169	491	203
D)	Average installation cost of water supply facilities (US$)	45,686	6,261	1,923	32,778	6,267
E)	Average cost for major repair of facilities (US$)	41,117	5,635	1,731	29,500	5,640
F)	Average unit water production cost (US$)	0.781	0.802	0.734	0.446	1.028

Table 2.14 Summary of Water Production Cost of Groundwater Users (Case B)

	Category	Hotel	Guest house	Restaurant	Factory	Other
A)	Average water use in WS (m^3/day)	30.35	4.62	8.89	39.00	8.89
B)	Average water use in DS (m^3/day)	47.27	5.65	9.91	85.4	8.51
C)	Average O/M cost (US$/month)	413	59	169	491	203
D)	Average installation cost of water supply facilities (US$)	45,686	6,261	1,923	32,778	6,267
E)	Average cost for major repair of facilities (US$)	47,970	6,574	2,019	34,417	6,580
F)	Average unit water production cost (US$)	0.815	0.835	0.745	0.460	1.048

Assumptions and equations applied:

- Duration of wet season (WS) is six months (May to October), One month is 30 days, One year is 365 days
- Installation cost is answered in a range and the range top figures are employed for calculation of D
- Amortization period is 15 years, Major repair required every 5 years costing 30 % and 35 % of the installation cost for Case A and Case B respectively,
- O/M cost = chlorine (disinfectant) and minor repair costs + Labor Cost + Energy cost

Formula to find unit water production cost : $F = [C/30 + (D + E)/(15 \times 365)] / [(A + B)/2]$

The result reveals that the production cost of one cubic meters of water differs from category to category. Factories that generally use large scale facilities are most efficient producers and "other" which is made up mostly of car wash stands is the least efficient producers. These figures are also larger than the current water tariff of public water supply system.

Table 2.15 Major Findings from Well Inventory Survey

Category	Findings
General	・280 big water consumers were surveyed based on the lists of establishments obtained.
Water supply facilities	・All the water sources are tube wells of at least 20 m with either a ground or a submersible pump. ・*Majority (77 %) of establishments use only one borehole for water supply.* ・*The average number of wells for hotels and guest houses is 1.37 for and 15 % of them has more than 2 wells.* ・Less than 4 % of the establishments have water meters or observation pipes installed at their wells. ・A little over 30 % of hotels, guest houses, and restaurants use both groundwater and public water supply. ・*The average depth of wells is around 44 m for hotels and factories, and around 30 m for the other categories.* ・Commonly used casing pipe is of 100 mm diameter for hotels and Factories and 49 mm for other categories. ・Ground pumps are commonly used for all the categories but up to 36 % of hotels and factories also use submersible pumps. ・Water treatment facilities are commonly used in large hotels and factories and the common type is sand filtration and related system. ・Most of the systems were constructed after the year 2000 at the time of construction of the buildings ・*The screen location varies depending on the depth of the well and average length is 9.6 m.* ・*The static water levels were measured to be around 1.5 m and maximum is 2.9 m below ground.* ・*The dynamic water levels were around 6 to 7 m below ground.* ・Majority of establishments (except for Factories) responded that it is either easy or moderate to connect to the public water supply system in terms of construction work. ・Majority of hotels (75 %) use both commercial and generator for power supply while majority of guest houses (86 %) depends only on commercial supply.
Water use and use amount	・Daily water use had to be estimated due to lack of water meter or reliable record. ・*Hotels and factories are the large water users with 30 to 40 m^3 of daily use.* ・*All establishments use 1.1 to 1.5 times more water during the dry season except for car wash sites* ・*Factories are large users of water although their number is small.* ・Large restaurants use more water ・*The water from both borehole and public supply is used mainly for general (multi) purposes.*
Awareness of environmental issues	・Large establishments are mostly satisfied with both quantity and quality of current water supply but small establishments are less satisfied, especially so about the quality. ・*Hotels, guest houses and restaurants are highly aware of the environmental issues (lowering of groundwater level and land subsidence) concerning groundwater use.*
Intention to switch to piped water supply by SRWSA	・*Majority (70 to 90 %) of hotels, guest houses, and restaurants intend to switch to the public water supply system while factories intend to keep using groundwater.* ・*Those that responded "depends" raised cost and usability as the conditions.* ・The reasons for switching are the environmental obligation and also usability.
Water quality	・*The water quality is similar to that of the city and surrounding area that is characterized by sporadic high iron contents and low pH.*

(Note) *The items in italic are discussed in more detail in this report

2-3 Field Water Quality Test

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 location of sampling is shown in Figure 2.16.

Table 2.16 Items of Analysis and Method

Item	pH	EC	Fe	Mn	NH_3-N
Method	Portable pH meter	Portable EC meter	Pack test	Pack test	Pack test

Most of the wells for the water quality test are tube wells equipped with an old steel suction hand pump and the depth of the wells ranges from 5 to 30 m. Some samples were also taken from open hand-dug wells with concrete lining and tube wells with a ground engine pump.

The EC values are generally very low (acidic) except for some open hand-dug wells. Some wells showed an iron concentration of as high as 8 mg/L but it seems to be limited to small areas as shown in Figure 2.17. Nitrogen in ammonium form (NH_3-N) is one of the indicators of immediate contamination by animal/human discharges and by fertilizers. The values are generally less than 0.2 mg/L with less than drinking standards. The following table compiles the results of the water quality test for the three areas along the southern margin of Siem Reap City: East of Siem Reap River, West of Siem Reap River and the area around Phnon Kroam hill.

Table 2.17 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*	*1600*	*0.3*	*0.1*	*1.5*
East	5.43	48	1.21	0	0.18
West	5.60	83	2.08	0	0.15
Phnon Kraom	4.90	518	0.45	0.17	0.15

(Note) water from hand-dug wells is not included in these calculations
* Drinking water quality standards, January 2004, Ministry of Industry, Mines, and Energy

Generally, the water quality of these areas is similar to that in the other parts of the city and its surroundings. As it has been known, it is characterized by low pH values and sporadic high Iron concentrations (see Figure 2.17). In every area, average values of pH and iron concentration exceed drinking water quality standards and it may need water treatment for drinking. It should be noted that this result is based only on field measurements and more detailed water quality analysis should be done in the case of developing the groundwater in these areas.

2-4 Survey Result of Core Samples

Under this study, a monitoring well (shallow well) was constructed in the premise of Kravan primary school on October 2009 and two monitoring wells (shallow and deep wells) were constructed in Khvein primary school on October 2009 and May 2011, respectively.

At the same time, in the same locations as the monitoring wells, a core boring of 80 m in depth were conducted at each site on October 2009 and the observation survey for the core samples was followed on January 2011. In addition, in the observation survey, core samples which JSA (Japanese Government Team for Safeguarding Angkor) carried out in the yards of Angkor ruins (Angkor Wat and Bayon shrine) in 1995 were also observed as reference samples.

The survey results were different from accepted concept on geological structures in Siem Reap area based on the study results of “the Study on Water Supply System for Siem Reap Region in Cambodia (2000)”, namely, geological structures that Quaternary formations of Alluvium and Diluvium were underlain by claystone (equivalent formations of Tertiary). Claystone in the core samples by this observation survey could not be observed.

According to the above study (2000), in Siem Reap area, geological structures are made up of 4 ones: Alluvium and Diluvium are distributed in the depth of ground surface to about 30 m to 50 m and are underlain by Tertiary formations with layer thickness of about 40 to 50 m, and basement rocks of sandstone, siltstone, shale, and tuffaceous breccia of Upper Jurassic, andesite, basaltic intrusive rocks, and diorite of Late Mesozoic to Tertiary are distributed in the depth of about 70 m to 80 m.

However, the observation results of the core samples in both sites of Khvein and Kravan led to the following results: (1) In the depth around 40 m, change of formation facies which clearly divide between Diluvium and Tertiary formations together with the boundary of both formations cannot be recognized and it can be deemed to be consecutive formations. (2) Formations equivalent to Tertiary formations does not exist in core samples as a result of core observation. .

Outline of observation results of core samples are as follows: Observation results of core samples (columnar sections) are shown in Supporting Report, Chapter 3, SR 3-2 (1) Survey Results of Core Samples in Khvein and Kravan Sites, and Observation Result of Core Samples of Angkor Ruins.

(1) Khvein Site

Clay layer is distributed in the depth of ground surface to 5 m. Under this layer, alternating layers of sand, sandy clay, and clayey sand with layer thickness of 1 m to 4 m are distributed. In the depth of 50 m to 63 m, these alternating layers are underlain by thick clay layer with layer thickness of about 12 m with interbeded layers of thin clayey sand (sandy clay) in the depth of 58 m and of 61m to 63 m. In the depth of 63 m to 80 m, fine sand layers are distributed.

According to this survey, in the depth around 40 m, there was no formation boundary between Diluvium of Quaternary and Tertiary formations and clay layer distributed in the depth of 50 m to 63 m is not consolidated stone such as claystone.

(2) Kravan Site

In the depth of ground surface to 7 m, alternating layers of silt, sandy clay, sand, and clay are distributed. Under the layer, up to the depth of 80 m, fine and/or medium sand layers are distributed.

As a result of this survey, in the similar way as Khvein site, In the depth around 40 m, there was no formation boundary between Diluvium of Quaternary and Tertiary formations and clay layer distributed in the depth of 50 m to 63 m was not consolidated stone such as claystone.

(3) Core Sample of Angkor Ruins

JSA carried out core boring survey of 100 m and 87 m deep in the yard of Angkor Wat (Sample No. AV-1B) and Bayon (Sample No. BY-1B) on March 1995 for ground investigation in Angkor ruins. Those core samples were stored in JSA office in Siem Reap City and observation survey for the core samples by this study was conducted to confirm underground geological structure in Siem Reap area on January 2011.

The core samples have been fairly consolidated by drying with passage of time of about 16 years since core borings were conducted. Further, there were many parts of no core samples by the reason why sand layer could not be sampled.

Observation results of core samples were as follows, (1) Basement rocks were observed in the depth of 74.20 m in Angkor Wat site, and in the depth of 83.50 m in Bayon site. (2) JSA Annual Report on the Technical Survey of Angkor Monument 1996 (July 1996) reported the change of formation facies between the upper layers and the lower layers in the depth around 40 m. However, in observation results by this survey with passage of time of about 16 years after core sampling, the change of formation facies between Quaternary and Tertiary formations could not be recognized. In addition, in these core samples, in the similar way to Khvein and Kravan sites, Formations equivalent to Tertiary formations could not be observed.

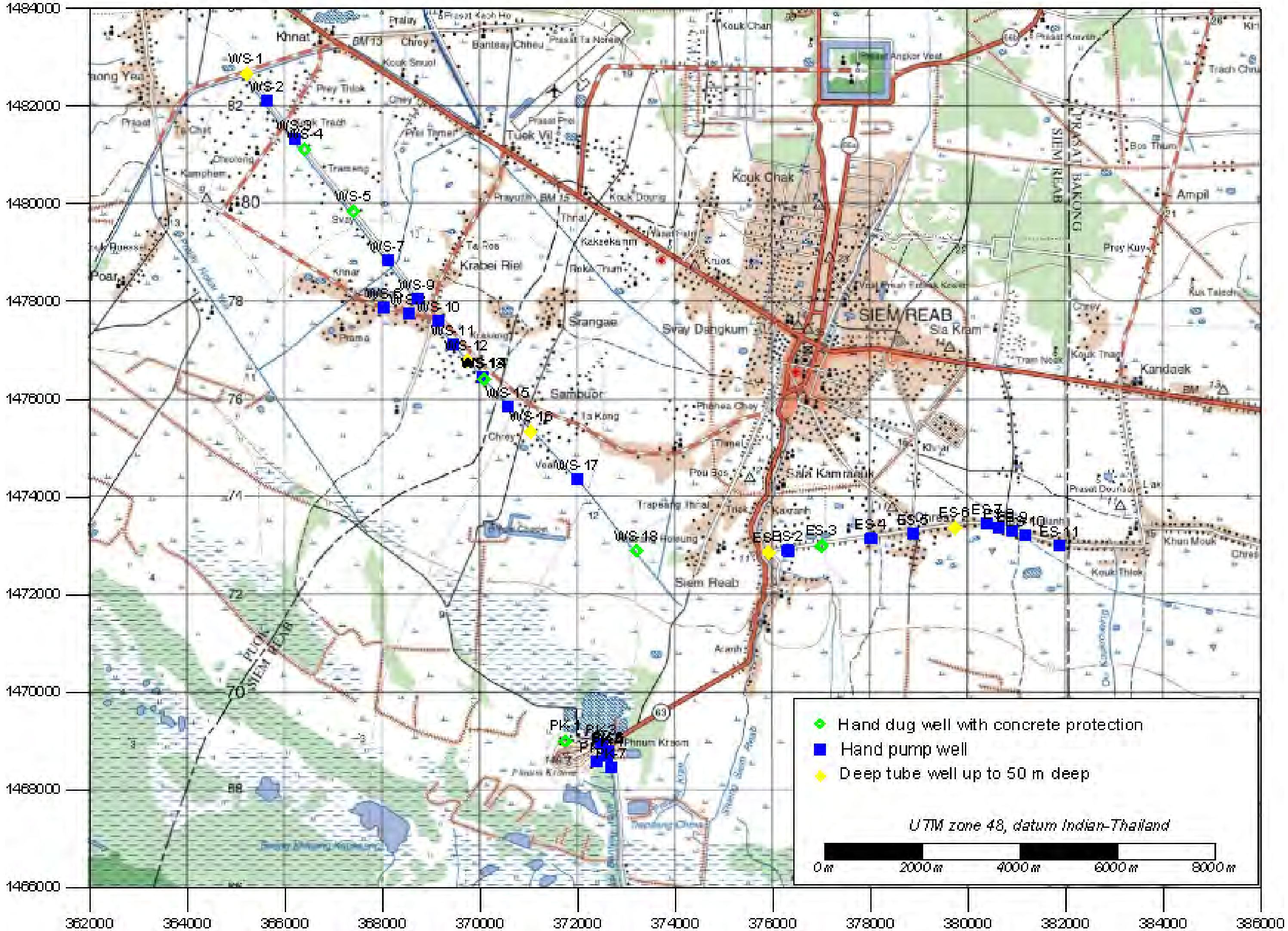


Figure 2.16 Location of Wells for Field Water Quality Tests

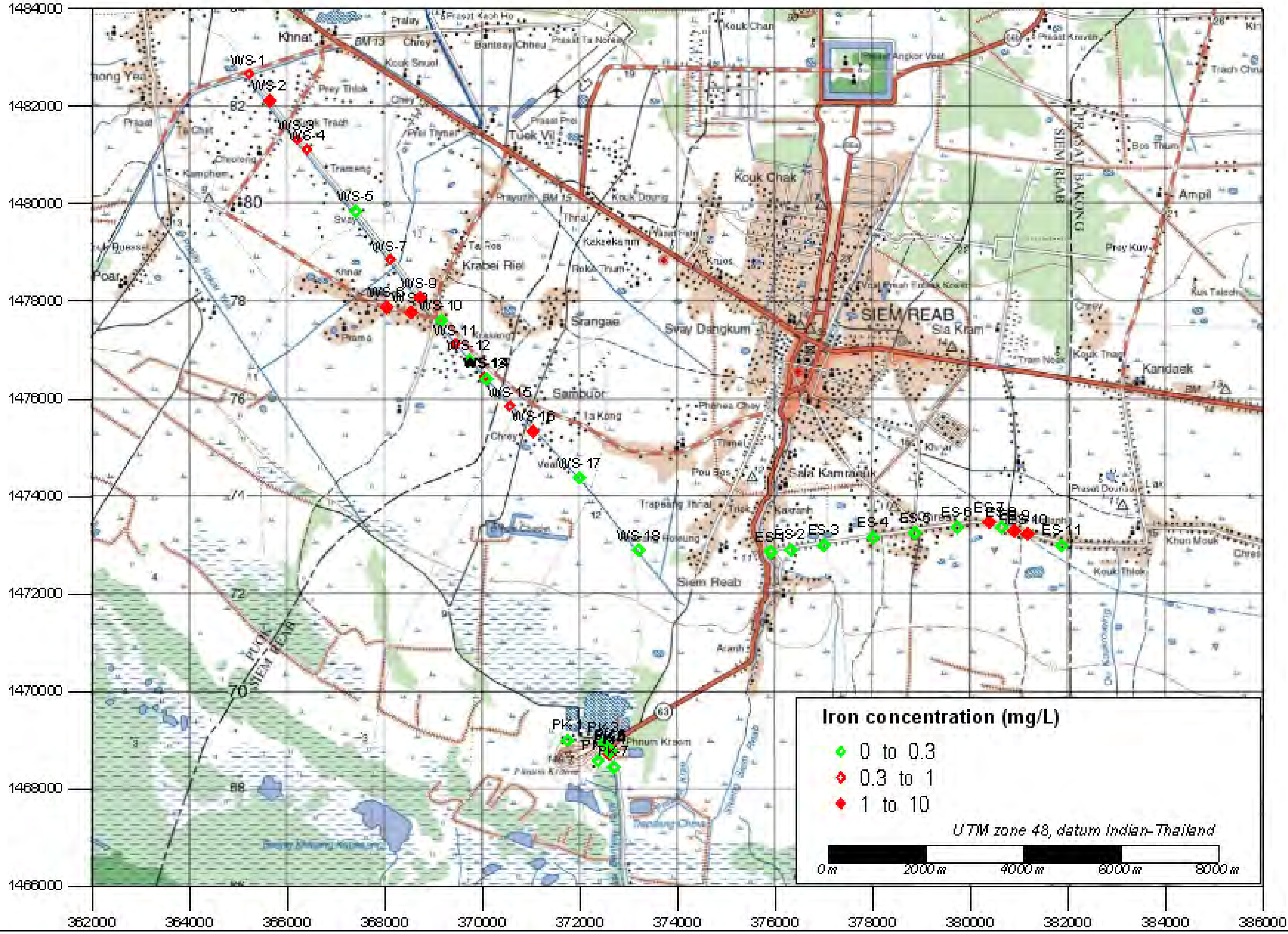


Figure 2.17 Distribution of High Iron Concentration Wells

Chapter 3.
Current Status of Groundwater Use

Chapter 3. Current Status of Groundwater Use

3-1 Present Status of Groundwater Monitoring

(1) Monitoring Activities of SRWSA

In the Study Area, 10 monitoring wells were constructed under the Study on Water Supply System for Siem Reap Region in Cambodia (2000) as shown in Figure 3.1. The monitoring wells are located in the school's yards and national parks in the heritage sites. An automatic monitoring system was employed by using data loggers with a solar buttery.

SRWSA has been collecting the monitoring data every month. Since July 2007, manual measurement of groundwater level has been conducted once a month to confirm the reliability and the accuracy of automatic monitoring systems.

However, as shown in the following table, activities done by SRWSA so far seems not necessarily enough in reference to recommendations made in the Basic Design Study Report on the Project for Improvement of Water Supply System on Siem Reap Town (2003). Recommendation conducted by the above Report and actual situations of SRWSA activities are shown in Table 3.2. In addition, existing monitoring wells, reliability of monitoring data, and necessity of calibration are shown in Table 3.3. SRWSA should take proper measures to improve this situation as described in Chapter 6, Conclusion and Recommendation.

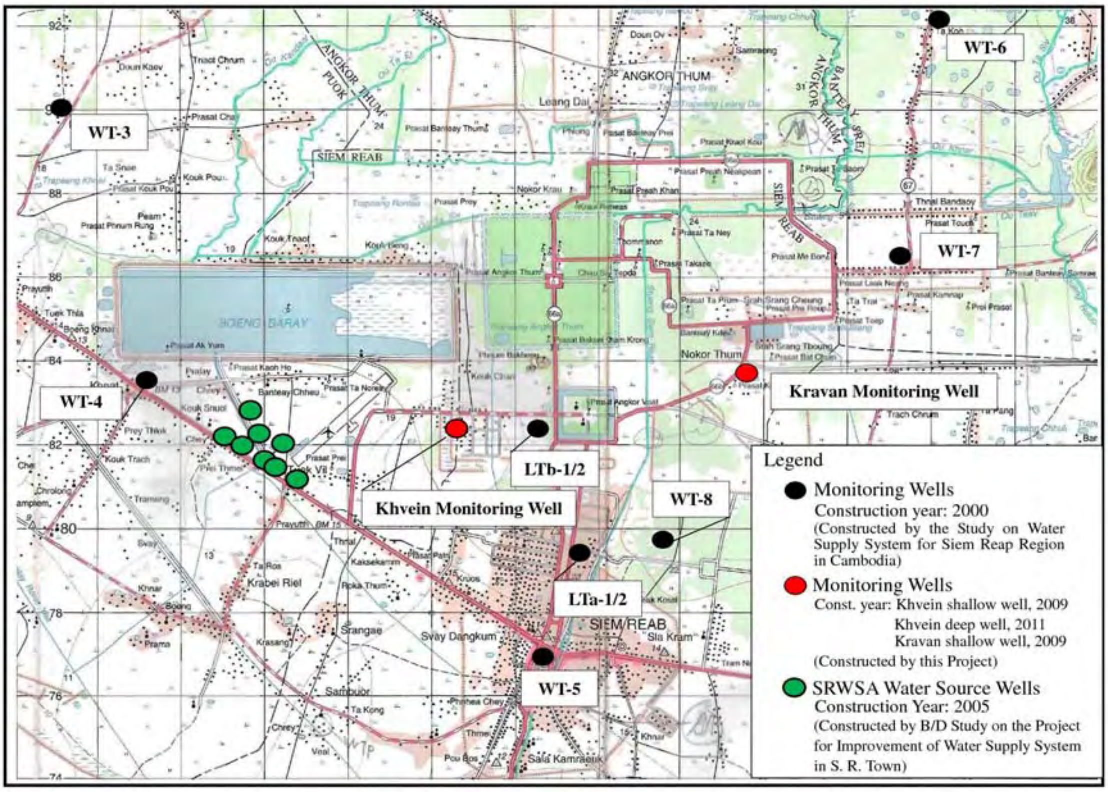


Figure 3.1 Location Map of New and Existing Monitoring Wells

The outline of monitoring wells is summarized in the following table.

Table 3.1 Outline of Monitoring Wells

No.	Well No.	Well Depth (m)	Casing Size and Materials	Screen Depth (m)	Remarks
1	WT-3	36	PVC 6"	20.38-32.20	
2	WT-4	29	PVC 6"	13.38-25.20	
3	WT-5	58	PVC 6"	42.38-54.20	
4	WT-6	29	PVC 6"	13.38-25.20	
5	WT-7	60	PVC 6"	44.38-56.20	
6	WT-8	83	PVC 6"	67.38-79.20	Under the building of New APSARA building (Now under construction)
7	LTa-1	72	PVC 6"	63.62-71.90	Measurment of Groundwater Level and land
	LTa-2	35	PVC 6"	26.61-34.90	Measurment of Groundwater Level and land
8	LTb-1	73	PVC 6"	64.61-72.90	Measurment of Groundwater Level and land
	LTb-2	40	PVC 6"	31.61-39.90	Measurment of Groundwater Level and land

Table 3.2 Monitoring Activities Done by SRWSA

No.	Recommendations made by 2003 B/D report*	Activities Done by SRWSA
1.	Proper O&M for the supplied monitoring facilities	Some damaged equipment are being left at the sites in disrepair, resulting in missing data.
2.	Making good use of the monitoring data	Data collection has been done; however, analysis on the collected data was not made.
3	Taking proper countermeasures when unusual monitoring data are found.	Manual measurement of groundwater level has been done since July 2007. However, detailed analysis on the collected data has not been conducted. For example, manual and automatic monitoring data were not compared even some malfunction items were found.
4	Disclosure of collected information	Due to difficulties of confirmation of data reliability, SRWSA has not disclosed the data till now.

(Note) 2003 B/D report*: Basic Design Study (report) on the Project for Improvement of Water Supply System in Siem Reap Town in the Kingdom of Cambodia (2003)

Table 3.3 Existing Monitoring Wells, Reliability of Monitoring Data, and Necessity of Calibration

No.	Well No.	Well Depth (m)	Available Monitoring Data Period	Current Operating Condition and Reliability of Monitoring Data	Necessity of Calibration of Monitoring Equipment
1	WT-3	36	2003/8-2008/4	• Removal of monitoring equipment excluding solar panel and lightning rod (2008/8/21) Removal Reason As WT-6 and LTa monitoring sites were more important than WT-3 site due to locations near the city center and/or many important ruins with no monitoring function, SRWSA transferred WT-3 equipment to them. • Transfer of WT-3 cable sensor to WT-6 site. • Transfer of WT-3 data logger to LTa site	After May 2005, There is no monitoring equipment.
				Reliability of monitoring data before removal of the equipment have good reliability..	
2	WT-4	29	2007/3-Present	Operational monitoring equipment	Necessity of calibration
				• Monitoring data (2007/3-2008/3) have good reliability. . • Monitoring data after the date of 2008/3 show low reliability.	
3	WT-5	58	2007/3-Present	Operational monitoring equipment.	Not necessity of calibration
				Monitoring data have good reliability.	
4	WT-6	29	2008/7- Present	Operational monitoring equipment.	Necessity of calibration
				Monitoring data show low reliability.	
5	WT-7	60	2003/8- Present	Operational monitoring equipment	Not necessity of calibration
				Monitoring data have good reliability.	
6	WT-8	83	2008/4-2010/9	• Operational monitoring equipment. • ASPARA museum building is under const-ruction. Monitoring facility is planned to be left in underground. Under the construction, the inside of monitoring facility was buried and submerged.	Necessity of calibration.
				Monitoring data show low reliability.	
7	LTa-1	72	2008/8- Present	Operational monitoring equipment	Necessity of calibration.
				• Reliability of monitoring data is low. • At the transfer time of WT-3 data logger, equipment's connection error between shallow and deep wells was happened. Thus, monitored data of both wells inverted.	
	LTa-2	35	2008/8- Present	Operational monitoring equipment.	Necessity of calibration.
				• Reliability of monitoring data is low. • At the transfer time of WT-3 data logger, equipment's connection error between shallow and deep wells was happened. Thus, monitored data of both wells inverted.	
8	LTb-1	73	2003/9- Present	Operational monitoring equipment.	Not necessity of calibration
				Monitoring data have good reliability.	
	LTb-2	40	2003/9- Present	Operational monitoring equipment.	Not necessity of calibration
				Monitoring data have good reliability.	

(Note) Present condition of the above table is as of September 13, 2009. On Khvein and Kravan monitoring wells, they were constructed after September 2009. As they kept accuracy of observation, their descriptions in the above table were omitted.

(2) Monitoring Activity by DOWRAM (Department of Water Resources and Meteorology)

The government of Cambodia enacted the "Water Resources Management Law" in June 2007 and the monitoring works for water resources were transferred from MIME to MOWRAM. At present, MOWRAM does not still carry out monitoring works on groundwater.

3-2 Construction of New Monitoring Wells

Under this study, a monitoring well (shallow well) was constructed in the premise of Kravan primary school on October 2009 and two monitoring wells (shallow and deep wells) were constructed in Khvein primary school on October 2009 and May 2011, respectively. The Khvein primary school is located at 2.3 km west of the Angkor Wat ruins. The Kravan primary school is located 3.2 km north east of Angkor Wat. These monitoring wells are constructed to monitor influence of the SRWSA production wells and the private wells in the city.

Same type of the monitoring equipment used for the existing monitoring wells were installed in the wells as detailed below:

Table 3.4 Outline of Newly Constructed Monitoring Wells in 2009 and 2011

No.	Well No.	Well Depth (m)	Casing Diameter and Materialas	Screen Depth (m)	Static Water Level (m)	Well Location	Construction Year
1	Khvein Well-1	40	UPVC 6"	16-20 24-28	0.40	Khvein Primary School	October 2009
2	Khvein Well-2	80	UPVC 6"				June 2011
3	Kravan Well	40	UPVC 6"	20-24 28-36	0.57	Kravan Primary School	October 2009

(Source) Construction report by Contractor (Octiber 2009 and June 2011)

In the same locations as monitoring well sites, core borings of 80 m depth and core size 66 mm were conducted to check geological conditions prior to well drilling. Observation results of core samples are shown in Supporting Report. The observation survey of the core boring samples showed the following results:

- Khvein site

  In Khvein site, clay formations are mainly distributed from ground surface to depth of 9 m. In depth of 9 m to 50 m, sand and sandy clay formations are manly distributed. Clay formations with thickness of about 13 m are distributed in depth of 50 m to 63.5 m. Under the clay formations, sand formations are also distributed in depth of 63.5 m to 80 m. Based on their hydrogeological conditions, it is considered that the layers in Khvein site can be divided into two aquifers of shallow and deep ones: shallow aquifer on upper formations than clay formations distributed in depth of 50 m to 63.5 m and deep aquifer on lower formations than the clay formations.

- Kravan site

  In Kravan site, clay or sandy clay formations in depth of ground surface to 7 m are mainly distributed. In the lower part of the clay or sandy clay formations, sand formations are distributed up to depth of 80 m. Based on the geological formations, it is considered that there is only one aquifer in Kravan site.

Based on the hydrogeological conditions by observation results of core samples as shown in the above, in Khvein site, two monitoring wells for shallow and deep aquifers were constructed and in Kravan site, one monitoring well for shallow aquifer was constructed. The monitored groundwater level at shallow and deep monitoring wells in Khvein site and the level at shallow monitoring well in Kravan site are shown in Supporting Report.

3-3 Private Wells

The Study Team conducted well inventory survey to assess the influence of lowering of groundwater table in the Study Area as described in the previous chapter. A total of 280 establishments were selected including 75 hotels, 115 guesthouses, 40 restaurants, 10 factory/manufactures, and 40 other establishments as car wash, schools, entertainment centers, and clinics. The data collected included such information as well owner, locations of wells (GPS data), number of wells, well depth, well diameter, screen depth, withdrawal volume of groundwater, water use/purpose, availability of treatment plant etc.

3-3-1 Distribution of Private Wells

A total number of the private wells with a capacity of over 10m3/day are 128 in the surveyed area. Hotels and factories account for over 70 % of the total number of private wells. The private well with a pumping capacity of more than 10m^3/day extracts 96 percent of the total volume of groundwater usage in the city.

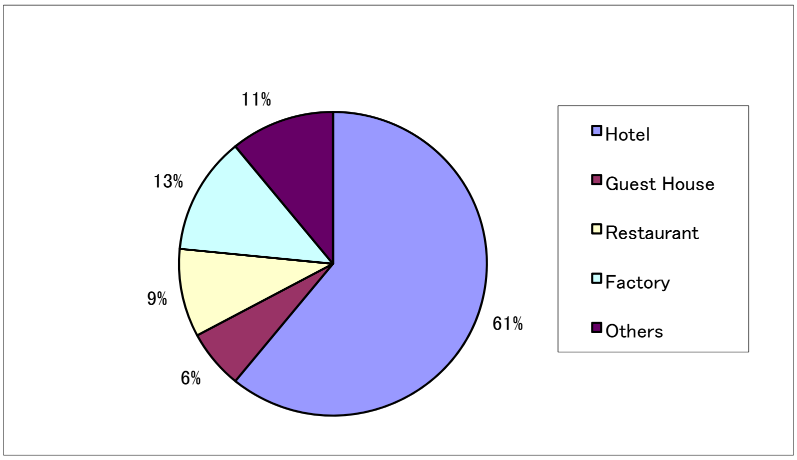


Figure 3.2 Distribution of Private Wells with Pumping Capacity of Over 10 m^3/day

Through the well inventory survey, the private wells with a pumping capacity of more than 10 m^3/day were identified by using the GPS data (UTM coordinate). The locations are illustrated in 1 km x 1 km grids as shown in Figure 3.3. Figure 3.4 also shows a total extraction volume by the private wells with a capacity of over 10m^3/day in each 1 km x 1 km grid. Private wells with a capacity of over 10m^3/day are mostly distributed in the city center.

In dry season, extraction volume of groundwater by private wells reaches a total of 5,553 m^3/day or 96 % of 5,786 m^3/d. The highest extraction of groundwater sources are made in the city center and along the national road number 6 as shown in Figure 3.4 while the 10 – 50 m^3/day extraction areas as shown in light blue color are located in the surrounding areas of the city center.

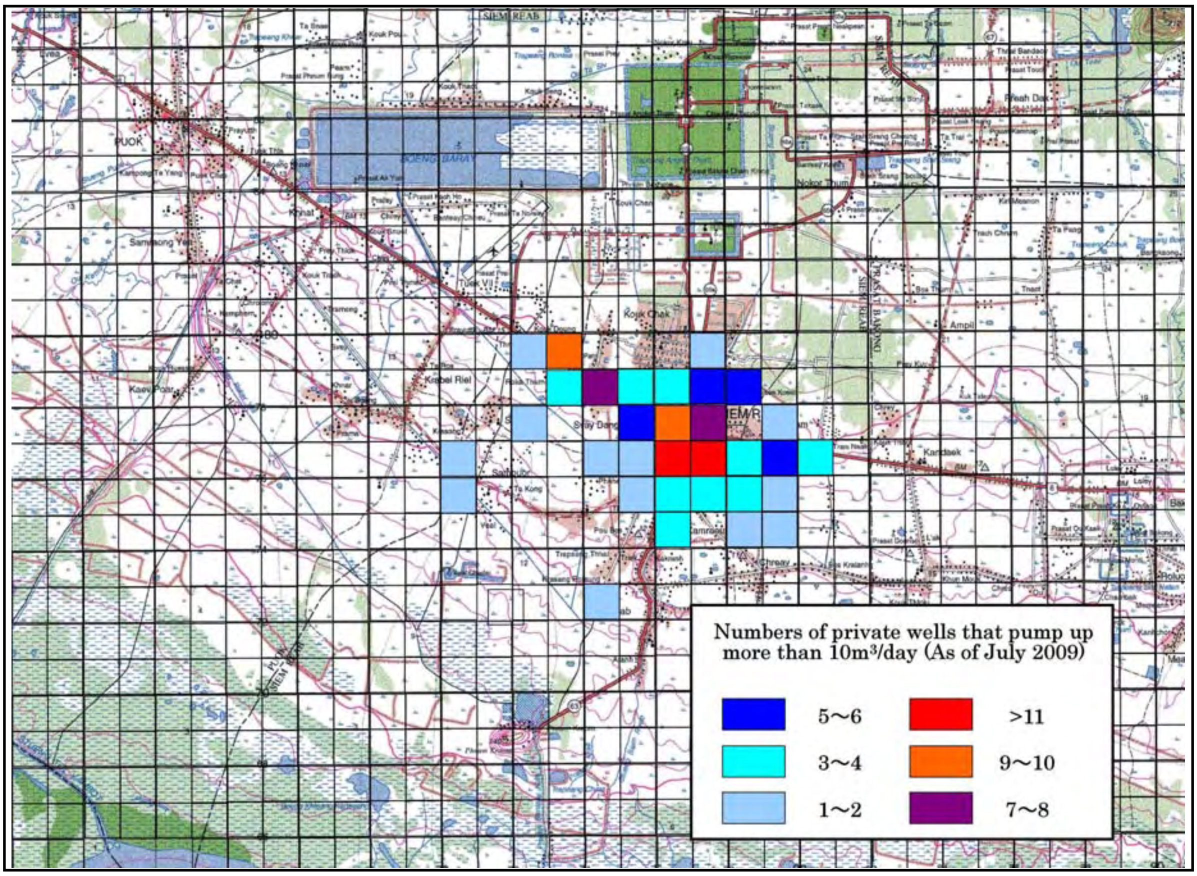


Figure 3.3 Distribution of Private Wells with Pumping Capacity of Over 10 m^3/day

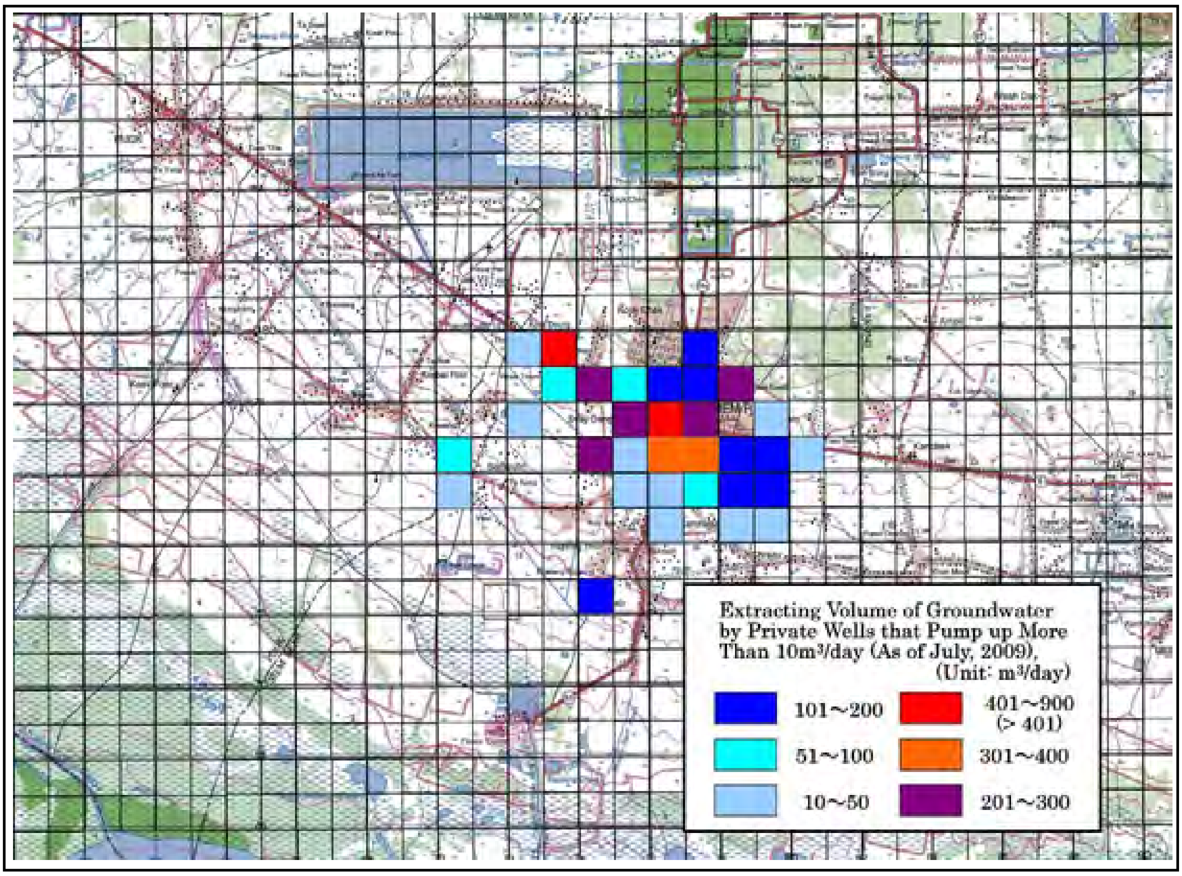


Figure 3.4 Distribution of Extraction Volume by Private Wells with Pumping Capacity of Over 10 m^3/day

3-3-2 Analysis on Tapped Aquifers and Withdrawal Volume

Based on information gathered in the well inventory survey, tapped aquifer and withdrawal volume of groundwater by the private wells were studied. In checking tapped aquifer, well depth is an important parameter. Every private well had information of well depth. But, setting depth of screens was recorded in only 26 % of a total of 383 wells. Majority of the wells have no information on screen depths.

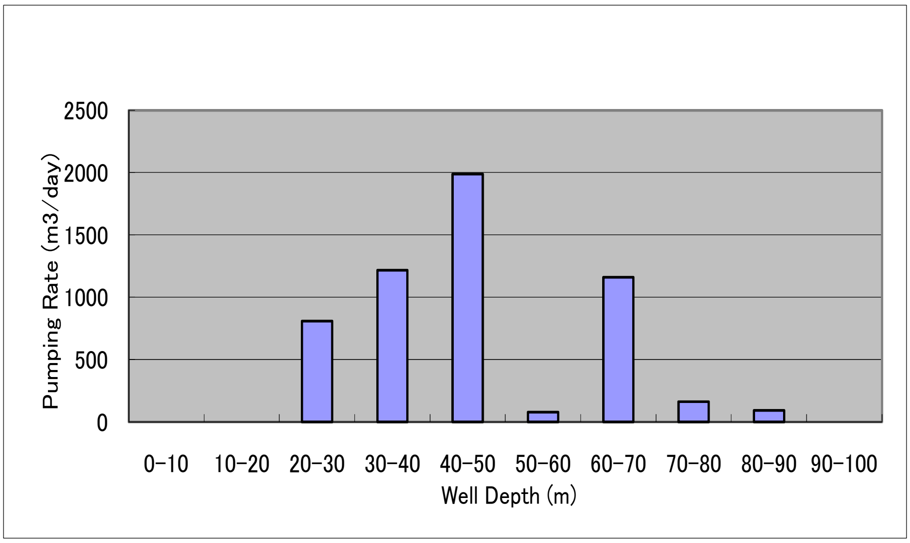


Figure 3.5 Well Depth and Extracted Volume of Groundwater by Private Wells

The collected data show that the screens are set within a depth of 5 to 10 m from the well bottom. Thus, tapped aquifer was identified assuming that the setting depth of screens was set at the depth within 10 m from the well bottoms. Figure 3.5 shows the relationship between well depth and extracted volume of groundwater of the private wells. Groundwater is mainly extracted in the depth of 20 to 50 m and 60 to 70 m.

The private wells are mostly located in the city center. Thus, WT-5 monitoring well located in the city center was used for this analysis. The tapped aquifer of WT-5 was identified in the Study on Water Supply System for Siem Reap Region in Cambodia (2000) as illustrated in Figure 3.6.

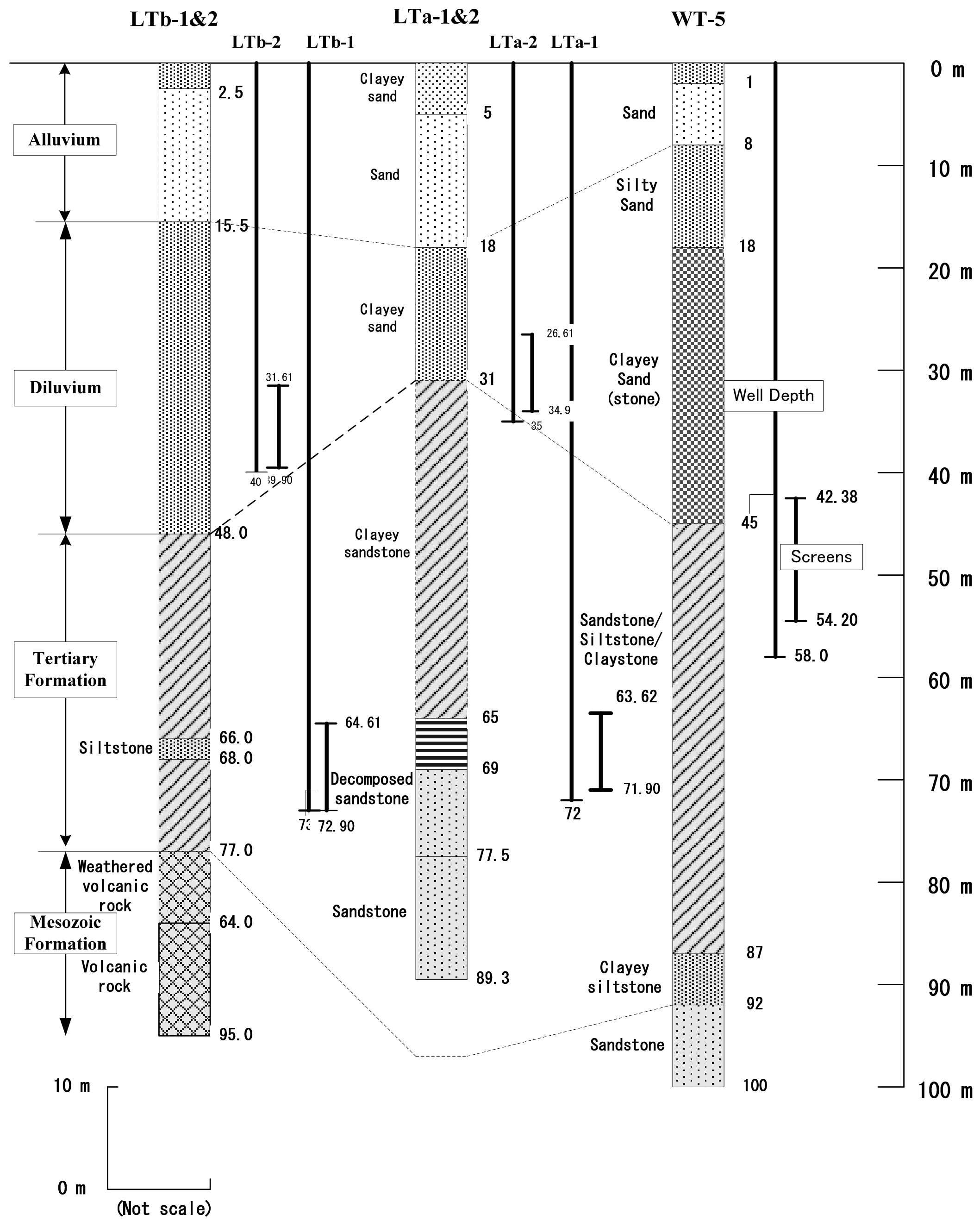


Figure 3.6 Well Structures and Geological Conditions of WT-5, LTa, and LTb

According to the Study on Water Supply System for Siem Reap Region in Cambodia (2000), Alluvium is distributed within the depth of 10 to 20 m. Diluvium is located within the depth of 10 to 40 m. Both layers are underlain by Tertiary layers with thickness ranging from 40 to 50 m. Under Tertiary layers, Mesozoic volcanic layers (rocks) are distributed. Alluvium layers are formed by clayey sand/sand. Diluvium is composed of silty sand/clayey sand (stone). Tertiary layers are made up of siltstone/clayey sandstone/clay stone.

Compared with the geological condition shown in Figure 3.6 and tapped aquifers of the private wells shown in Figure 3.5, the private wells are estimated to extract groundwater from the Diluvium and partially from a part of Tertiary formations. Considering the above situations, Tertiary formations of siltstone/clayey sandstone/clay stone may partially have fissures/fractural zones, though they are generally classified as aquiclude.

3-3-3 Analysis on Influence of Pumping Up of Private Wells

Influence of pumping up of the private wells was studied using data of WT-5 and LTb monitoring wells. LTa well data was not used in this study by the reason why a result of cross-check between automatic and manual recording data didn't accord. WT-5 monitoring well is located in the yard of SRWSA office near the Siem Reap River. The old treatment plant used three wells with a depth of about 60 m for water supply until November to December, 2005. The monitoring data of WT-5 recorded before November to December 2005 indicated a large daily fluctuation pattern with lowering of water level of 140 to 157 cm (as of January 2004) as shown in Figure 3.7.

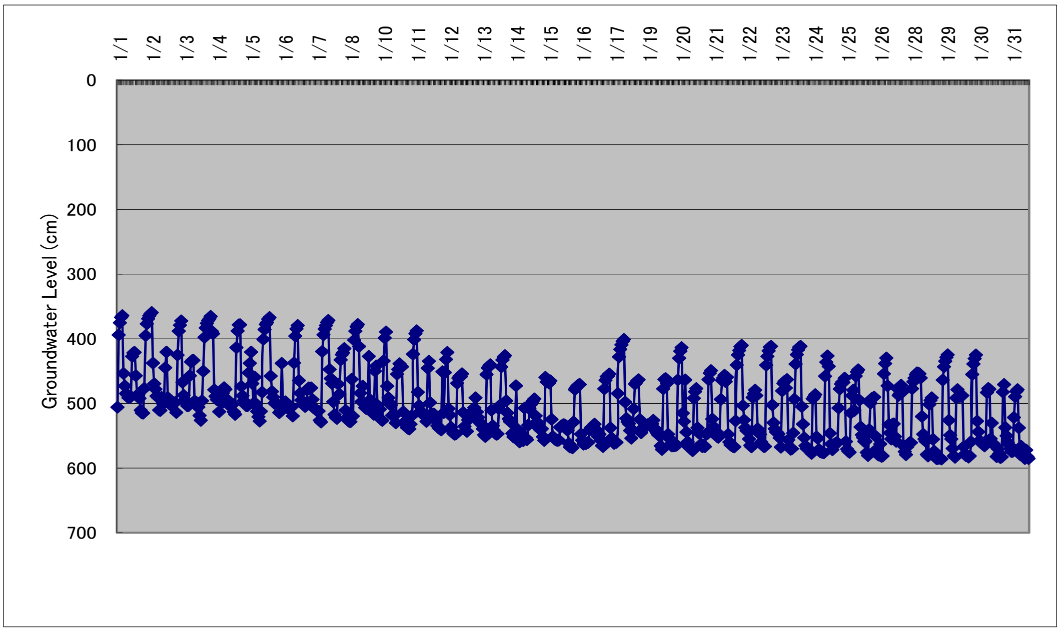


Figure 3.7 Groundwater Level at WT-5, January 2004

After the water treatment plant was abandoned, the monitoring data recorded from 7 to 9 January 2008 indicated small daily fluctuation pattern ranging from approximately 3 to 6 cm in the morning time from 7:00 to 11:00 and from approximately 1 to 3 cm in the evening time from 16:00 to 19:00. The lowering ranges were almost same trend in the rainy and the dry seasons. This range of water level fluctuation is considered to be influenced by exploitation of groundwater in the city. The example of daily fluctuation at WT-5 monitoring station from 7 to 9 January 2008 is shown in Figure 3.8.

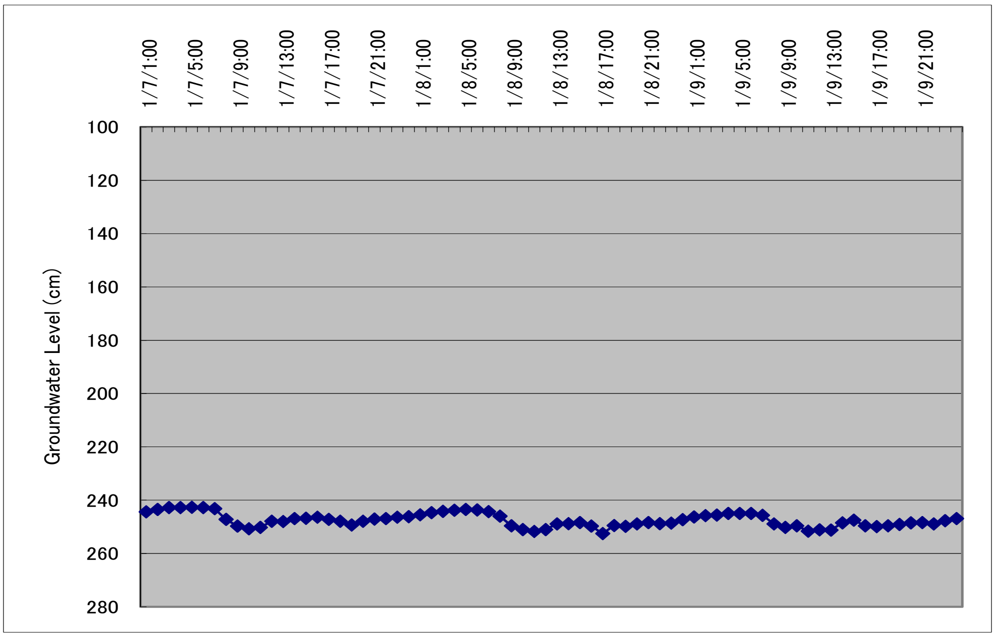


Figure 3.8 Groundwater Level at WT-5, 7-9 January 2008

On the same day, LTb-2 shallow monitoring well recorded fluctuations from 15 to 17 cm in water level which was larger than that of WT-5. One interpretation is that that the WT-5 screen was set at the Tertiary aquifer, considering the magnitude of daily groundwater level fluctuation and its columnar section. The LTb-2 screens were set in the Diluvium layers so that the lowering of groundwater level at LTb-2 can be larger than that of WT-5. Extraction volume of groundwater from Diluvium layers by the private wells is more than that of Tertiary layers. Daily groundwater fluctuation pattern at LTb-2 is shown in Figure 3.9.

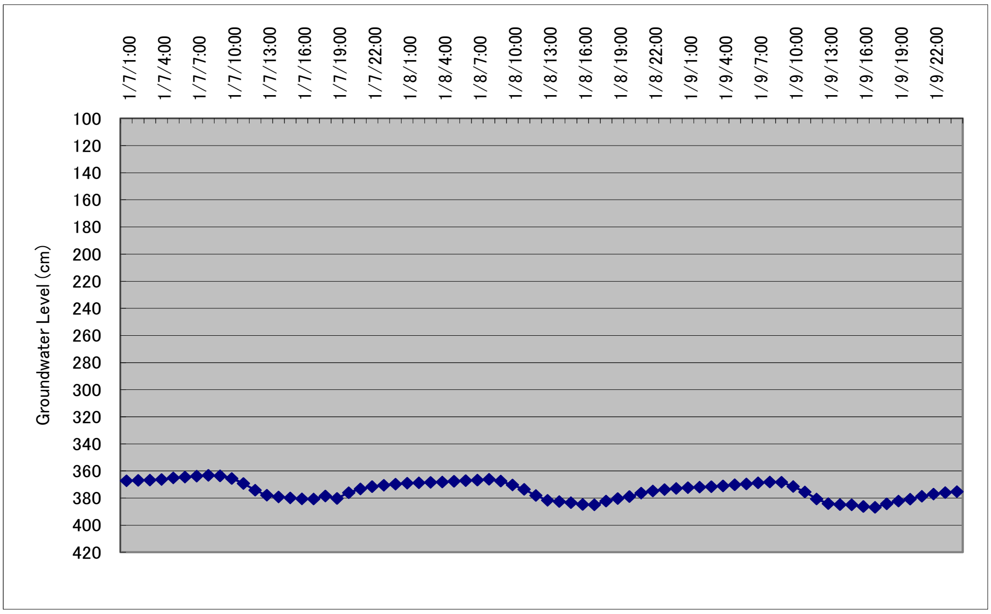


Figure 3.9 Recorded Daily Fluctuation of Groundwater Level at LTb-2, 7-9 January 2008

15 to 17 cm of the fluctuation range of LTb-2 monitoring well is very small compared to yearly fluctuation of groundwater level of about 2-3 m in Siem Reap area.

Monitoring data at LTb-1 deep well didn't indicate clear daily fluctuation pattern. Thus, the fluctuated monitoring data of WT-5 well, located in the city center, showing the lowering of groundwater level from 3 to 5 cm, can be translated to be influence of pumping of groundwater by private wells in Tertiary formation. The pumping by private wells did not have an impact to the LTb-1 monitoring site which is located about 5 km from WT-5 monitoring well. Monitoring data of LTb-1 deep well on 7-9 January 2008 is shown in Figure 3.10.

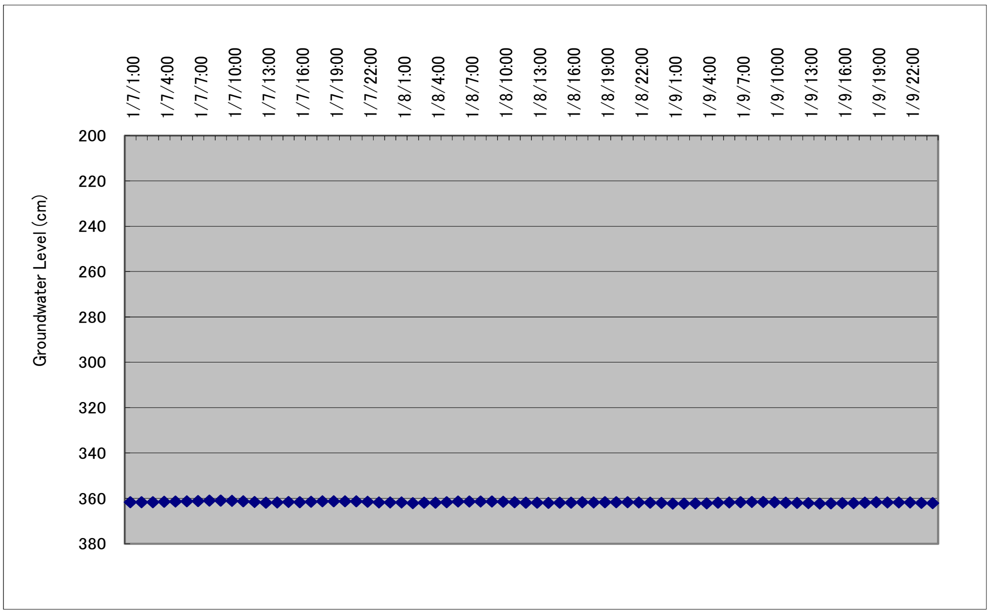


Figure 3.10 Recorded Groundwater Level at LTb-1 Deep Well, 7-9 January 2008

3-4 SRWSA Production Wells

The existing eight wells were constructed at an interval of 450 m in October 2005. The wells are situated 1.7 km south of the West Baray along the National Road No. 6. The locations of the wells are illustrated in Figure 3.1.

3-4-1 Well Structures and Intake Aquifers

Intake layers (aquifers) of the SRWSA production wells were reviewed through geological logs and well structures. The classification of geology is based on the results of the Study on Water Supply System for Siem Reap Region in Cambodia (2000). Table 3.5 summarizes the specifications of SRWSA Production wells.

Table 3.5 Well Structures of SRWSA Production Wells

No.	Well Depth (m)	Well Diameter (mm)	Well Screen (m)	Static Water Level (m)
PW-1	60 m	250 mm	14.0-23.6, 26.0-38.8, 40.0-43.2	- 1.41
PW-2	60 m	250 mm	16.50-19.52, 21.72-44.00	- 1.86
PW-3	60 m	250 mm	14.02-23.45, 26.63-42.49	- 1.41
PW-4	60 m	250 mm	29.12-44.92	- 1.37
PW-5	60 m	250 mm	14.72-40.40	- 1.18
PW-6	60 m	250 mm	14.95-40.43	- 1.51
PW-7	60 m	250 mm	21.72-44.00	- 1.89
PW-8	60 m	250 mm	19.72-45.21	- 2.23

(Note: Static Water Level* Completion Report by Contractor, 2005)

The columnar sections are classified by Alluvium, Diluvium, and Tertiary formation. Alluvium is mainly formed by sand and sandy clay. Diluvium is formed by silty clay/sandy clay and silty sand. Tertiary formation is formed by sandy clay/silty clay. Examination of the relationship between the geology and the setting depth of screens indicates that the wells intakes groundwater from aquifers distributed in the lower part of Alluvium and main portions of Diluvium. The relationship between geology and screen portions is shown in Figure 3.11.

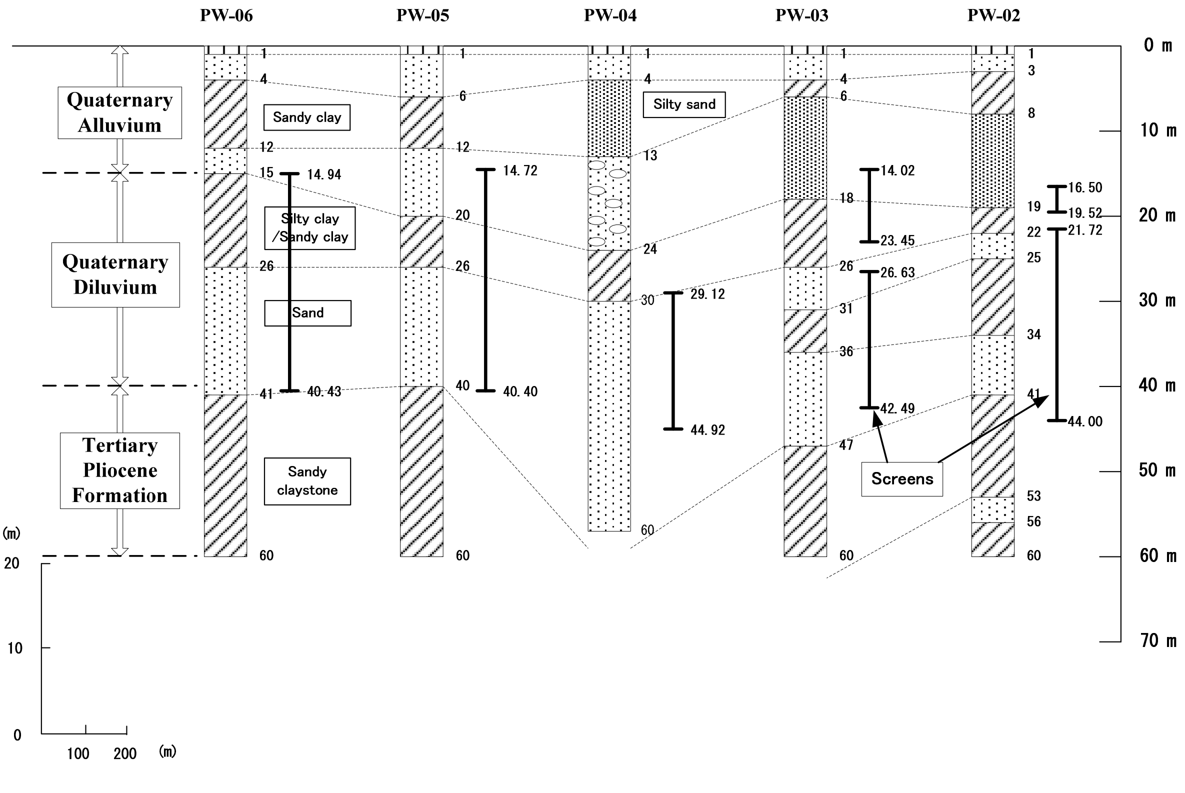


Figure 3.11 Intake Aquifers of SRWSA Production Wells

3-4-2 Operation of SRWSA Production Wells

The SRWSA production wells started pumping up in November 2005. At the beginning, the production did not reached the designed capacity of 8,000 m^3/day due to the delay in the expansion of the water supply network. As the water supply network developed, the production capacity increased every month. In December 2007 the production capacity reached 8,000 m^3/day and exceeded 9,000 m^3/day in August 2009. The pumping rate by each production well and total volume of inflow to the existing water treatment plant has been recorded using an automatic recording system installed at the monitoring room of the plant. However, data was not recorded from April 2008 to March 2009 due to damage of the monitoring systems by lightning. Rehabilitation of the monitoring systems was made under assistance of JICA expert at the beginning of March 2009.

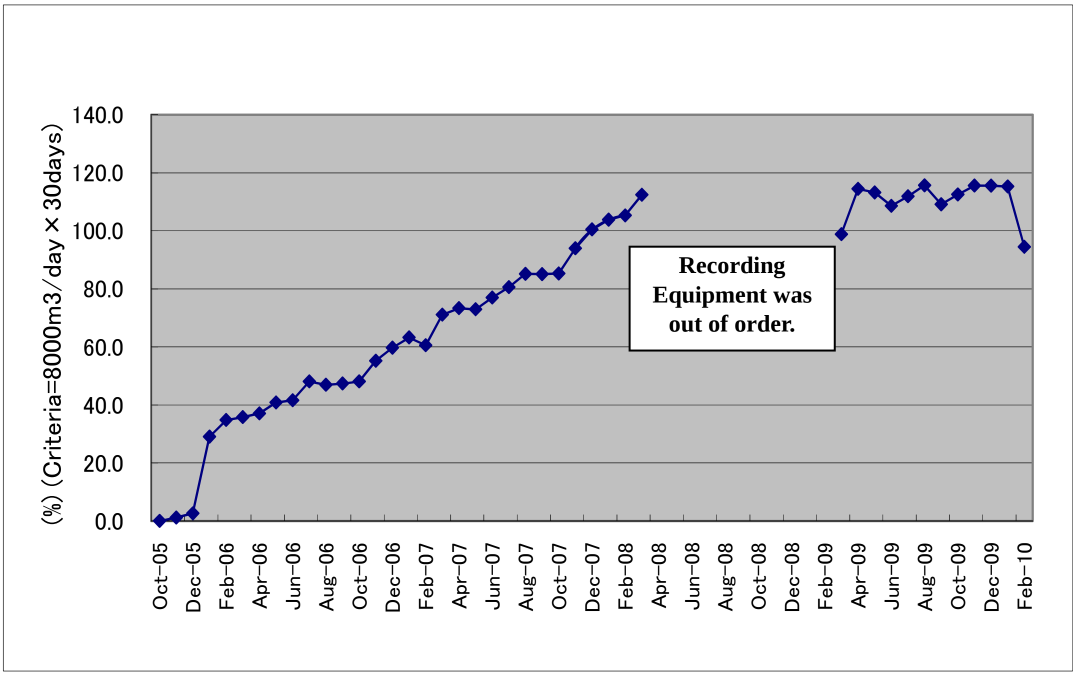


Figure 3.12 Monthly Data of SRWSA Production Wells, October 2005 to February 2010

3-4-3 Analysis on Influence of Pumping Up of SRWSA Production Wells

WT-4 and Khvein monitoring wells were used to study influence of pumping up of the SRWSA production wells. WT-4 and Khvein shallow wells are situates 2.6 km and 4.1 km from the SRWSA production wells, respectively.

(1) Well Structures and Aquifers of WT-4

The screens of WT-4 monitoring well are installed at the lower portion of Alluvium and main portion of Diluvium. This means the screens of WT-4 monitoring well are located at the same tapped aquifers as the SRWSA production wells. Figure 3.13 shows the geological conditions and the setting depth of screens of the WT-4 monitoring well.

(2) Analysis of WT-4 Data

Figure 3.14 shows verified WT-4 monitoring data. Only those data from Mar. 2007 through Feb. 2008 were indentified to be reliable by comparing the manual measurement data and the automatic recorded data. The monitoring data during this period were used for this analysis.

The recorded data shows that the fluctuation of groundwater levels of WT-4 was 1.6 m in 2007 to 2008. The highest groundwater level was in October at the end of rainy season and the lowest groundwater level was recorded at the beginning of May at the end of dry season.

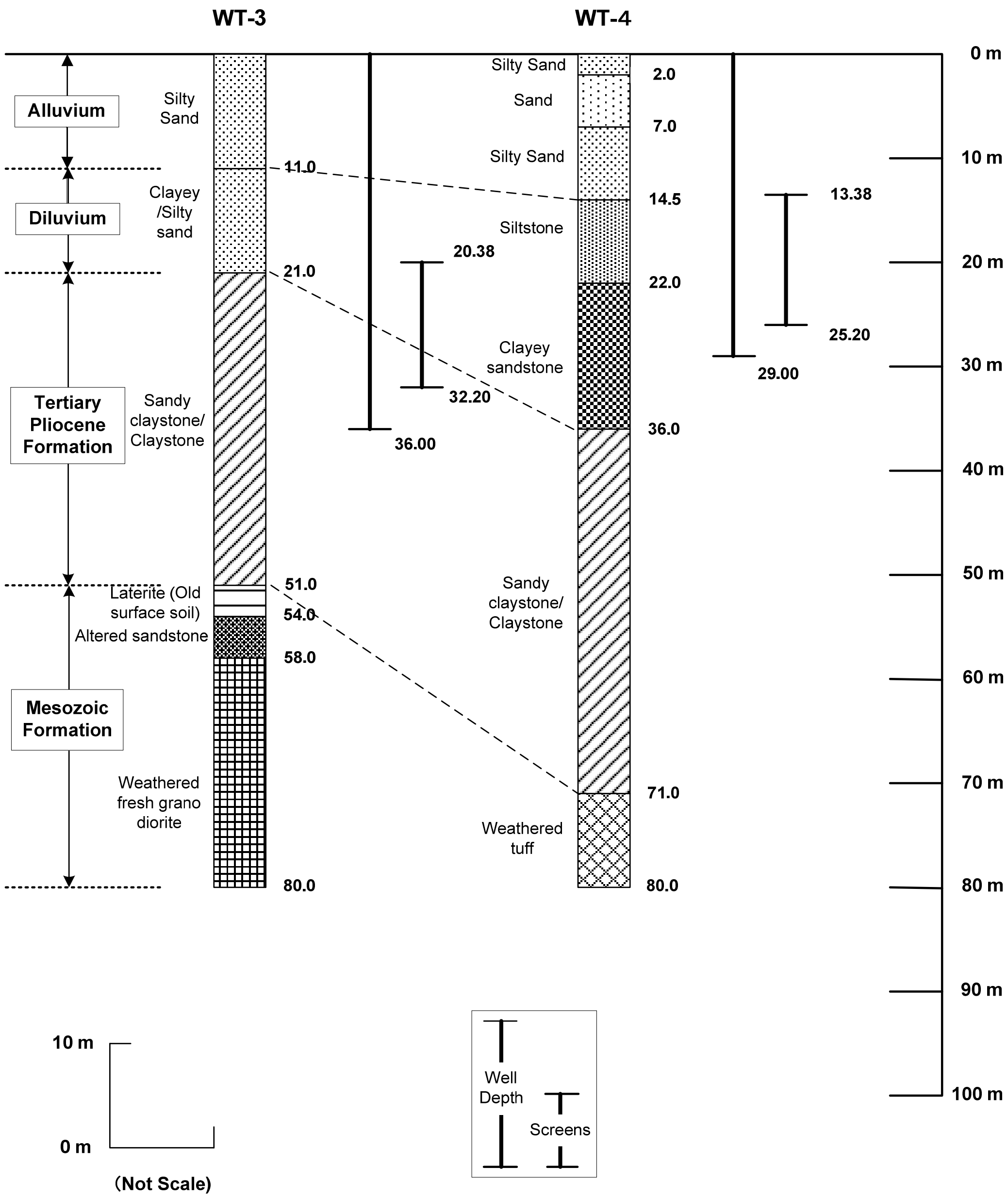


Figure 3.13 Geological Conditions and Depth of Screens of WT-4

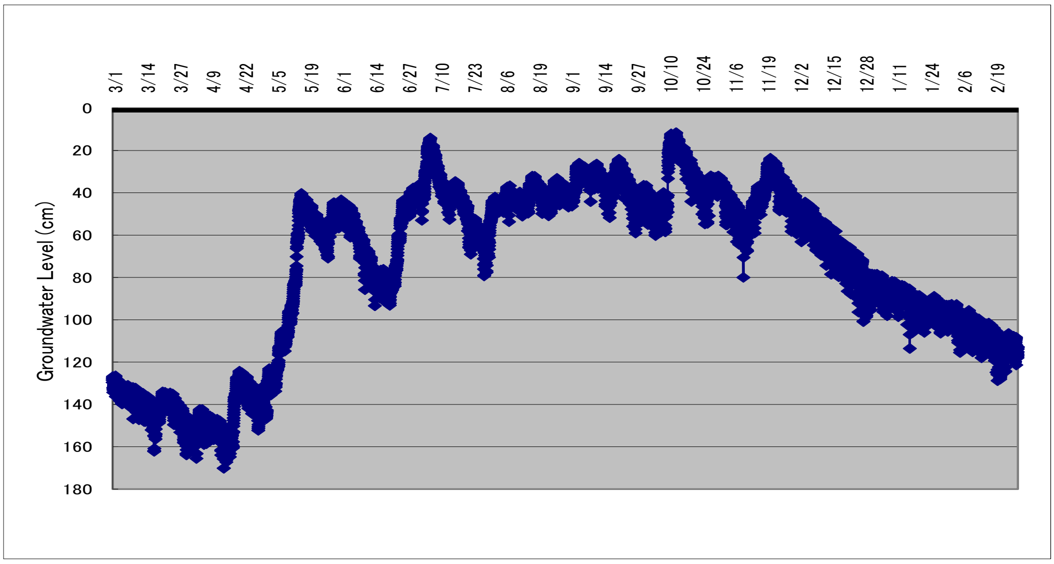


Figure 3.14 Groundwater Level at WT-4, March 2007 to February 2008

As showed in the Study on Water Supply System for Siem Reap Region in Cambodia (2000), yearly groundwater level fluctuation pattern was influenced by the seasonal precipitation. Only those data recorded during the dry season were selected to minimize influence of rainfall in this study,

This analysis was conducted by comparing the data when withdrawal of groundwater from the SRWSA production wells was stopped, and the monitored groundwater levels at WT-4.

Further, in order to minimize influence of pumping of neighboring private wells, this analysis was conducted using data during mid-night when pumping of the private wells and the SRWSA production wells were not in operation.

Monitoring data of two days on 8 and 9 January 2008 was then used as full pumping day on 9 January and halting day of pumping up of groundwater for about 4 hours on 8 January. Operating condition of SRWSA production wells on 8 and 9 January 2008 is shown in Figure 3.15 and daily pattern of monitoring data in Figure 3.16 and Figure 3.17.

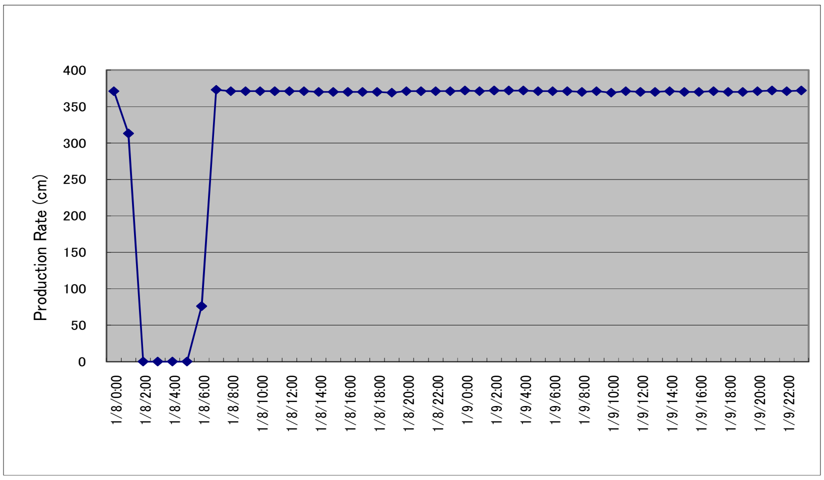


Figure 3.15 Operating Record of SRWSA Production Wells, 8 and 9 January 2008

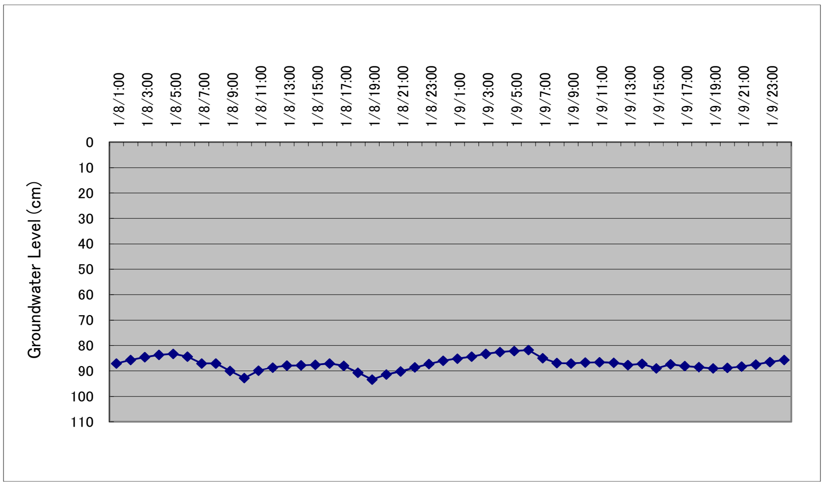


Figure 3.16 Daily Fluctuation of Groundwater Level of WT-4 on 8 and 9 January 2008

Operating Conditions of SRWSA production wells are as follows:

Day	Operating/Non- operating hours	Pumping rate
8 Jan. 2008	Full operating (0:00, 7:00-23:00) Halting of pumping up (2:00 – 5:00) Decrease of pumping rate (1:00, 6:00)	369 – 373 m^3/hour (Total: 7,062 m^3/day)
9 Jan. 2008	24 hours: Full operating	369 – 372 m^3/hour (Total: 8,901m^3/day)

(Note) Full operating means operation of all production wells and halting means the halting of all production wells.

As shown in the following figure showing the fluctuation of groundwater level for two days, the lowering in observed in the morning (5:00-10:00) and in the evening (17:00-19:00). Magnitude of the fluctuation approximately ranges from 5 to 8 cm. The fluctuation of groundwater level is considered to occur when neighboring private wells are operating.

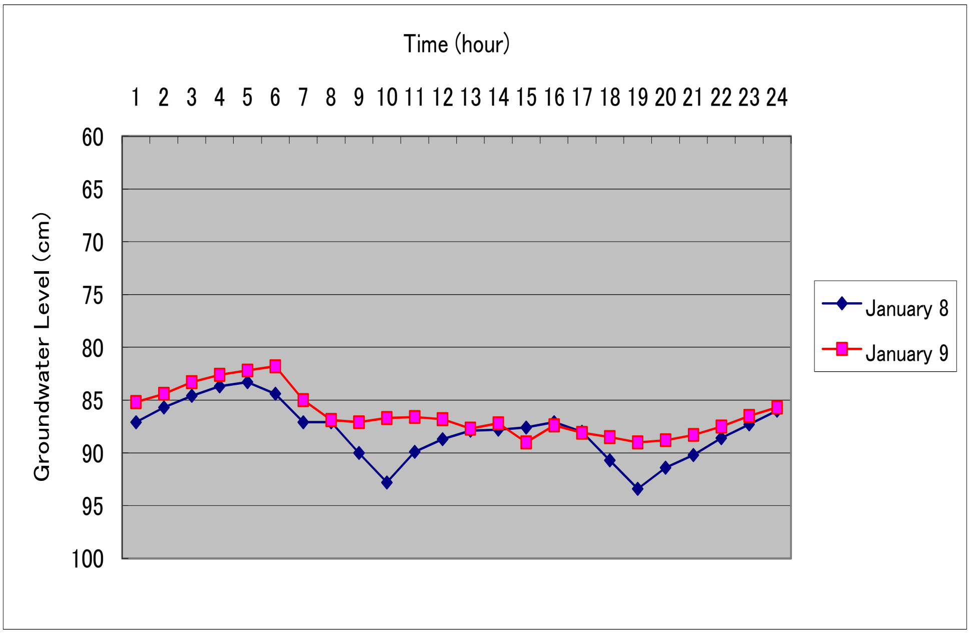


Figure 3.17 Comparison of Daily Fluctuation on 8 and 9 January 2008 of WT-4

Figure 3.17 shows comparison of daily fluctuation of groundwater level within 24 hours on two days on 8 and 9 January 2008. Their daily fluctuation patterns indicate that:

- Data on 8 January 2008 shows that SRWSA stopped pumping up from 0:00. After 2:00 up to 5:00, the pumping was fully stopped. Then, from 5:00, pumping up was stated up again. However, fluctuation tendency of groundwater level showed the same as that of 9 January when SRWSA operated the pumps for 24 hours in reference to Figure 3.17. This phenomenon indicates that SRWSA wells do not have any impact to WT-4. Because, if the SRWSA wells have some impact on WT-4, the water level at that time between 2:00 to 5:00 on 9 January should be lower than that of 8 January.
- Thus, interference radius of pumping of the SRWSA production wells is considered not to have a negative influence on monitored groundwater level of WT-4.
- The same tendency was confirmed on the monitored data on 14 to 16 December 2007.
- Likewise, the correlation between the operating conditions (pumping rates) of the SRWSA production wells and the monitored groundwater levels at WT-4 were studied based on correlation analysis method. Results shows that the determination coefficients were calculated to be R^2=0.148547 for the case on 8 and 9 January 2008 and R^2=0.12983 for case on 14 to 16 December 2007. Therefore, correlations between the pumping rates and the monitored groundwater levels were not identified.
- As a result, in WT-4 monitoring well located about 2.6 km away from the SRWSA production wells, the influence of pumping of SRWSA wells were not observed.

In the similar way, the same comparison on 8 and 9 January 2008 was conducted on LTb-2 data. Figure 3.18 shows comparison result of daily fluctuation in both days.

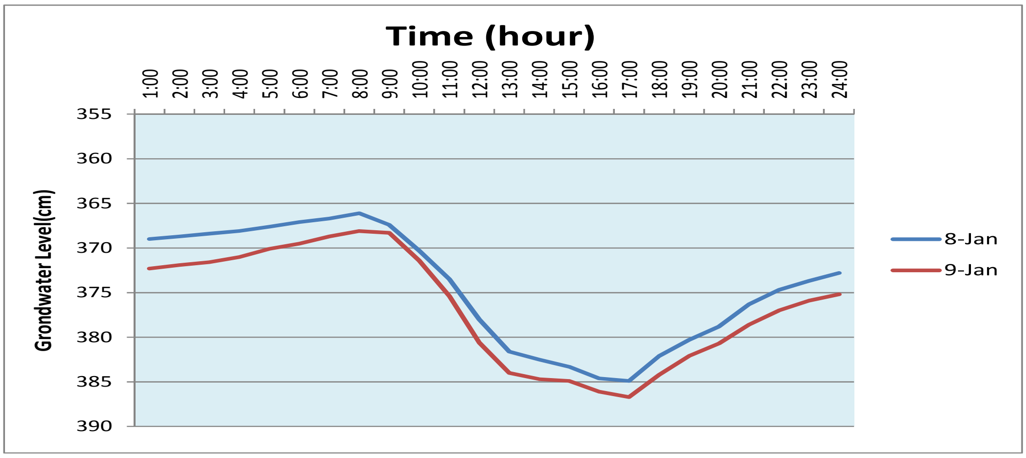


Figure 3.18 Comparison of Daily Fluctuation on 8 and 9 January 2008 of LTb-2

Figure 3.18 shows the followings:

- Though SRWSA wells stopped to pump up groundwater on Jan. 8, from 2:00 to 5:00, daily fluctuation pattern of groundwater levels is almost the similar to that in full pumping mode on Jan. 9. Thus, likewise to WT-4, daily fluctuation pattern doesn't indicate influence of pumping of SRWSA wells.
- Difference of groundwater levels in both days is caused by seasonal drawdown in the dry season. The daily drawdown is about 3 cm.
- Compared with WT-4, daily fluctuation is large with range of 18 to 19 cm. Its drawdown starts from 8:00 in the morning. The lowest level happens in 17:00 in the evening. Since LTb-2 well is located near the city center, compared with distance from SRWSA wells, this large daily fluctuation is considered to be caused by pumping of many private wells located in the city center.

(3) Analysis of Khvein Shallow Well Data

The Khvein monitoring shallow well was constructed in October 2009 under this study and the monitoring equipment was installed in February 2010. Monitoring was started from February 17 2010. The well is situated about 4.1 km away and northwest of the SRWSA production wells. The location is illustrated in Figure 3.1. It is considered that SRWSA production wells and Khvein shallow well are tapped in the same shallow aquifers as Alluvium and Diluvium. In the same manner as that of WT-4 monitoring well, the influence of pumping by the SRWSA production wells was studied.

Operation of the pumps of the SRWSA production wells was temporarily halted about two hours in the midnight on 7 and 9 May 2010 as shown in Figure 3-19. Based on the data recorded during the stopping of the SRWSA production wells, the influence against monitored water level at Khvein shallow well were analyzed.

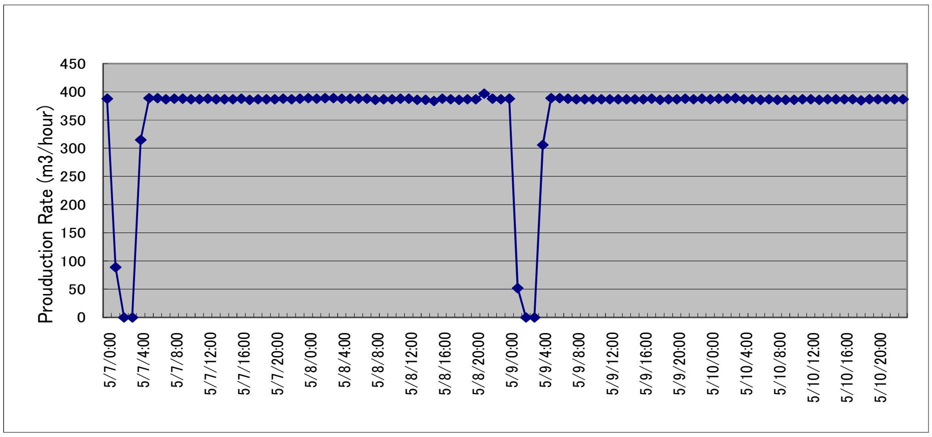


Figure 3.19 Operation of SRWSA Production Wells, 7 to 10 May 2010

Operating Conditions of SRWSA production wells are summarized below:

Day	Operating/Non- operating hours	Pumping rate
7 May 2010	Full operating (0:00, 5:00-23:00) Halting of pumping up (2:00 – 3:00) Decrease of pumping rate (1:00, 4:00)	387 - 389 m^3/hour (Total: 8,154 m^3/day)
8 May 2010	24 hours: Full operating	384 - 389 m^3/hour (Total: 9,306 m^3/day)
9 May 2010	Full operating (0:00, 5:00-23:00) Halting of pumping up (2:00 – 3:00) Decrease of pumping rate (1:00, 4:00)	386 - 389 m^3/hour (Total: 8,106 m^3/day)
10 May 2010	24 hours: Full operating	386 – 389 m3/hour (Total: 9,285 m^3/day)

(Note) Full operating means operation of all production wells and halting means the halting of all production wells.

The fluctuation patterns of groundwater levels based on 24 hours full operation on 8 and 10 May 2010 and halting of pumping of the SRWSA production wells for two hours on 7 and 9 May 2010 were compared. Comparison of fluctuation patterns of groundwater levels are shown in Figure 3-20.

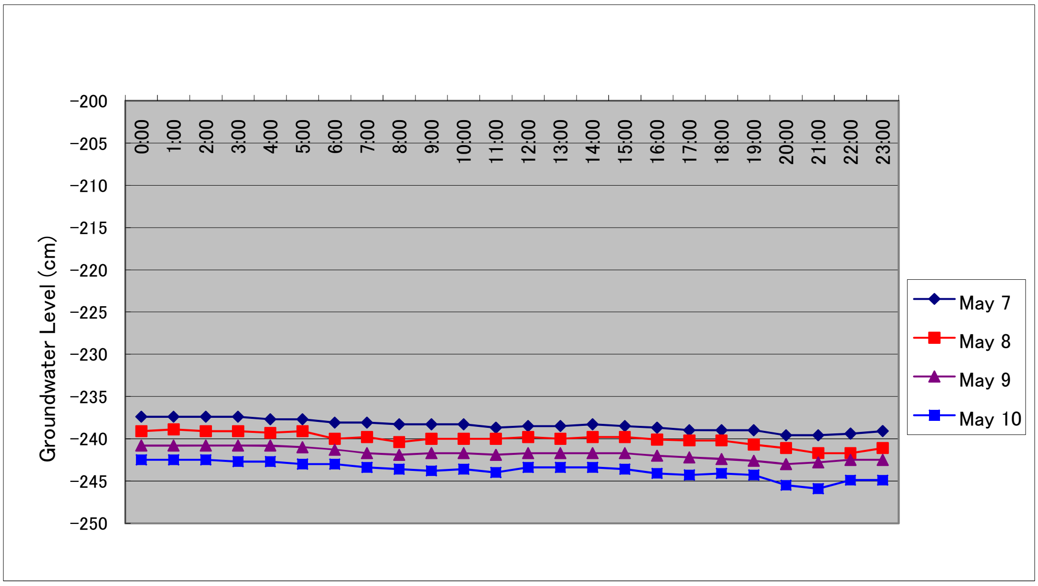


Figure 3.20 Comparison of Daily Fluctuation of Khvein Shallow Well, 7 to 10 May 2010

Figure 3-20 indicates that:

- For this period, the recorded groundwater level generally lowers every day by 1.7 cm. It was in dry season. Though all of the SRWSA production wells were stopped for two hours from 2:00 to 3:00 on 7 and 9 May 2010, groundwater level did not go up. All of the groundwater levels for these four days have shown the similar fluctuation patterns.
- If the SRWSA production wells have some impact to the Khvein monitoring well, the data recorded from 2:00 to 3:00 on 8 and 10 May 2010 should be lower compared to those of the data recorded from 2:00 to 3:00 on 7 and 9 May 2010. The actual data shows that water levels recorded were not significantly different. Thus, it is considered that the SRWSA production wells didn't influence to the Khvein monitoring shallow well.
- This phenomenon suggests that the SRWSA production wells doesn't influence against the environment including around the Angkor Wat ruins which is located 6.5 km away from the SRWSA production wells.

Chapter 4.
Hydrological Conditions in Siem Reap

Chapter 4. Hydrological Conditions in Siem Reap

In Siem Reap, both the domestic water use and a small amount of industrial water use are mainly taking groundwater as the water supply source. More than half of domestic water use is supplied by SRWSA using 8 production wells located in the southwest of Siem Reap Town. However, because of rapid increase of the population, tourists and daily water use quantity per capita, the water demand is now more than the water supply capacity of SRWSA. Therefore, a lot of private wells have been constructed mainly in the urban area to supplement water supply.

When groundwater is developed the groundwater level drawdown and change of groundwater flow will surely occur. Therefore, to keep the effect of groundwater drawdown within allowable limits is an essential consideration when formulating a groundwater development plan.

4-1 River Basin Division in Water Supply Area

When a river basin is taken as the extent for hydrological analysis, the flow of surface water between different basins can be dismissed, and in most cases groundwater flow between different basins can also be dismissed. Therefore, the processing of hydrological analysis would become simple to improve the precision of the analysis. To make clear the river basin divisions, a 90 m mesh DEM (Digital Elevation Model) data SRTM (Shuttle Radar Topography Mission, USNASA) were taken as the basic data. And GIS hydrology tools were used to delineate the river basin boundaries.

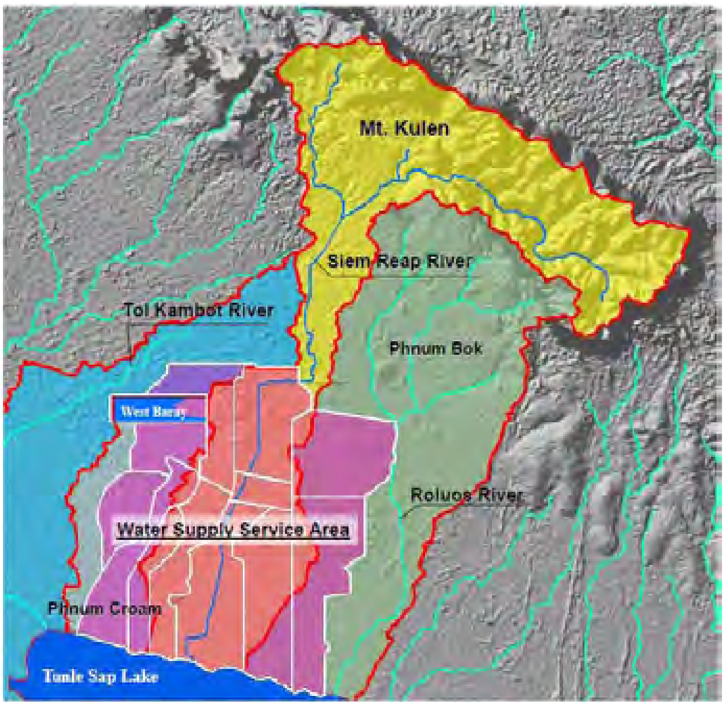


Figure 4.1 Water Supply Service Area and Relevant River Basins

Figure 4.1 shows the extent of the three river basins that affect the water supply service area. The water supply area is mostly comprised of the Siem Reap river basin, with the west side comprised of part of the Tol Kambot river basin, and the east side comprised of part of the Roluos river basin.

The Siem Reap River and the Roluos River originate in the Kulen Mountains, and the Tol Kambot River is a small tributary of the Staeng Sangka River. All the three rivers finally discharge into the Tonle Sap Lake.

The recharge area of the water supply service area is shown in Figure 4.2. It consists of the three abovementioned river basins, the Siem Reap river basin in its entirety and parts of the other two. The total recharge area of the water supply area is 1,277km^2, of which 552km^2 is the water supply service area.

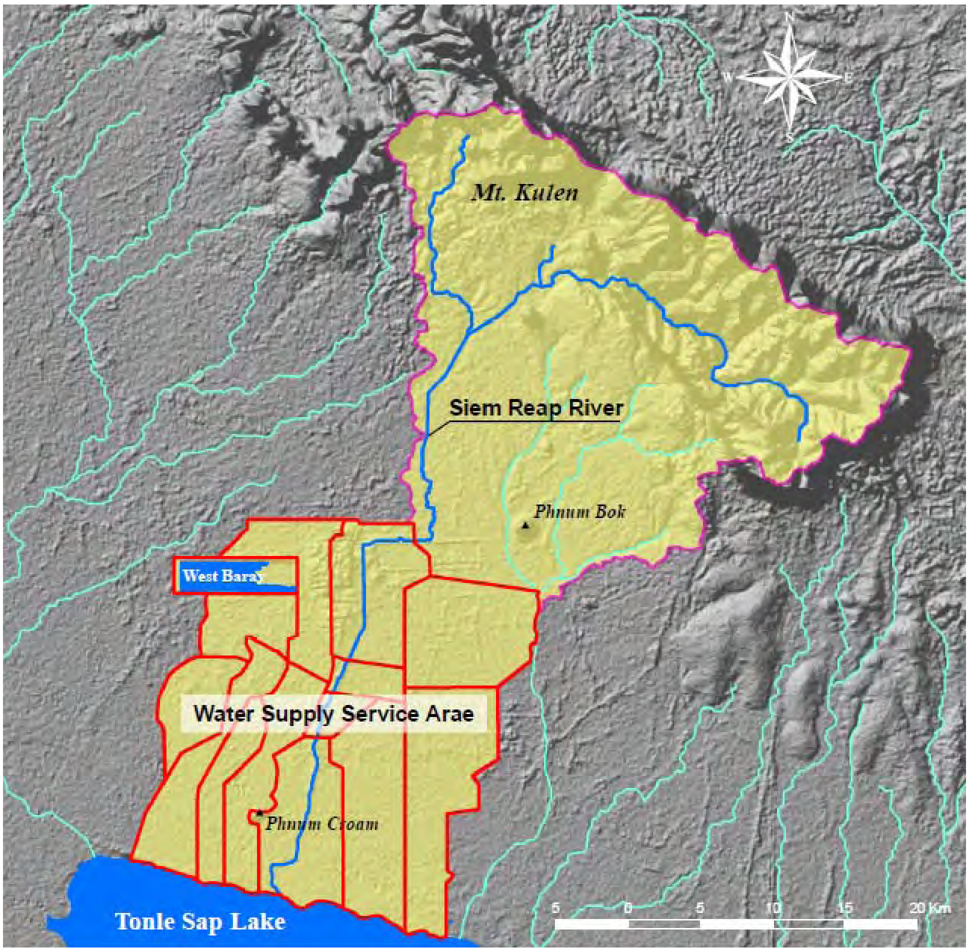


Figure 4.2 Recharge Area of the Water Supply Service Area

4-2 Climatic Conditions

Water resources in the water supply area can be divided into recharge from precipitation, discharge by rivers, and consumption by evaporation or evapotranspiration, percolation into groundwater and discharge by groundwater. All of the above components concerned with the water resources in Siem Reap can be summarized into the groundwater balance equation as follows:

$$\Delta W = R - D - E + F_{in} - F_{out}$$

Here:

ΔW: Increase or decrease amount of groundwater

R: Amount of precipitation

D: Amount of river discharge

E: Amount of evaporation or evapotranspiration

F_{in}: Amount of groundwater flow in from other basins to the study area

F_{out}: Amount of groundwater flow (discharge) to outside area (Tonle Sap Lake)

As shown in the groundwater balance equation, groundwater recharge consists of two components: precipitation and flow in from other basins. Because there is no flow in from other basins to the study area when the water balance is analyzed in the unit of river basin, the precipitation becomes the only recharge component in the equation. In plain area like Siem Reap, the water exchange amount between rivers and groundwater is generally small because of all hydraulic gradient and hydraulic conductivity and flow section are relatively small. The amount of groundwater flow out to Tonle Sap Lake is also small because of the same reason of small water exchange between river and groundwater. Therefore, the precipitation and evaporation can be taken as the most important two components for water balance analysis in the study area.

Figure 4.3 shows monthly average amount of precipitation and evaporation. Like other Southeast Asian countries, the precipitation in Siem Reap is characterized by its seasonal changes. A year can be clearly distinguished into 2 seasons: rainy season and dry season. The rainy season continues half a year from May to October; and the dry season the other half from November to April. The total amount of precipitation in the rainy season is above 1,200 mm; accounts for 89% of the whole precipitation in a year. In contrast, total precipitation amount in the dry season is about 150 mm; only 11% of whole annual precipitation.

Another climatic characteristic in Siem Reap is the monthly average of evaporation amount that changes little throughout the year, from 105 to 175 mm, compared to the large fluctuation of monthly precipitation.

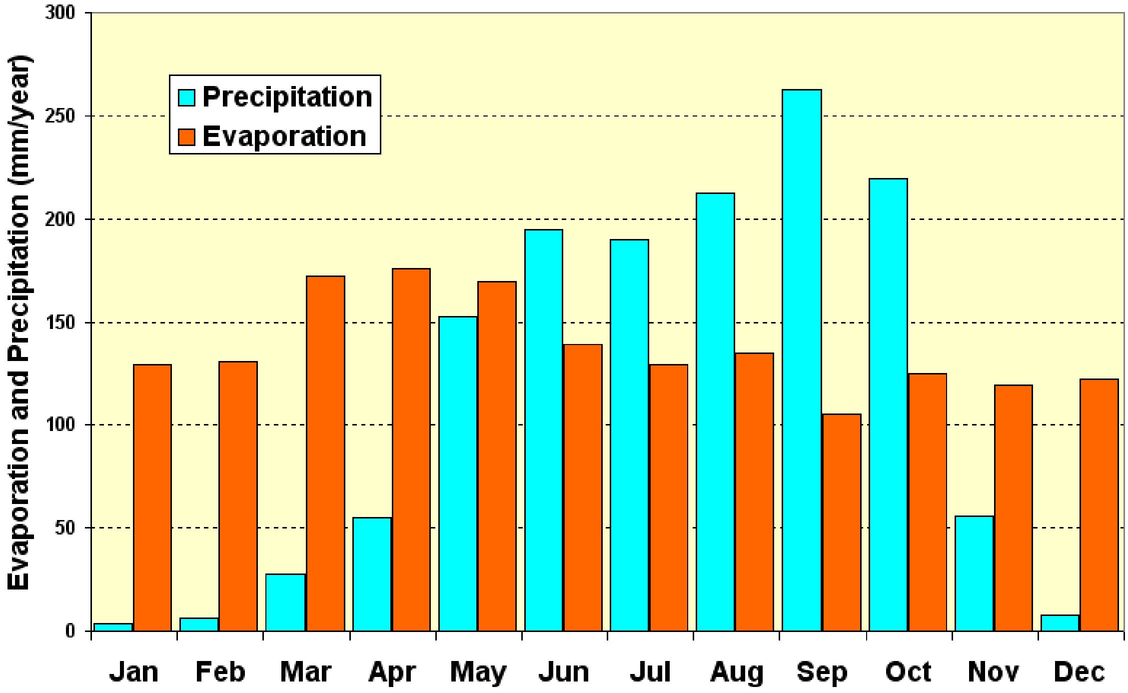


Figure 4.3 Distribution of Monthly Precipitation and Evaporation in the Study Area
The graph was created by summarizing observation result in the meteorological observation station Siem Reap City from 1988 to 2008.

4-3 Available Meteorological Data

There are 3 hills located in the water supply area, Phnum Pok in the eastern part with an elevation of 272 m, Phnon Kraom in the southern part with an elevation of 140 m, and Phnum Bakheng between the heritage sites, Angkor Wat and Angkor Thom, with an elevation of 99 m. Except the three small hills, the whole water supply service area is characterized by a plain topography with a gentle declination from 50 m in the north side to 1 m in the south side.

Generally, the amounts of precipitation and evaporation change largely in the mountainous area and are distributed homogeneously in the plain area. However, even in the plain area the precipitation and evaporation is not exactly the same everywhere. Therefore, collecting as much precipitation observation data as possible would be useful for improving the precision of hydrological analysis.

For precipitation analysis, observation results from 5 meteorological stations have been collected from the Meteorology and Hydrology Office of Siem Reap (The Ministry of Water Resources and Meteorology). Figure 4.4 shows locations of the 5 meteorological stations.

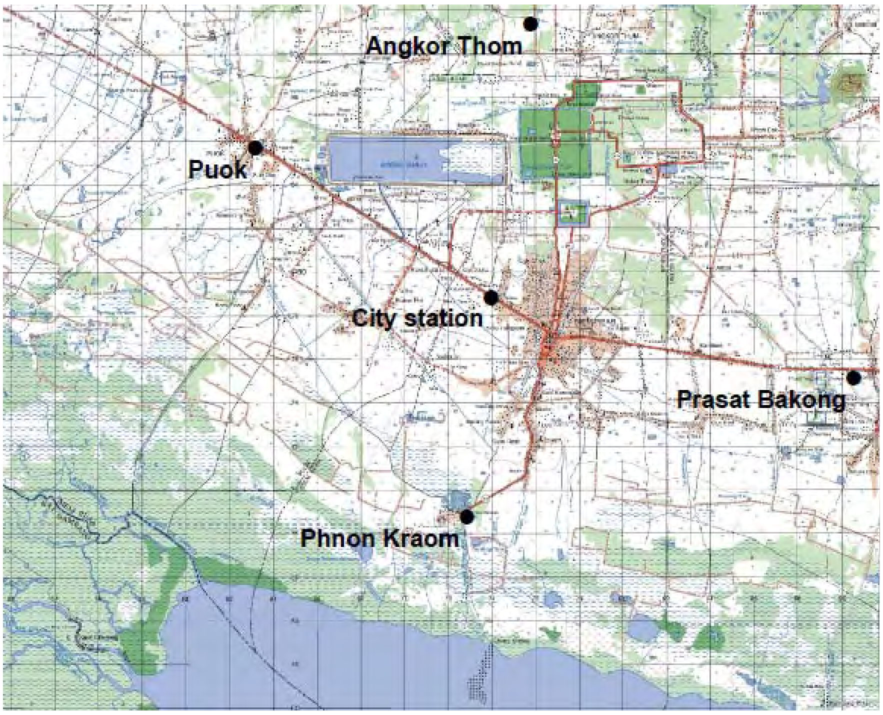


Figure 4.4 Location of Meteorological Stations Within the Study Area

Table 4.1 shows the basic information of the 5 meteorological stations, including station name, location (coordinates), methods and duration of observations, and so on.

Table 4.1 Basic Information about the Meteorological Stations for Precipitation Analysis

St. Name	City station	Prasat Bakong	Puok	Angkor Thom	Phnon Kraom
Easting	373503	390067	362714	375314	372399
Northing	1479133	1475413	1485942	1491624	1469041
Longitude	103° 48' 97 "	103° 24' 84 "	103° 50' 66 "	103° 45' 05 "	104° 20' 23 "
latitude	13° 24' 65 "	13° 36' 15 "	13° 29' 58 "	13°13' 44 "	13° 07' 27 "
Altitude	15	15	15	15	15
Recorder	Automatic & Manual	Manual	Manual	Manual	Manual
Data length	1988-2008	2001-2008	2003-2008	2001-2008	2004-2007
Average	1459.9	1470.6	1418.8	1088.4	1303.0
Max	1766(1995)	1685(2005)	1550(2005)	1334(2008)	1534(2005)
Min	1141(2002)	1039(2002)	1276(2003)	562.1(2007)	1196(2006)

- All stations except the city station are supported by Mekong River Committee (MRC)
- UTM datum is Indian-Thailand"
- Altitude is not accurate
- The unit of maximum and minimum precipitation is mm
- The occurrence years of maximum and minimum precipitation are given in parenthesis

4-4 Available Groundwater Monitoring Data

4-4-1 Existing Monitoring Wells

Eight (8) groundwater monitoring wells were drilled in the study area in a previous survey (The Study on Water Supply System for Siem Reap Region in Cambodia, 2000). The specifications of these monitoring wells are shown in Table 4.2 and Table 4.3.

Table 4.2 Basic Information about Existing Automatic Observation Wells

Code	Location	Observation Duration	Depth (m)	Head (cm)
WT-3	Ph Kouk Phnou Sch.	Jul_03 - Apr 08	80	0.76
WT-4	Ph. Khant Srok Puork Sch.	Jul_03 - Now	80	0.82
WT-5	Water Treatment Plant (SRWSA)	Aug_03 - Now	110	0.60
WT-6	Banteay Srei High Sch,	Aug_03 - Now	80	0.93
WT-7	Preahdak Primary Sch.	Aug_03 - Now	80	0.90
WT-8	APSARA Office Building	Aug_03 - Jan_04	95	0.89
LTa-1	SOS Kindergarden	Aug_03 - Now	72	1.77
LTa-2			35	1.79
LTb-1	Angkor Wat (Police Station)	Aug_03 - Now	73	1.66
LTb-2			40	1.66

Table 4.3 Basic Information about Existing Automatic Observation Wells

Code	Elevation (m)	Screen Depth (m)	Longitude	Latitude
WT-3	16.45	20.38-32.20	103° 45' 5.9"	13° 28' 37.3"
WT-4	13.66	13.38-25.20	103° 46' 3"	13° 25' 8.3"
WT-5	15.84	43.82-54.20	103° 51' 39.2"	13° 21' 41.2"
WT-6	32.86	13.38-25.20	103° 56' 27.9"	13° 28' 58.5"
WT-7	26.03	44.38-56.20	103° 56' 16.7"	13° 26' 45"
WT-8	17.07	67.38-79.20	103° 52' 49.3"	13° 22' 51.8"
LTa-1	17.43	63.62-71.90	103° 51' 51.5"	13° 22' 58"
LTa-2		26.61-34.90		
LTb-1	21.32	64.61-72.90	103° 51' 31.4"	13° 24' 40.7"
LTb-2		31.61-39.90		

(Note) The automatic observation of WT-3 was stopped in April 2008, because the log was removed.

No automatic observation data is available for WT-8 from January 2004, because the equipment was lost.

The series of WT are groundwater level observation wells, and the series of LT are groundwater and land displacement observation wells.

Automatic observation systems were installed in the monitoring wells making it possible to conduct continuous observation in short time intervals. However, caused by problems like the breakdown of the observation equipment, battery power deficiencies and so on, relatively large errors have been found in the data from almost all of the monitoring wells. If the original data was used directly in analysis without earnestly inspection, huge mistake would occur to lead wrong analysis result. Therefore, the manual observation was started by SRWSA from 2007 to be used for examination and/or modification of automatic observation results.

4-4-2 Inspection of Groundwater Monitoring Result

(1) Monitoring Site WT-3

Figure 4.5 shows the original monitoring data obtained from automatic recording logs of the groundwater monitoring well WT-3. Except some periods of missing data and obvious observation errors, periodic groundwater level fluctuation is clearly shown by the figure.

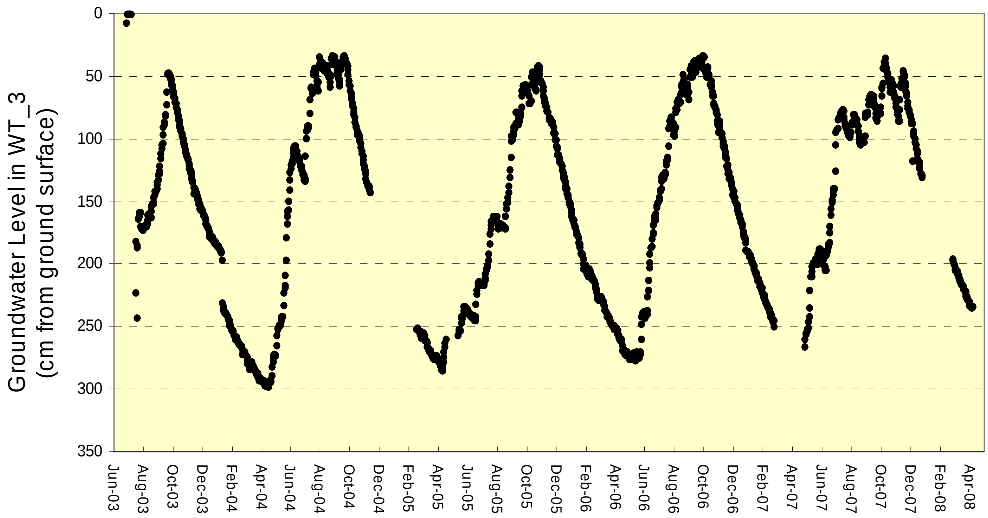


Figure 4.5 Observation Result of Groundwater Level Fluctuation (WT-3)

The above graph shows the original data from monitoring site of WT-3. As erroneous data has been found in the original data, it is indispensible to inspect the data before using. The inspection results are given in Table 4.8.

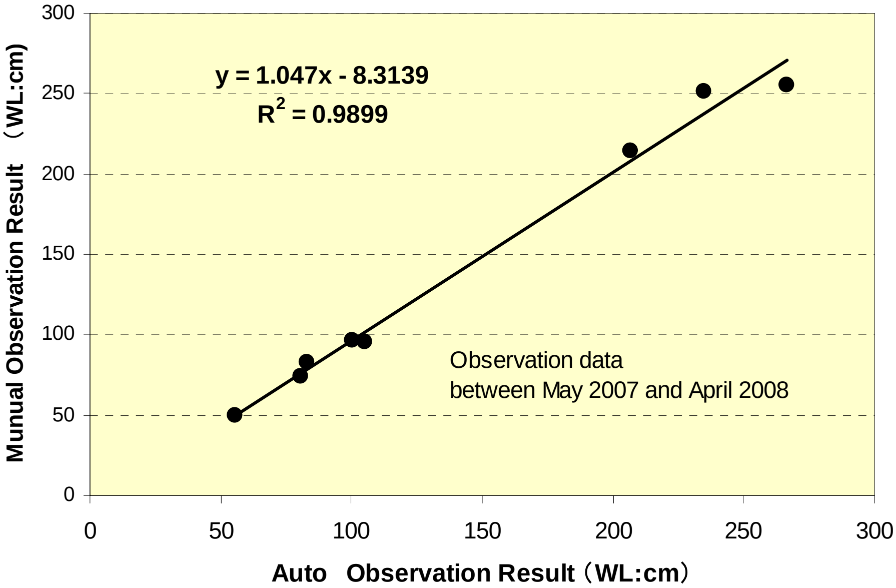


Figure 4.6 Examination of Auto Observation Result with Manual Observation Data (WT-3)

A high correlation can be found by comparing the auto observation result with manual observation result as shown in Figure 4.6. Therefore, it can be considered that the auto observation equipment at WT-3 correctly recorded the groundwater level fluctuation within the whole monitoring duration from 2003 to 2008.

(2) Monitoring Site WT-4

Figure 4.7 shows the original monitoring data obtained from automatic recording logs of the monitoring well WT-4. Compared to the observation results from monitoring well WT-3, the result from monitoring well WT-4 shows intense and abnormal fluctuation in groundwater levels.

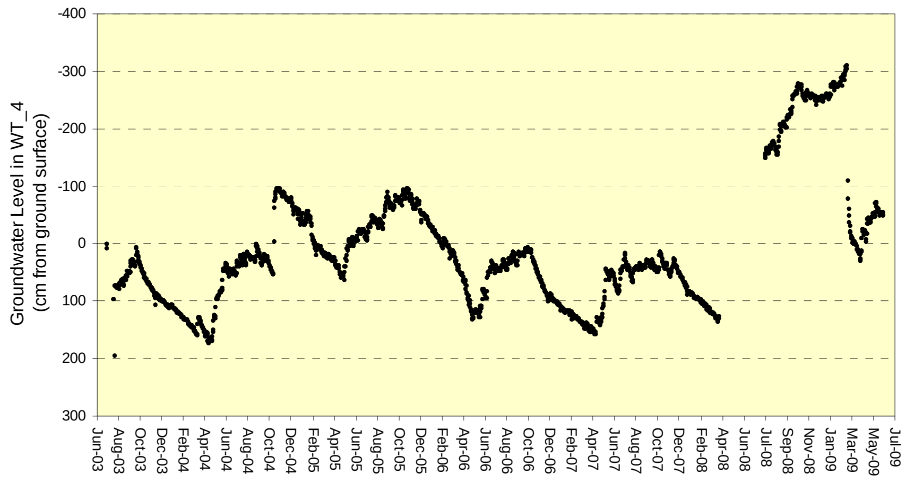


Figure 4.7 Observation Result of Groundwater Level Fluctuation (WT-4)

The above graph shows the original data from monitoring site of WT-4. As erroneous data has been found in the original data, it is indispensible to inspect the data before using. The inspection results are given in Table 4.8.

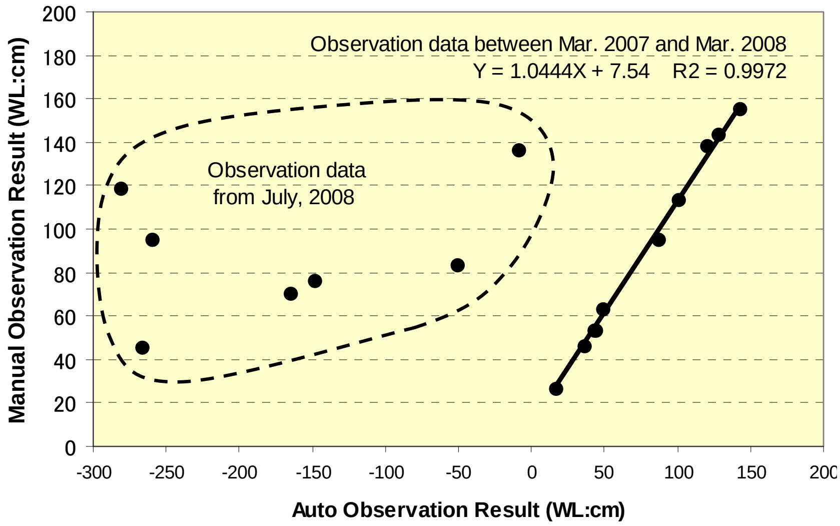


Figure 4.8 Examination of Auto Observation Result with Manual Observation Data (WT-4)

As shown in Figure 4.8, the examination of the auto observation results using the manual observation data shows a high correlation for period of about one year from March 2007 to March 2008. However, no significant correlation can be identified after March 2008 between the two data sets. That is, large errors can be confirmed to have been included in the auto observation results from March 2008, and it is impossible to correctly revise the data. The result of inspection indicates that the reliable data duration for WT-4 is limited from March 2007 to March 2008.

(3) Monitoring Site WT-5

Figure 4.9 shows the original monitoring data obtained from automatic recording logs of the monitoring well WT-5. Observation result in this groundwater monitoring well site shows two kinds of groundwater fluctuation patterns. The groundwater level changes in a range from 2 m to 7 m below ground surface before November 2005; and in another range from 1 m to 4 m after March 2006.

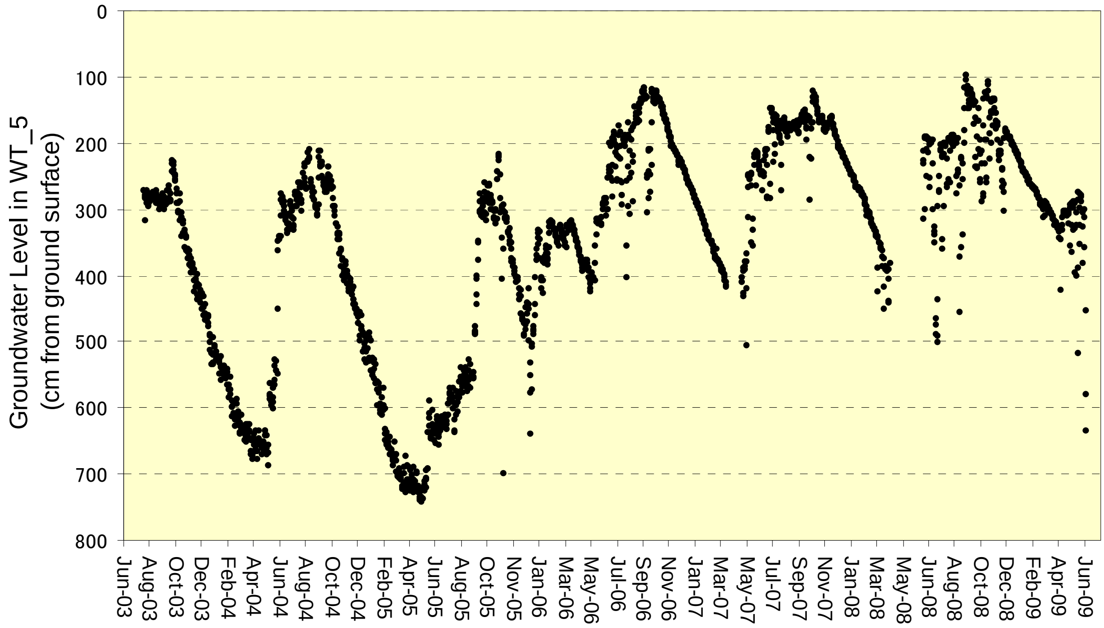


Figure 4.9 Observation Result of Groundwater Level Fluctuation (WT-5)

The above graph shows the original data from monitoring site of WT-5. As erroneous data has been found in the original data, it is indispensible to inspect the data before using. The inspection results are given in Table 4.8.

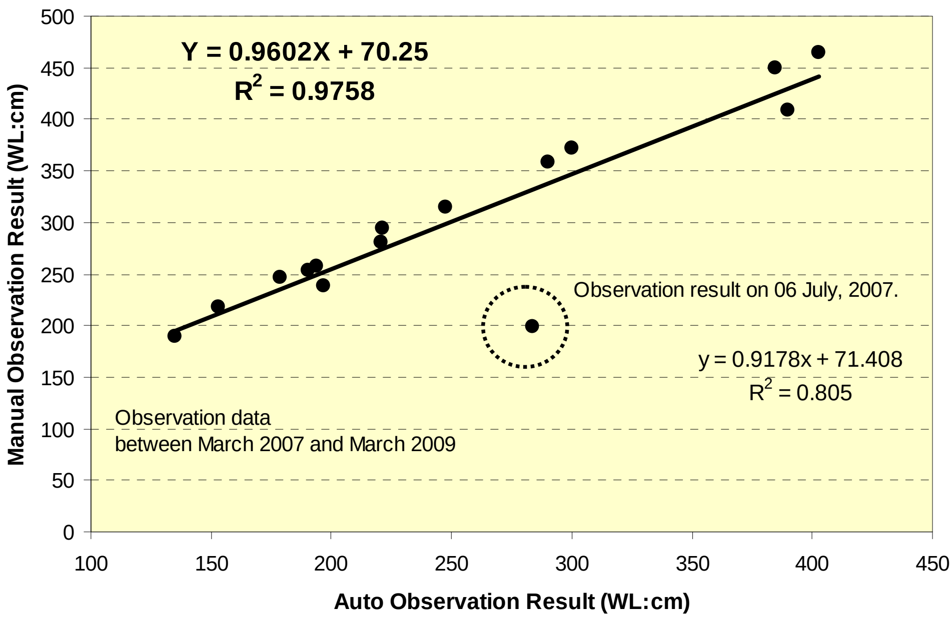


Figure 4.10 Examination of Auto Observation Result with Manual Observation Data (WT-5)

Because manual observation started from March 2007, it's impossible to check or correct the data before March 2007. On the other hand, when examine the correlation between the two data sets of auto observation and manual observation, a relatively high correlation can be confirmed except the few obviously erroneous data, as shown in Figure 4.10. The result of inspection indicates that the reliable data duration for WT-5 can be considered from March 2007 to March 2009. However, when the reliable data from WT-5 is used for analysis, attention has to be paid because some wrong data are still included within this duration.

(4) Monitoring Site WT-6

Figure 4.11 shows the original monitoring data obtained from automatic recording logs of the monitoring well WT-6. The figure shows the water level fluctuation from 9 m above ground surface and 3 m below the ground surface. It is clear that the result of groundwater level of 9 m over ground surface is not true. But if this value is changed to 1 m below ground surface by referring groundwater level from other observation wells, the lower water level would be 13m below the ground surface. The groundwater level cannot be as low as this value by adjustment from the result of groundwater level simultaneous observation survey.

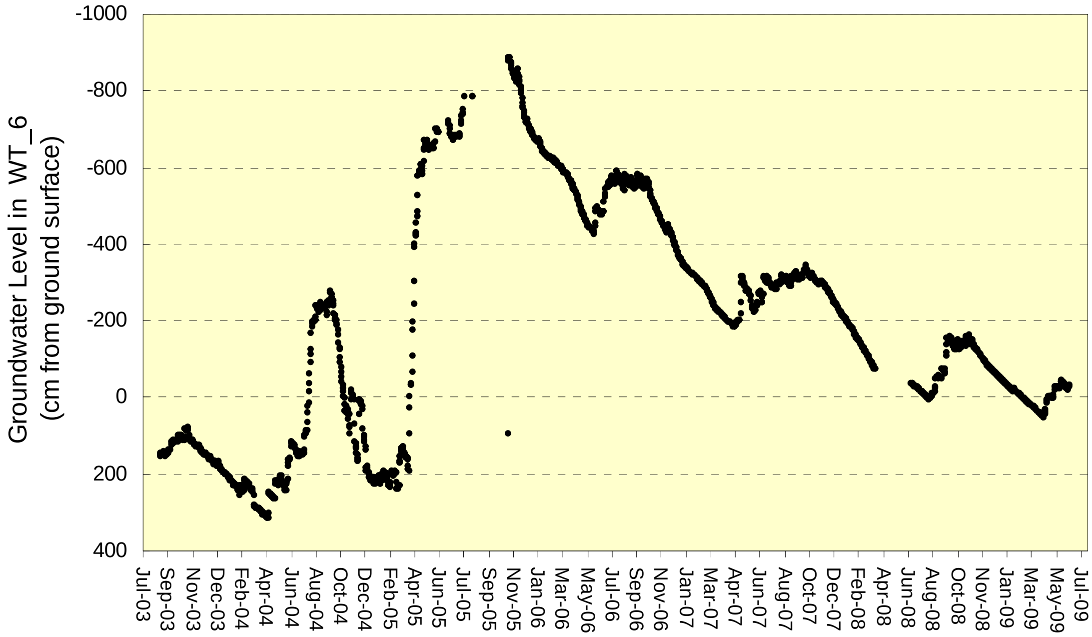


Figure 4.11 Observation Result of Groundwater Level Fluctuation (WT-6)

The above graph shows the original data from monitoring site of WT-6. As erroneous data has been found in the original data, it is indispensible to inspect the data before using. The inspection results are given in Table 4.8.

When comparing the results of the two data sets between auto observation and manual observation, high correlation can be confirmed in the period from July 2008 to June 2009 as shown in Figure 4.12. The figure also shows the fact that there is no significant correlation between the two data sets before March 2008. Therefore, the result of inspection indicates that the reliable data duration for WT-6 is limited from July 2008 to June 2009.

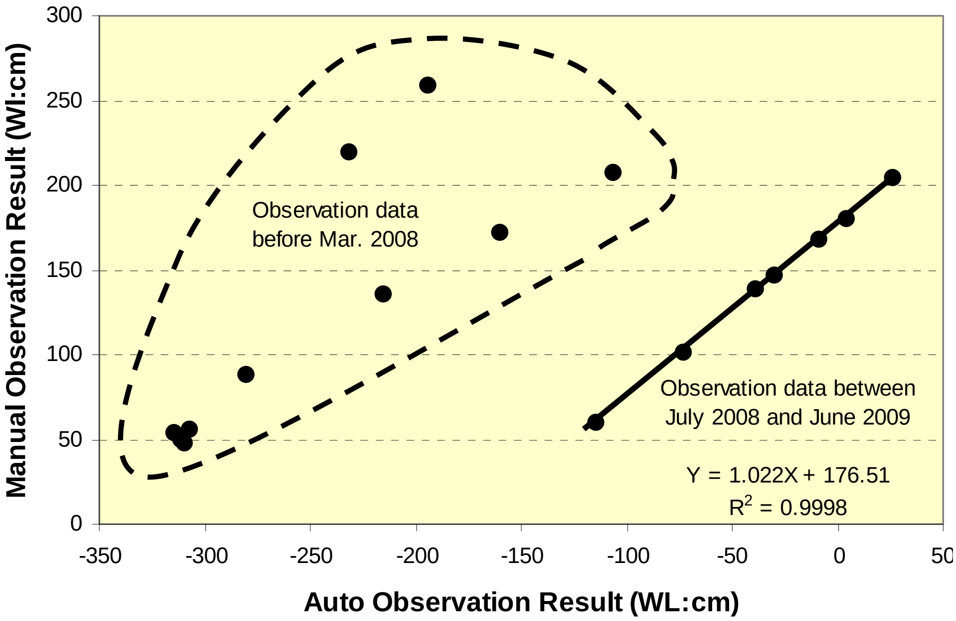


Figure 4.12 Examination of Auto Observation Result with Manual Observation Data (WT-6)

(5) Monitoring Site WT-7

Figure 4.13 shows the original monitoring data obtained from automatic recording logs of the monitoring well WT-7. Groundwater level in monitoring well site WT-7 is sometimes above ground surface. This is generally considered as an abnormal value. However, a photo in Figure 4.14 shows that the groundwater level was about 10 cm above the ground surface of the cabin, when the well site was checked in September 2009 during this survey. In addition, the remains of mud in the lower part of the well pipe indicate that the groundwater level had been as high as 20 cm above ground surface. Therefore, the data might be considered to have recorded the groundwater fluctuation of site WT-7 correctly. The figure shows a relatively regular groundwater level fluctuation pattern, except some obviously erroneous data.

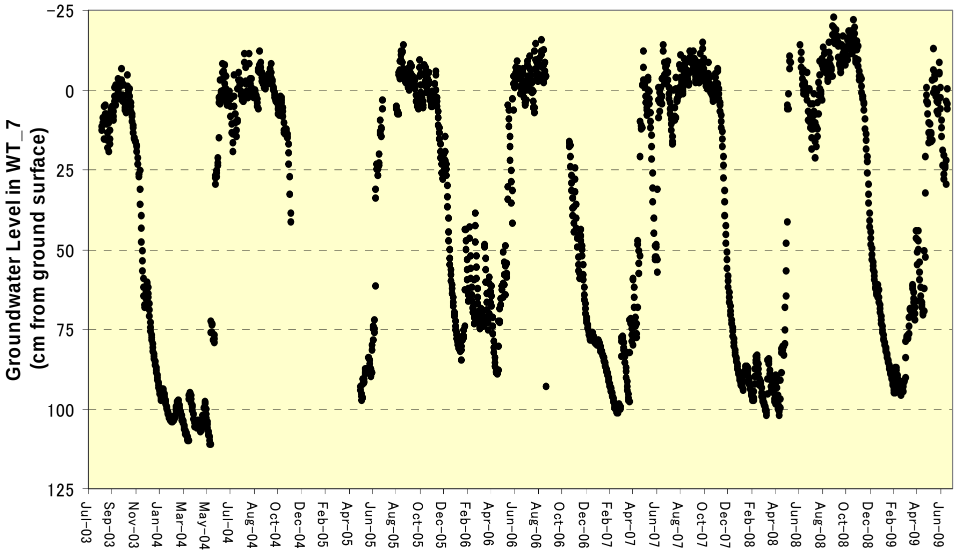


Figure 4.13 Observation Result of Groundwater Level Fluctuation (WT-7)

The above graph shows the original data from monitoring site of WT-7. As erroneous data has been found in the original data, it is indispensible to inspect the data before using. The inspection results are given in Table 4.8.

Figure 4.14 Photograph of the Observation Cabin of Monitoring Site WT-7 (September 11, 2009)

A high correlation can be seen in Figure 4.15 between the two data sets over whole corresponding observation period from March 2007 to June 2009. Because Figure 4.13 showed the regular groundwater level fluctuation in this site, all of the results of groundwater level observation in monitoring well WT-7 can be considered as available for groundwater analysis from 2003 to 2009.

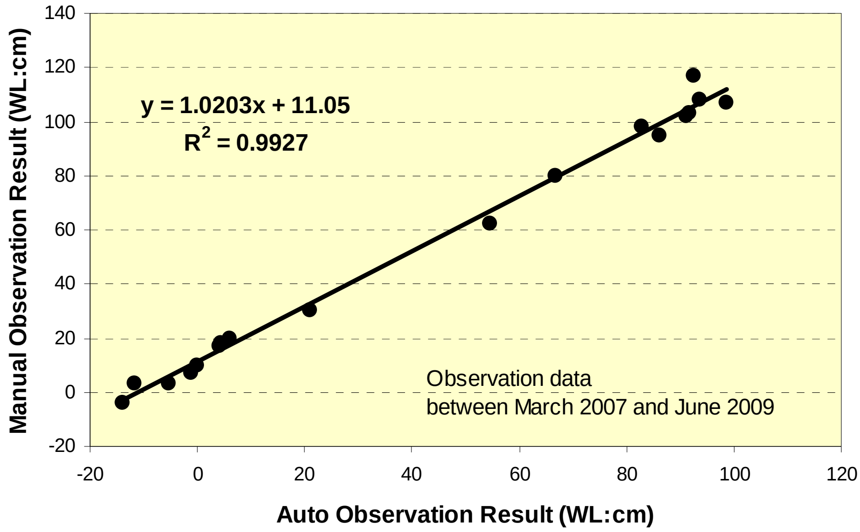


Figure 4.15 Examination of Auto Observation Result with Manual Observation Data (WT-7)

(6) Monitoring Site WT-8

Figure 4.16 shows the original monitoring data obtained from automatic recording logs of the monitoring well WT-8. Automatic observation equipment was installed in this site in 2003. However, the equipment was lost within a year of installation. Therefore, only 5 months of data for the well is available from August, 2003 to January, 2004.

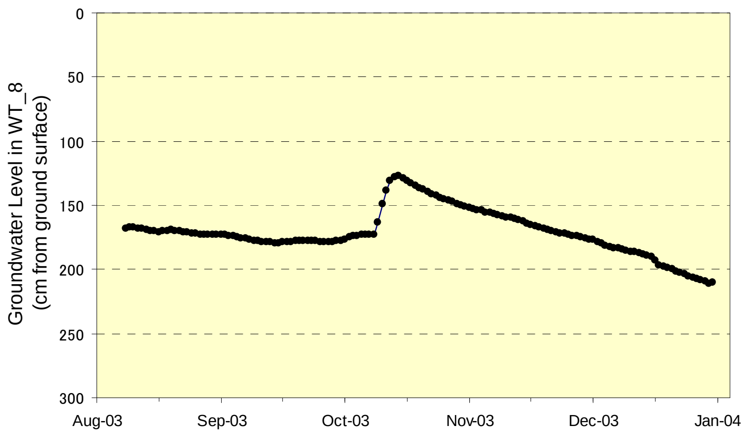


Figure 4.16 Observation Result of Groundwater Level Fluctuation (WT-8)

The above graph shows the original data from monitoring site of WT-8. As erroneous data has been found in the original data, it is indispensible to inspect the data before using. The inspection results are given in Table 4.8.

(7) Groundwater and Land Displacement Monitoring Site LTa

Monitoring site LTa is not only for groundwater level observation, but also for observation of land subsidence. Two observation wells were constructed in the same site, for observation of water levels and land displacements in the shallow aquifer and the deep aquifer, respectively.

Figure 4.17 shows the original monitoring data of groundwater levels for the deep and shallow aquifers in the site of LTa.

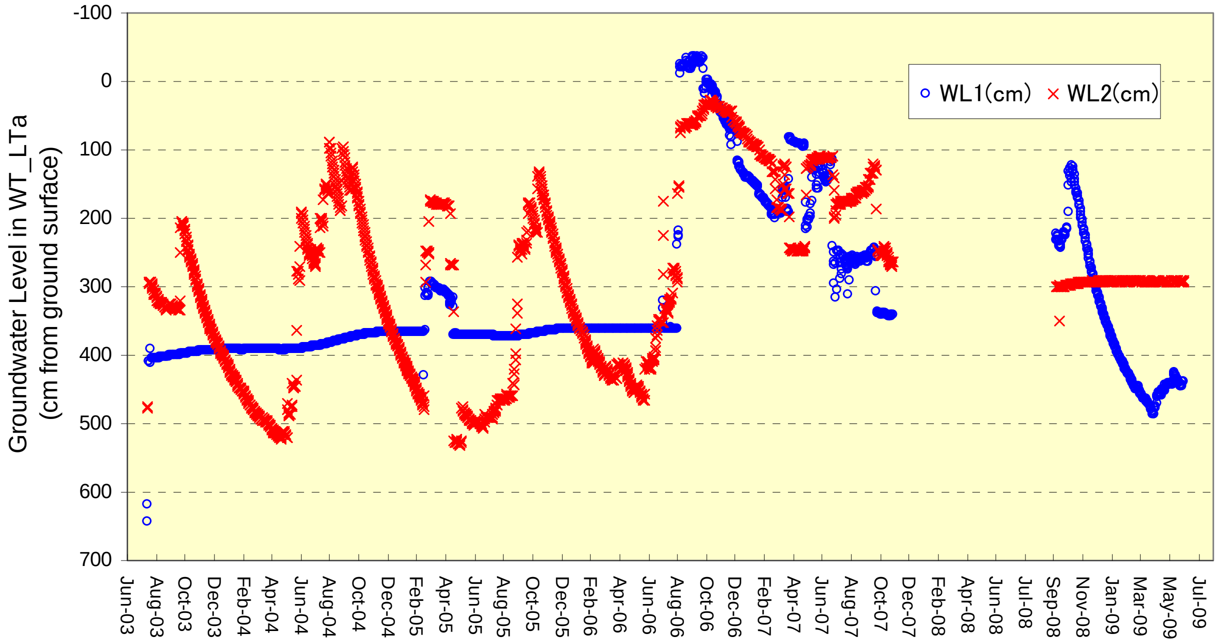


Figure 4.17 Observation Result of Groundwater Level Fluctuation (LTa)

The above graph shows the original data from monitoring site of LTa. As erroneous data has been found in the original data, it is indispensible to inspect the data before using. The inspection results are given in Table 4.8.

In the first 3 years, from August 2003 to August 2006, the result can be considered as properly taken to clearly show the difference of groundwater fluctuation between the shallow and deep aquifers. However, the result became confused from August 2006 to September 2008, including a period of missing data of about 1 year. After the missing data period, the observation was restarted from September 2008, but the fluctuation pattern of the shallow aquifer and deep aquifer becomes exactly opposite, showing the problem of contrary connection of sensors and data logs.

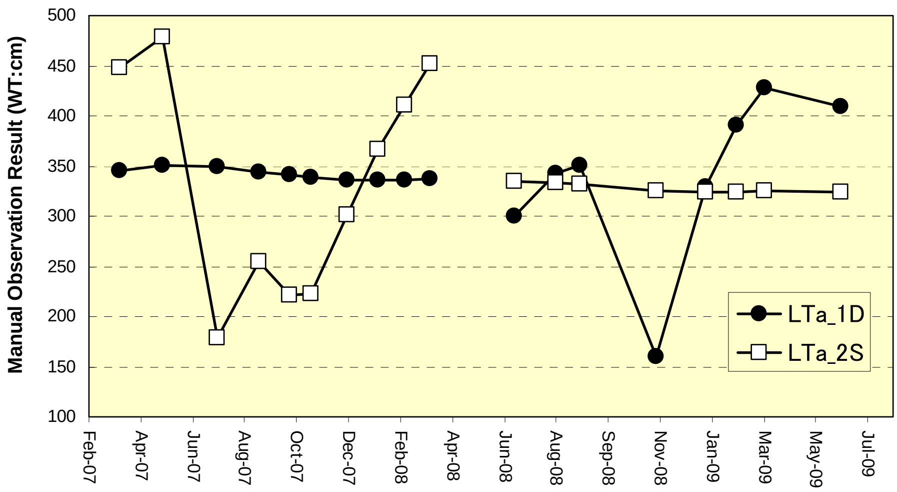


Figure 4.18 Manual Observation Result in Monitoring Site (LTa)

An attempt was made to check the automatic observation results using the manual observation results. However, as shown in Figure 4.18, the manual observation gave the same results as the auto observation, that is, the pattern of groundwater level fluctuation thoroughly changed in 2008. The only imaginable reason for this kind of result is that after the period of missing data (from March 2008 to June 2008), the wrong well numbers were recorded on the manual observation sheet.

Even though the data was rearranged, the examination by comparing the automatic observation result with manual observation result, still gives no acceptable correlation between the two data sets as shown in Figure 4.19 and Figure 4.20. Therefore, the groundwater monitoring data in well site of LTa should be considered as unavailable for analysis.

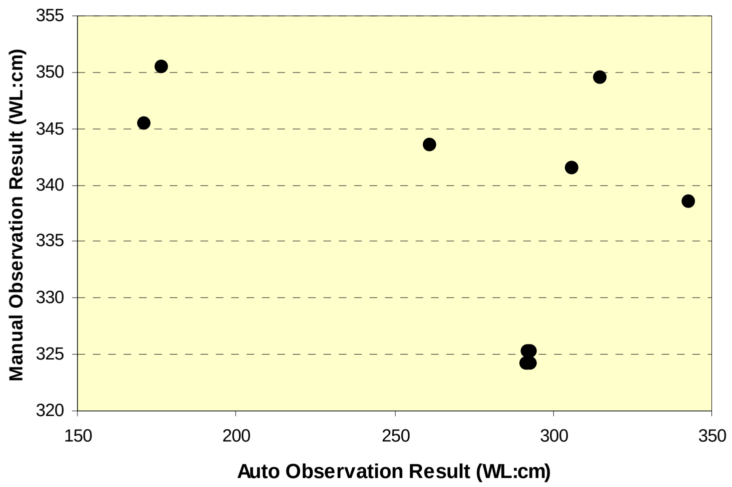


Figure 4.19 Examination of Auto Observation Result with Manual Observation Data (LTa; Deep aquifer)

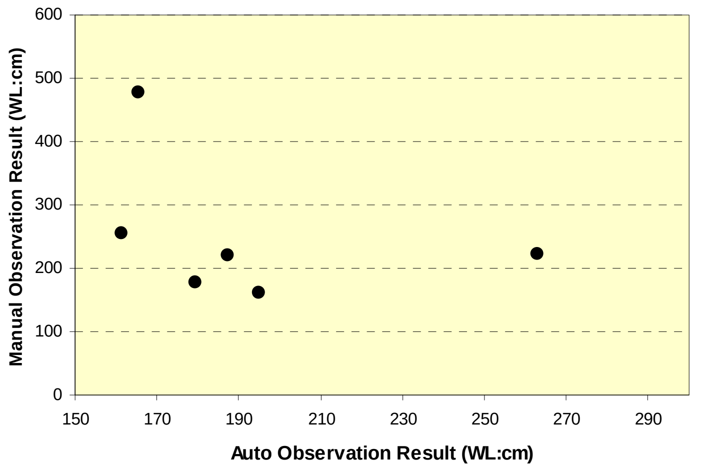


Figure 4.20 Examination of Auto Observation Result with Manual Observation Data (LTa; Shallow aquifer)

(8) Groundwater Level Monitoring Site LTb

The same as monitoring well site LTa, two wells were constructed in site LTb for groundwater level and land displacement observation in the shallow and deep aquifers, respectively. Figure

4.21 shows the original monitoring data of groundwater levels for the deep and shallow aquifers in the site.

As mentioned above, in another land displacement observation well LTa, the groundwater level result includes too much error that makes the water level observation result difficult for groundwater analysis. In contrast, the groundwater level observation result in site LTb shows high regular fluctuation patterns for both the shallow and deep aquifers.

Relatively high correlations can also be found from Figure 4.22 and Figure 4.23 for confirmation of reliability of the groundwater level observation results in the two aquifers. Even though the manual observation duration is from March 2007 to March 2009, all data in this site of LTb can be considered as reliable for groundwater analysis because of the high regular fluctuation patterns in both shallow well and deep well.

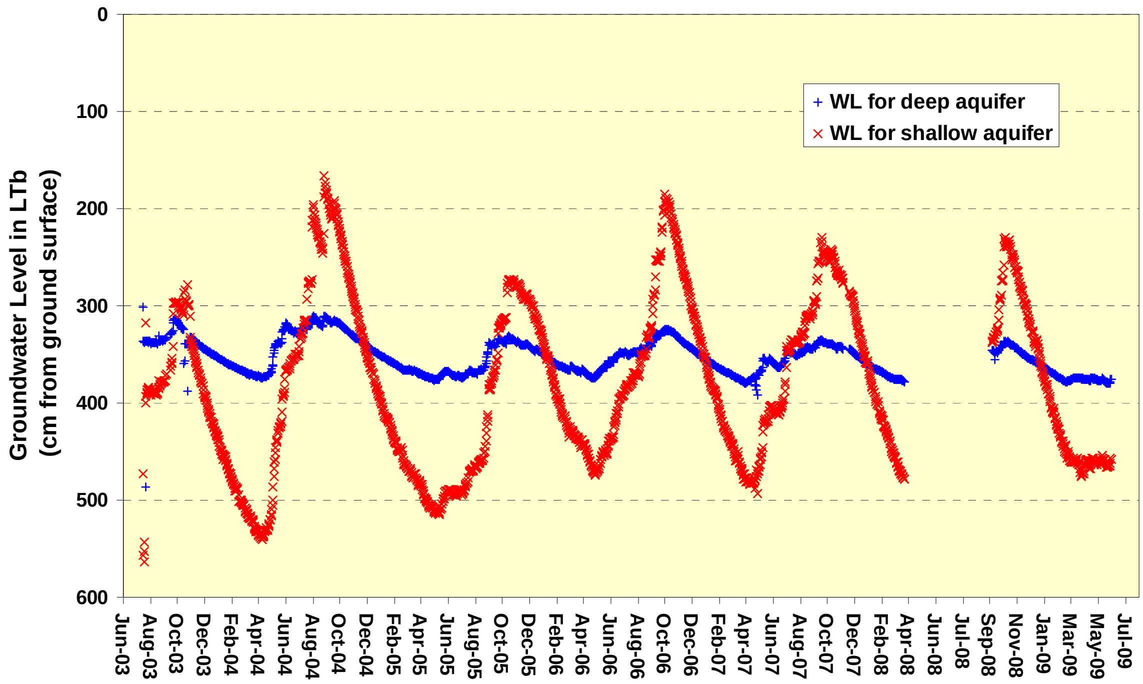


Figure 4.21 Observation Result of Groundwater Level Fluctuation (LTb)

The above graph shows the original data from monitoring site of LTb. As erroneous data has been found in the original data, it is indispensible to inspect the data before using. The inspection results are given in Table 4.8.

The only reliable groundwater level observation results for both the shallow and deep aquifers in the same site released very important information in the Siem Reap area. The following conclusions can be reached from the examination of groundwater fluctuations results shown in Figure 4.21.

1) Groundwater level fluctuation pattern:

Both the deep aquifer and the shallow aquifer have a similar groundwater level fluctuation pattern. Groundwater level goes up in the rainy season, and down in the dry season, indicating the groundwater recharges for both aquifers are based on alternation of seasons. In the rainy season the recharge amount is more than consumption, and vice versa.

2) The water level difference between the two aquifers

Both the shallow aquifer and the deep aquifer have similar level fluctuation pattern, as mentioned above. However, values of groundwater level in the two aquifers are different almost throughout the whole observation period. A very clear fact is that, compared to the deep aquifer, the water level in the shallow aquifer is higher in the rainy season, but lower in the dry season.

It is supposed that everyone has some common sense about water flow. Water flows from a higher to a lower place. This common sense is also the cardinal rule of groundwater flow. In a stricter sense of groundwater flow mechanism, groundwater flows from areas of high energy to areas of low energy. The energy here is the sum of potential energy and kinetic energy. In the natural condition in Siem Reap, the groundwater flows at a negligibly slow speed. Therefore, the groundwater flow can be considered as mostly controlled by potential energy, that is, by groundwater level. Hence, if the groundwater flows between the shallow aquifer and deep aquifer, the groundwater flow direction will change as:

- Flowing downward from the shallow aquifer to the deep aquifer in the rainy season, and
- Flowing upward from the deep aquifer to the shallow aquifer in the dry season.

The real groundwater flow direction is not only controlled by water level, but also depends on the aquifer structure or permeability. Even though the obvious water level difference has been shown in Figure 4.21 between shallow aquifer and deep aquifer, the flow amount may be so small that almost no flow happens, if the permeability between the two aquifers is small enough.

3) The water level fluctuation range:

The water level fluctuation range in a deep aquifer is much smaller than that in a shallow aquifer. As it is well known that in a sealed container full of water, water pressure is momentarily transmitted completely and evenly throughout the container. On the other hand, both shallow aquifer and deep aquifer are recharged by precipitation as mentioned above. In the rainy season, the shallow aquifer can directly get recharge from precipitation and then the water level goes up. If the water level in deep aquifer depends on the shallow aquifer directly above it, immediately or within very short time the ground water level in deep aquifer should equal or nearly equal to the water level in shallow aquifer.

However, as shown in Figure 4.21, over almost the whole observation period, the water level in the deep aquifer is different from that in the shallow aquifer. And the water level in deep aquifer can never get to the peaks and/or dips in the shallow aquifer. This fact indicates the shallow aquifer and the deep aquifer belong to different aquifer systems. Rather than shallow aquifer, the water level in deep aquifer is controlled mainly by the water level in the surrounding places of the deep aquifer itself. An aquiclude must exist between the deep aquifer and shallow aquifer to make the water level between the two aquifers different almost all of the time. And to make the water level fluctuation range different in the two aquifers.

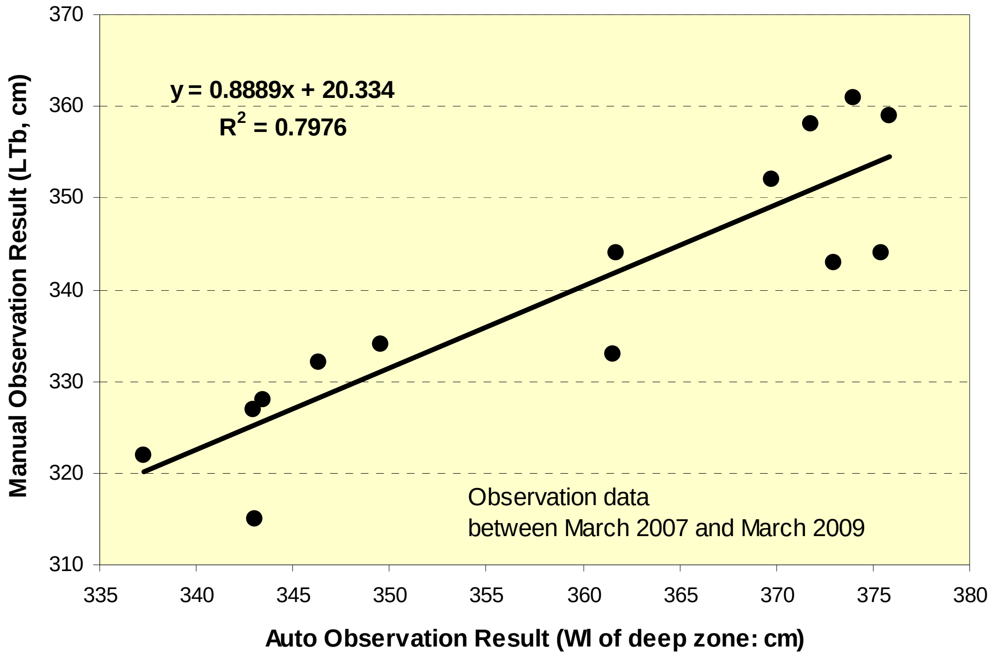


Figure 4.22 Examination of Auto Observation Result with Manual Observation Data (LTb; Deep Aquifer)

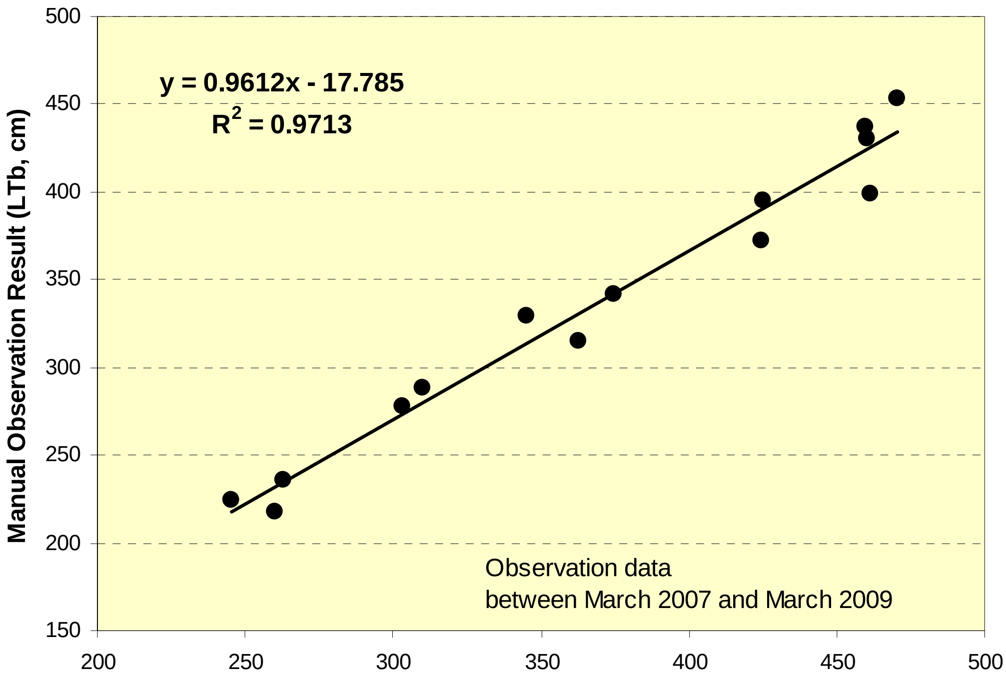


Figure 4.23 Examination of Auto Observation Result with Manual Observation Data (LTb; Shallow Aquifer)

4-4-3 Result of Land Displacement Monitoring

(1) Result of Land Displacement Observation in Site of LTa

Figure 4.24 shows the original monitoring results of land displacement for deep and shallow aquifers of the monitoring site LTa. Except the obvious error observation data from November 2006 to July 2008, the observation results show the following points:

1) Land displacement has been observed in both the deep aquifer and the shallow aquifer.

2) The patterns of land displacement fluctuations in both aquifers are almost the same.

3) The land displacement fluctuation coincides with groundwater level fluctuation, changes according to the alternation of seasons.

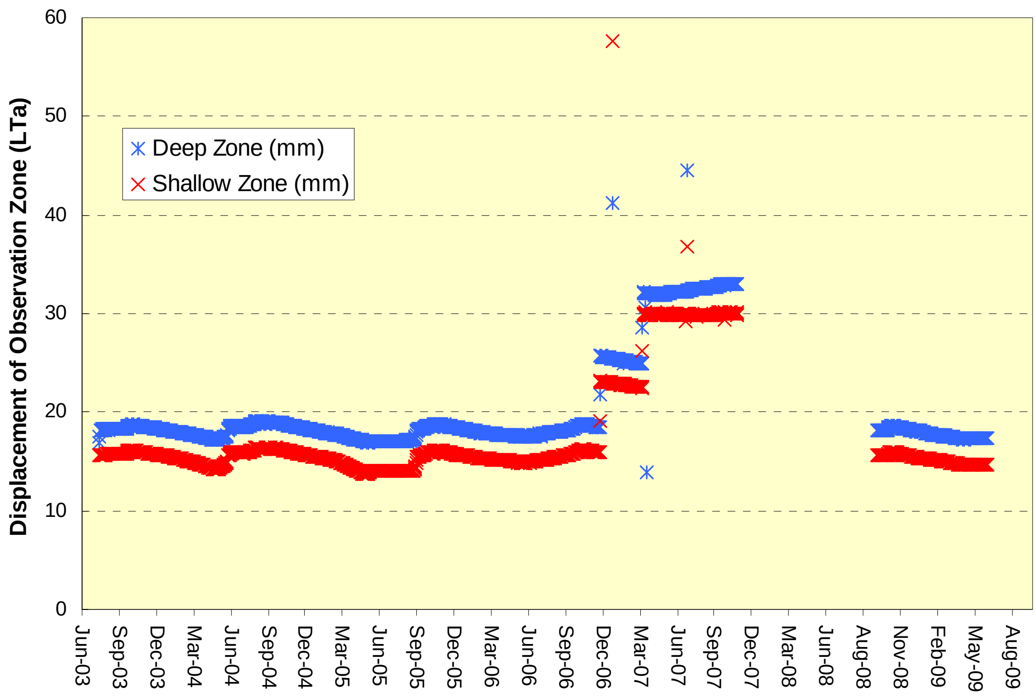


Figure 4.24 Land Displacement Observation Result in LTa

To confirm the tendency of land displacement within the circulations of seasonal fluctuation, the monthly average displacement value was calculated and shown in Table 4.4 and Table 4.5 for the deep aquifer and the shallow aquifer, respectively.

The observation of land displacement in the deep aquifer was started from August 2003 and continued for about 6 years up to May 2009, when the groundwater analysis began in this survey. However, as shown in Table 4.4, total length of missing data is as long as about 23 months, about 1/3 of the whole observation period. Examination by the available data results in a maximum displacement range of 18.96−17.06 = 1.9 (mm) for the deep aquifer (with depth of 71.9 m from ground surface).

Table 4.4 Monthly Summarizing Result of Measured Values in Land Displacement Measurement Gauge in Deep Aquifer of LTa

(mm)

Month	2003	2004	2005	2006	2007	2008	2009	Max.	Min.	Avrg,
Jan.	--	18.21	18.12	18.20	--	--	18.03	18.21	18.03	18.15
Feb.	--	17.99	17.88	17.98	--	--	17.76	17.99	17.76	17.92
Mar.	--	17.76	17.64	17.80	--	--	17.57	17.80	17.57	17.71
Apr.	--	17.50	17.30	17.72	--	--	--	17.72	17.30	17.56
May	--	17.24	17.06	17.61	--	--	17.33	17.61	17.06	17.37
Jun.	--	18.07	17.09	17.59	--	--	17.37	18.07	17.09	17.64
Jul.	--	18.55	17.06	17.77	--	--	--	18.55	17.06	17.98
Aug.	18.14	18.87	17.11	18.01	--	--	--	18.87	17.11	18.20
Sep.	18.26	18.96	17.82	18.21	--	--	--	18.96	17.82	18.44
Oct.	18.49	18.91	18.59	18.67	--	18.21	--	18.91	18.21	18.63
Nov.	18.60	18.64	18.71	18.60	--	18.52	--	18.71	18.52	18.63
Dec.	18.42	18.38	18.47	--	--	18.27	--	18.47	18.27	18.40
Max.	18.60	18.96	18.71	18.67		18.52	18.03	18.96		
Min.	18.14	17.24	17.06	17.59		18.21	17.33		17.06	
Avrg,	18.38	18.26	17.74	18.01		18.33	17.61			18.02

(Note) This measured value does not directly indicate land displacement value but only scale value from criteria.

For the shallow aquifer in the same site of LTa, the observation period and length of missing data are the same as for the deep aquifer. Based on the available data, the maximum land displacement in the shallow aquifer is 16.31－13.86 = 2.45(mm) as shown in Table 4.5.

Table 4.5 Monthly Summarizing Result of Measured Values in Land Displacement Measurement Gauge in Shallow Aquifer of LTa

(mm)

Month	2003	2004	2005	2006	2007	2008	2009	Max.	Min.	Avrg,
Jan.	--	15.59	15.47	15.56	--	--	15.37	15.59	15.37	15.52
Feb.	--	15.31	15.24	15.36	--	--	15.20	15.36	15.20	15.29
Mar.	--	15.00	14.85	15.22	--	--	15.00	15.22	14.85	15.06
Apr.	--	14.63	14.24	15.11	--	--	--	15.11	14.24	14.77
May	--	14.30	13.86	14.96	--	--	14.69	14.96	13.86	14.55
Jun.	--	15.37	14.07	14.93	--	--	14.72	15.37	14.07	14.89
Jul.	--	15.89	14.04	15.16	--	--	--	15.89	14.04	15.25
Aug.	15.69	16.20	14.01	15.43	--	--	--	16.20	14.01	15.51
Sep.	15.76	16.31	14.96	15.65	--	--	--	16.31	14.96	15.80
Oct.	15.96	16.26	15.89	16.09	--	15.64	--	16.26	15.64	16.02
Nov.	15.99	16.00	16.03	16.02	--	15.88	--	16.03	15.88	15.99
Dec.	15.78	15.72	15.78	--	--	15.60	--	15.78	15.60	15.73
Max.	15.99	16.31	16.03	16.09	--	15.88	15.37	16.31		
Min.	15.69	14.30	13.86	14.93	--	15.60	14.69		13.86	
Avrg,	15.84	15.53	14.79	15.41	--	15.76	15.00			15.33

(Note) This measured value does not directly indicate land displacement value but only scale value from criteria.

When the two Tables, Table 4.4 and Table 4.5, are compared, the result seems abnormal. In cases where land displacement is observed in both the shallow and the deep aquifer in the same location, the land displacement in the deep aquifer can be calculated by the following equation:

$D_{deep} = D_{shallow} + D_{deep-shallow}$

Here:

D_{deep}: Land displacement between ground surface and the observation location of the deep aquifer.

$D_{shallow}$: Land displacement between ground surface and the observation location of shallow aquifer.

$D_{deep-shallow}$: Land displacement between the observation location of the deep aquifer and the observation location of the shallow aquifer.

Generally, land displacement in the deep aquifer is larger than in the shallow aquifer, or at least the same as the shallow aquifer. The only situation corresponding to the result of displacement in the deep aquifer smaller than the shallow aquifer is that the displacement between the shallow and deep aquifers moves in the opposite directions. That is, when the shallow aquifer is shrinking, the zone between the shallow aquifer and the deep aquifer is expanding. For this situation to occur, the water levels in different aquifers need to move in opposite directions. That is, when the water level in a shallow aquifer goes up, the water level in a deep aquifer goes down.

As shown in Figure 4.17 and discussed above, the water levels change in both aquifers has the same pattern, even though the ranges are different. That is, water level in both aquifers goes up in the rainy season and goes down in the dry season. And Figure 4.24 also shows the same pattern of displacement in both aquifers. Opposite displacement in the two aquifers can never be found in the figure.

As possibility of the cause, the following can be considered as reason of this problem: The equipment is not suitable for land displacement observation, because the precision is not high enough for very small amount of land displacement.

Figure 4.25 shows the fluctuation of land displacement in the deep aquifer corresponding to the change of season. In 6 months of rainy season, from May to October, the displacement goes in an upward direction, and in the other 6 months, the dry season from November to April, the displacement goes in a downward direction. Over the duration of the 6 years of observation, except the period of missing data, the range of land displacement is about 2 mm.

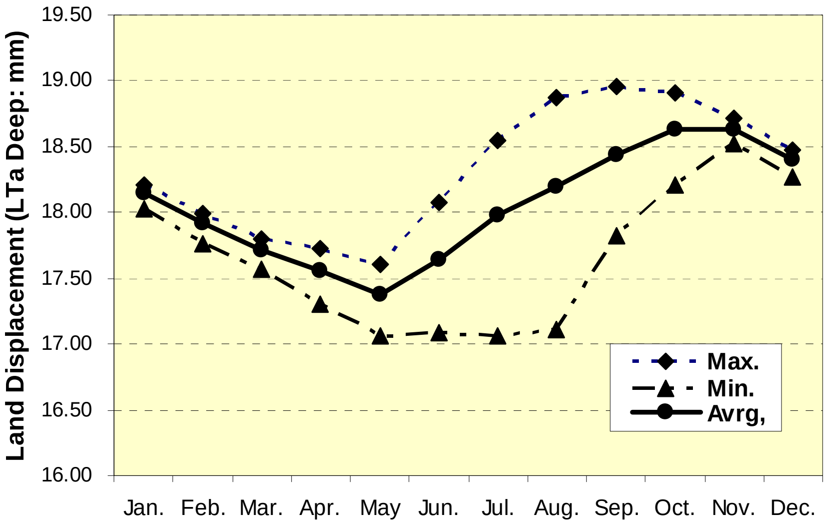


Figure 4.25 Monthly Fluctuation of Land Displacement in Deep Aquifer of LTa

Figure 4.26 shows the patterns of land displacement in the shallow aquifer. Like the deep aquifer, land displacement in the shallow aquifer fluctuates following the alternation of seasons. Over the duration of the 6 years of observation, except the period of missing data, the range of land displacement is about 2.5 mm.

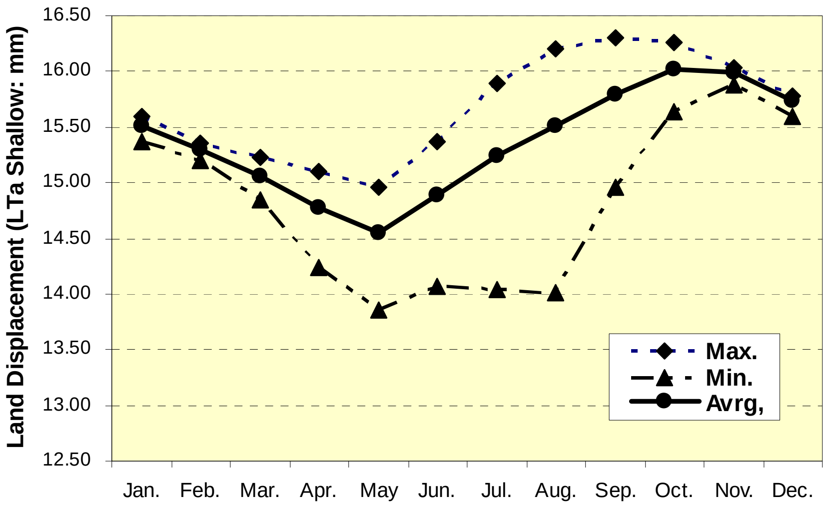


Figure 4.26 Monthly Fluctuation of Land Displacement in Shallow Aquifer of LTa

Figure 4.27 shows high coincidences of land displacement fluctuation in the shallow aquifer of LTa, with fluctuations of groundwater level and precipitation.

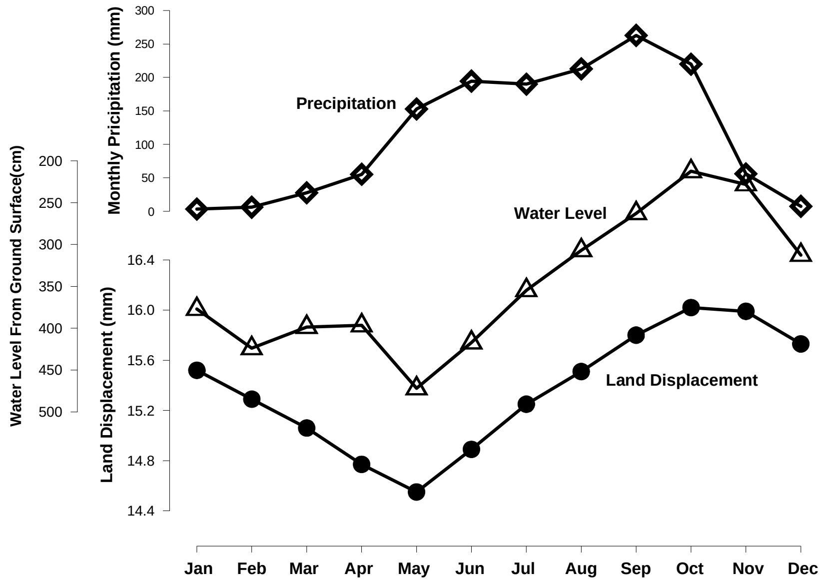


Figure 4.27 Monthly Average Values of Precipitation, Water Level and Land Displacement in LTa (Shallow Aquifer; During August 2003 to June, 2009)

The same coincidence cannot be identified in the deep aquifer of the same site of LTa as shown in Figure 4.28. Land displacement fluctuated in a similar pattern with precipitation. However, the groundwater level changes in a different pattern from those of land displacement and precipitation. Such a result is against the principle of groundwater recharge and land compaction. If a very special reason cannot be confirmed around the site of LTa, it would be a very high possibility that the observation result was wrongly recorded.

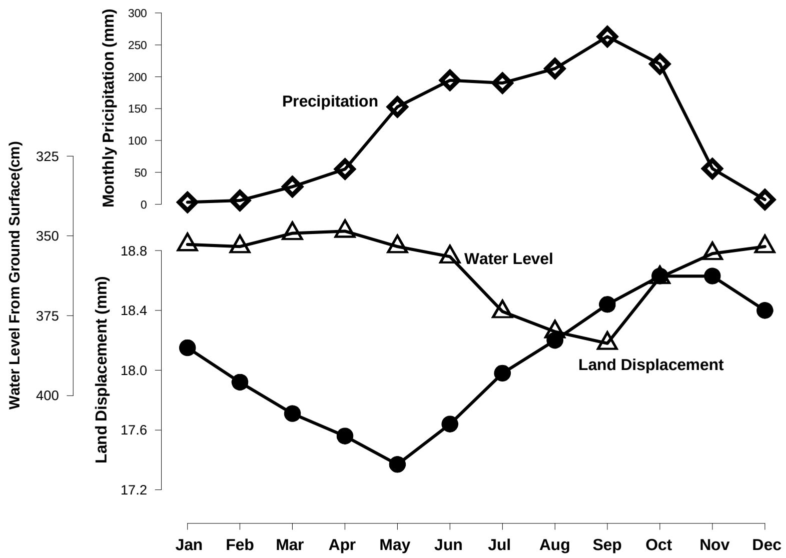


Figure 4.28 Monthly Average Values of Precipitation, Water Level and Land Displacement in LTa (Deep Aquifer; During August 2003 to June 2009)

Figure 4.29 shows the yearly average of land displacement in monitoring site of LTa (refer to Table 4.4 and Table 4.5). With merely 6 years land displacement observation results, it may be hard to conclude that land subsidence has really occurred, even though some signs of land subsidence can be found from these figures.

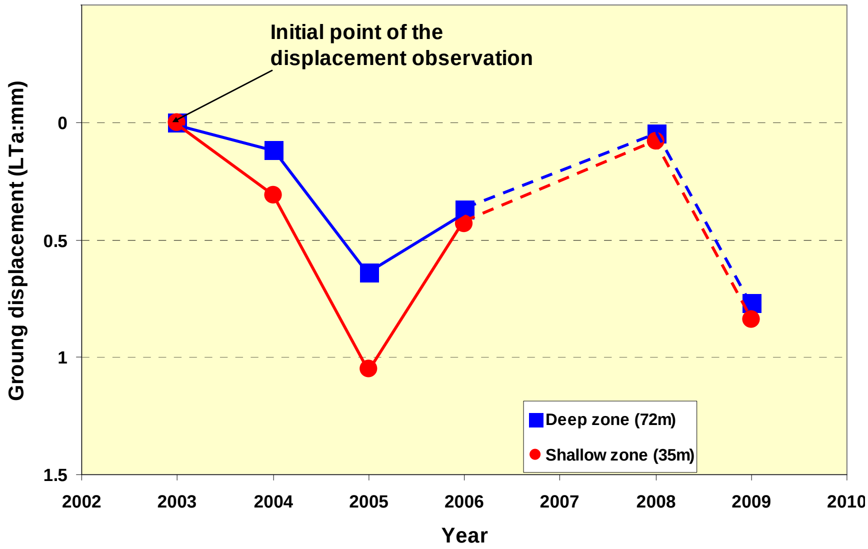


Figure 4.29 Yearly Average of Land Displacement in LTa and Result of Land Displacement Observation in LTb

Figure 4.30 shows the original monitoring results of land displacement for the deep and shallow aquifers of the monitoring site LTb. The land displacement observation in LTb started from July 2003. 6 years observation data has been collected up to July 2009. As shown in the figure, the land displacement can be considered as properly observed except some observation error and 6 months missing data from March to September in 2008.

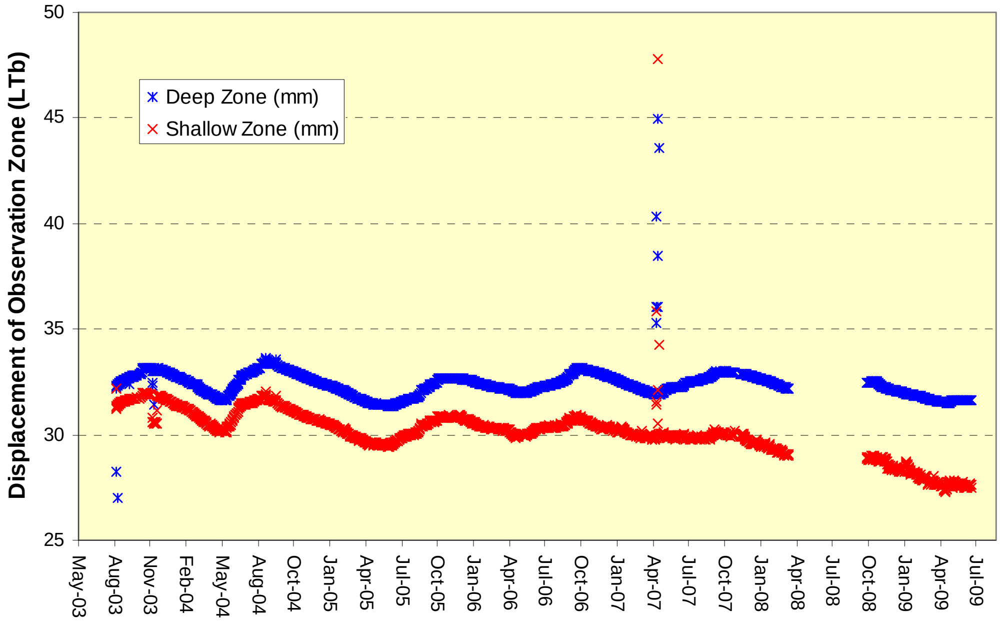


Figure 4.30 Land Displacement Observation Result in LTb

Similar to seasonal fluctuation of groundwater level, the figure shows clearly seasonal fluctuation of land displacement for both the shallow and deep aquifers. Land displacement goes up in the rainy season and down in the dry season.

The same as the analysis processing of LTa, monthly average of land displacement in the deep and shallow aquifers are calculated and shown in Table 4.6 and Table 4.7, respectively.

Maximum and minimum values of each year indicate similar seasonal fluctuation ranges for both the shallow and deep aquifers to be as about 1 mm. Over the duration of the 6 years observation from 2003 to 2009, yearly average values indicate that land displacement changes from 32.83 to 31.71 mm (deep aquifer) and 31.61 to 27.82 (shallow aquifer), respectively. Because the observation result of the last year (2009) does not include the value of the rainy season, the change of land elevation should be smaller than 1.12 mm (32.83 - 31.71) for the deep aquifer and 3.79 mm (31.61 - 27.82) for the shallow aquifer.

Table 4.6 Monthly Summarizing Result of Measured Values in Land Displacement Measurement Gauge in Deep Aquifer of LTb

(mm)

Month	2003	2004	2005	2006	2007	2008	2009	Max.	Min.	Avrg,
Jan.	--	32.71	32.39	32.56	32.62	32.62	31.93	32.71	31.93	32.51
Feb.	--	32.45	32.20	32.40	32.37	32.43	31.80	32.45	31.80	32.30
Mar.	--	32.09	31.94	32.26	32.16	32.23	31.65	32.26	31.65	32.08
Apr.	--	31.79	31.66	32.16	31.97	--	31.55	32.16	31.55	31.88
May	--	31.81	31.47	32.01	32.07	--	31.62	32.07	31.47	31.84
Jun.	--	32.56	31.40	32.08	32.24	--	31.62	32.56	31.40	32.08
Jul.	--	32.99	31.47	32.27	32.45	--	--	32.99	31.47	32.43
Aug.	32.44	33.36	31.69	32.41	32.59	--	--	33.36	31.69	32.64
Sep.	32.70	33.31	32.01	32.71	32.84	--	--	33.31	32.01	32.81
Oct.	33.07	33.06	32.44	33.11	32.97	32.49	--	33.11	32.44	32.89
Nov.	32.99	32.84	32.68	33.00	32.91	32.28	--	33.00	32.28	32.81
Dec.	32.97	32.59	32.66	32.83	32.80	32.09	--	32.97	32.09	32.70
Max.	33.07	33.36	32.68	33.11	32.97	32.62	31.93	33.36		
Min.	32.44	31.79	31.40	32.01	31.97	32.09	31.55		31.40	
Avrg,	32.83	32.62	32.01	32.49	32.49	32.36	31.71			32.37

(Note) This measured value does not directly indicate land displacement value but only scale value from criteria.

Table 4.7 Monthly Summarizing Result of Measured Values in Land Displacement Measurement Gauge in Shallow Aquifer of LTb

(mm)

Month	2003	2004	2005	2006	2007	2008	2009	Max.	Min.	Avrg,
Jan.	--	31.37	30.57	30.62	30.23	29.53	28.35	31.37	28.35	30.29
Feb.	--	31.10	30.32	30.39	30.09	29.31	28.02	31.10	28.02	30.05
Mar.	--	30.67	30.04	30.30	29.94	29.11	27.76	30.67	27.76	29.78
Apr.	--	30.30	29.77	30.20	30.01	--	27.59	30.30	27.59	29.70
May	--	30.37	29.57	29.98	29.96	--	27.64	30.37	27.64	29.65
Jun.	--	31.22	29.52	30.10	29.89	--	27.58	31.22	27.58	29.92
Jul.	--	31.56	29.71	30.32	29.85	--	--	31.56	29.71	30.60
Aug.	31.47	31.75	30.00	30.39	29.86	--	--	31.75	29.86	30.87
Sep.	31.67	31.52	30.33	30.59	29.99	--	--	31.67	29.99	30.96
Oct.	31.89	31.22	30.67	30.77	30.01	28.88	--	31.89	28.88	30.76
Nov.	31.29	30.95	30.84	30.51	29.98	28.75	--	31.29	28.75	30.52
Dec.	31.66	30.74	30.82	30.34	29.67	28.39	--	31.66	28.39	30.47
Max.	31.89	31.75	30.84	30.77	30.23	29.53	28.35	31.89		
Min.	31.29	30.30	29.52	29.98	29.67	28.39	27.58		27.58	
Avrg,	31.60	31.06	30.18	30.38	29.96	29.00	27.82			30.12

(Note) This measured value does not directly indicate land displacement value but only scale value from criteria.

Figure 4.31 and Figure 4.32 show the patterns of land displacement of monitoring site LTb in the deep and shallow aquifers, respectively. Land displacement fluctuates following the alternation of seasons. The lowest monthly average elevation appears in May, the end of the dry season, and the highest elevation in October, the end of the rainy season.

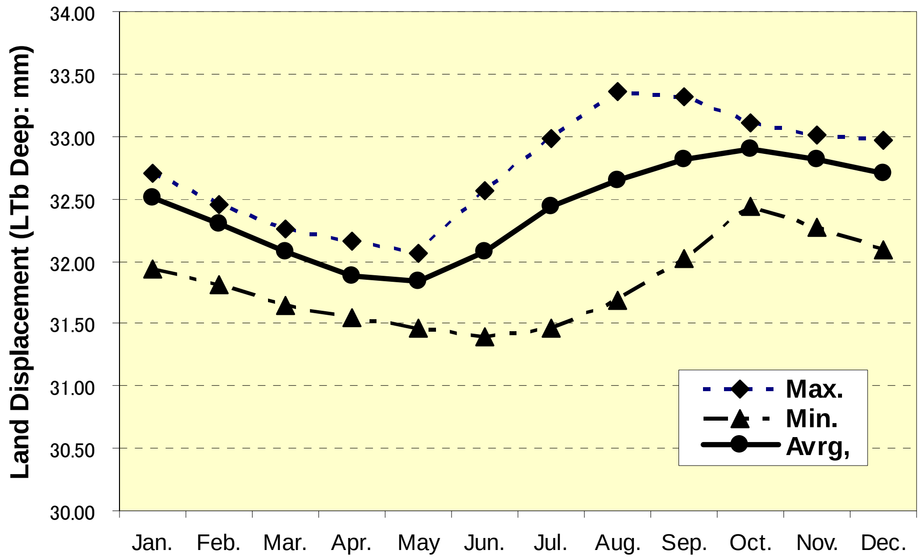


Figure 4.31 Monthly Fluctuation of Land Displacement in the Deep Aquifer of LTb

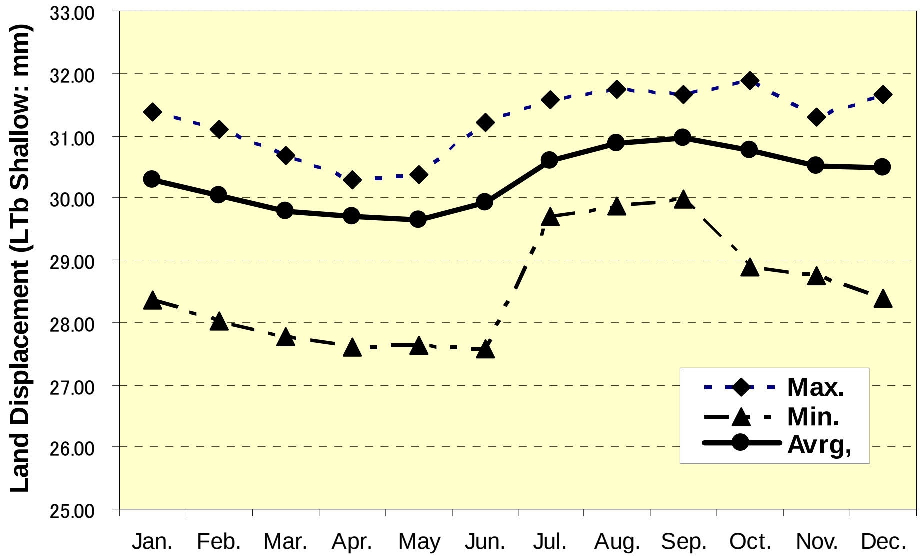


Figure 4.32 Monthly Fluctuation of Land Displacement in the Shallow Aquifer of LTb

Figure 4.33 and Figure 4.34 show the patterns of land displacement together with concerned factors of groundwater level and precipitation, for the deep and shallow aquifers, respectively. Generally, both groundwater level and land displacement goes up according to precipitation increasing in the rainy season, and goes down following precipitation decreasing in the dry season. However, compared to the change of precipitation, land displacement has more coincidence with groundwater level.

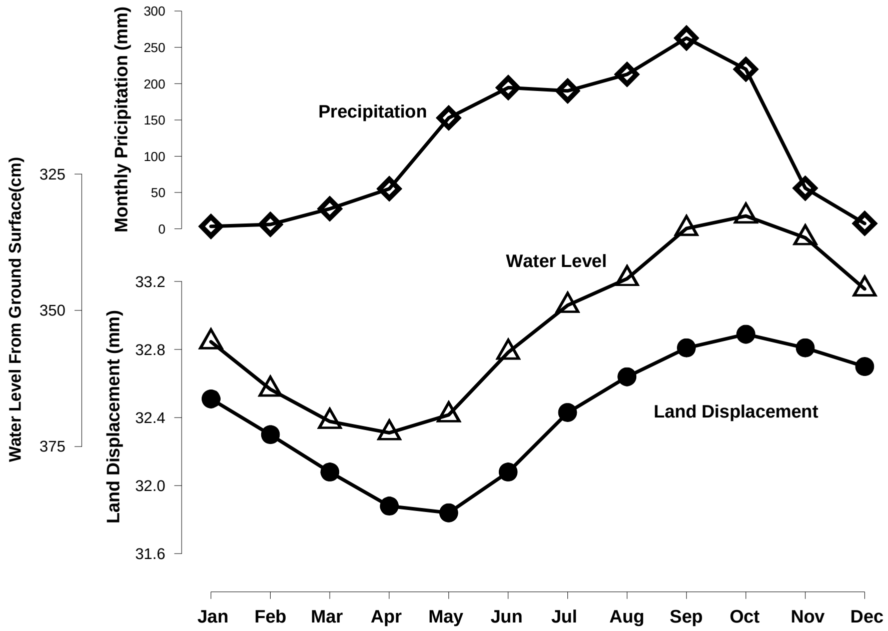


Figure 4.33 Monthly Average Values of Precipitation, Water Level and Land Displacement in Observation Site LTb (Deep Aquifer)

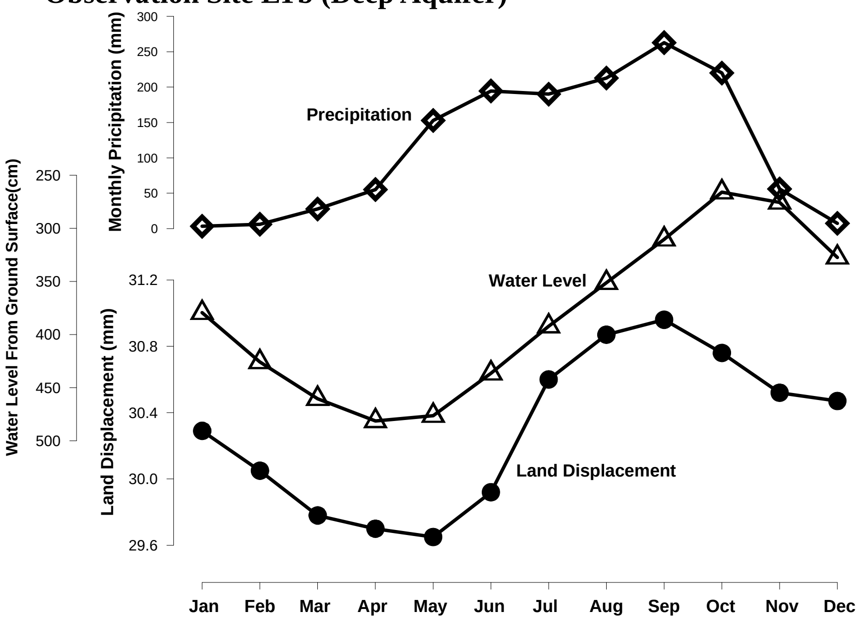


Figure 4.34 Monthly Average Values of Precipitation, Water Level

(2) Land Displacement in Observation Site LTb (Shallow Aquifer)

Figure 4.35 shows the yearly average value of land displacement in monitoring site of LTb (refer to Table 4.6 and Table 4.7). Like the result in site of LTa, the result shown in the figure can be considered as abnormal because the amount of displacement in the deep aquifer is smaller than in the shallow aquifer.

As possibility of the cause, the following can be considered as reason of this problem: The precision of the equipment is not high enough for very small amount of land displacement observation.

By the reasons of low accuracy of measurement equipment and of no appearance of land subsidence in artificial concrete building, it is considered that land subsidence does not obviously occur. However, it will be necessary to continuously monitor the observation data of land subsidence from now on.

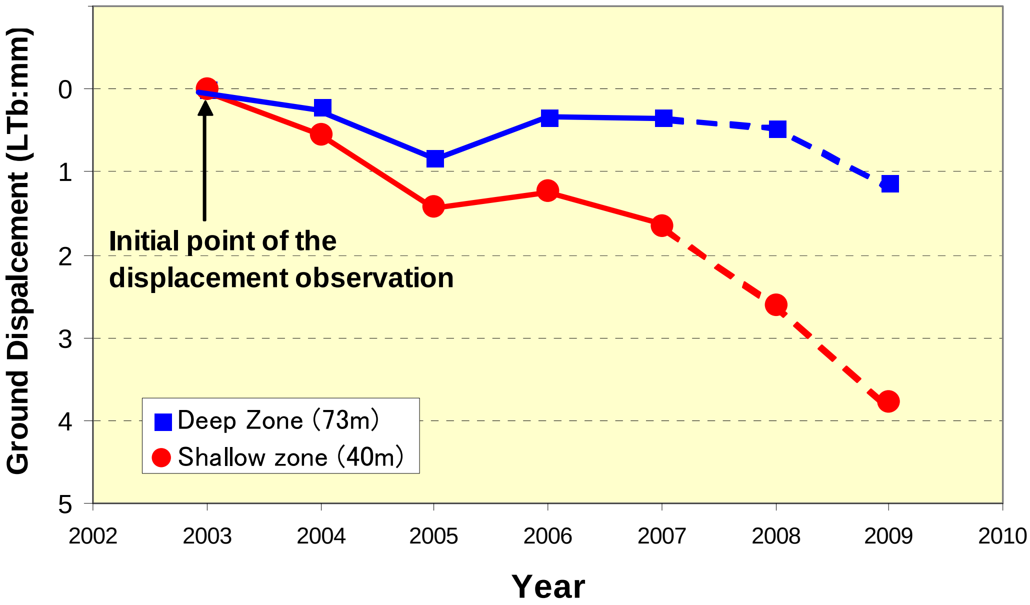


Figure 4.35 Yearly Average of Land displacement in LTb

4-5 Groundwater Recharge Analysis

4-5-1 Examination of Data Availability

Daily precipitation data from 5 meteorological observation stations and daily groundwater level data from 7 monitoring well sites in Siem Reap have been collected. Groundwater level fluctuates following the alternation of seasons or balance of precipitation and evaporation. Compared to precipitation, the fluctuation of evaporation is much smaller. Therefore, fluctuation of groundwater level can be considered as mainly following the fluctuation of precipitation.

As for the recharge of precipitation to groundwater, it is a complicated process involving several factors. In case of a storm or heavy rain, most, or the majority of precipitation will not percolate into groundwater, but discharge to rivers, and then drain to Tonle Sap Lake. On the other hand, in case of low rainfall, again, precipitation cannot recharge groundwater because the rainfall would be consumed by evaporation before getting into the groundwater table.

The relation between amounts of precipitation and groundwater recharge are controlled by factors of topography, distance of the rainfall location to the river, geology, soil type, climate (evaporation and humidity), land use, depth of groundwater level, and so on. To get enough values of all these parameters in daily units is actually impossible. Therefore, based on experiments in different kinds of simplified conditions, a lot of empirical equations have been created and used for groundwater recharge estimation. As most of the empirical equations are based on a special condition, that is, to fix almost all other factors and make only one or two factors change, the precision of the these equations' application might be a problem, especially under conditions whereby the factors omitted from the empirical equations actually play a relatively large role in groundwater recharge in the study area.

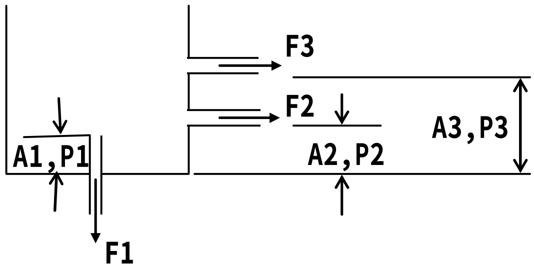
Of many methods for groundwater recharge analysis, the tank model can be considered as an excellent method that was developed by a world famous hydrologist SUGAWARA. The tank model is a kind of black box model. Although it is almost impossible to make clear values of all the concerned factors in the unit of day, it is absolutely true that the actual daily groundwater level change is the comprehensive result of all concerned factors and their daily changes. That is, when the amounts of precipitation and evaporation are directly linked to the groundwater level fluctuation by tank model, the recharge and consumption amount of groundwater will be possibly calculated as the result of comprehensive affection of all the relative factors. Because the relative factors change form site to site, it is necessary to make different tank models for all available sites for groundwater recharge and consumption calculations there.

The basic concept of the tank model is shown in Figure 4.36. A water tank is assumed as a representative of surface water system in an analysis area. All the precipitation in the area will fall into the tank to cause the water level in the tank to go up.

In case the daily precipitation is relatively small, e.g. less than daily evaporation amount, the water level increase amount is also small, not over the height of outlet F1, and then no groundwater recharge occurs. This small precipitation will store in the tank for a short time and then being consumed by evaporation.

In case of heavy rain, the water level in the tank will go up over the outlet F1 and then the recharge occurs from precipitation to groundwater. As a result of groundwater recharge, the groundwater level goes up.

Based on the fact whenever there is heavy rain, there is also discharge to rivers, the outlet F2 is specified to make the surface water discharge together with groundwater recharge. When there is a storm, the majority of precipitation discharges to rivers and then drains to Tonle Sap Lake, so that groundwater level increasing cannot be in proportion to the change in precipitation. This kind of water discharge and drainage are simulated in the tank model by specification of outlet F3.



A1: Minimum rainfall amount (mm) for occurrence of groundwater recharge.
A2: Minimum rainfall amount (mm) for occurrence of surface runoff.
A3: Minimum rainfall amount (mm) for occurrence of surface runoff peak.
F1: Outlet from the tank for groundwater recharge
F2: Outlet from the tank for surface runoff
F3: Outlet from the tank for surface water runoff peak
P1: Coefficient for groundwater recharge
P2: Coefficient for surface runoff.
P3: Coefficient for surface runoff peak.

Figure 4.36 Concept of the Tank Model

To use the tank model for groundwater recharge analysis, the data of precipitation, evaporation and groundwater level observation has to be confirmed to correspond. The Thiessen division method is used to confirm the correspondence of meteorological observation stations and groundwater monitoring sites as shown in Figure 4.37.

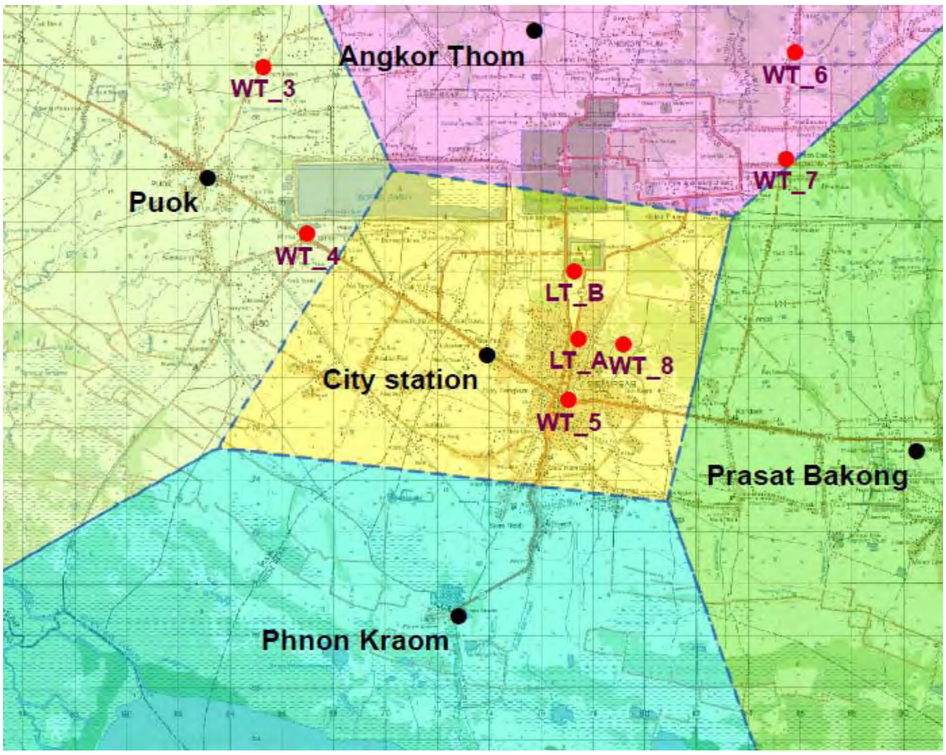


Figure 4.37 Locations of Groundwater Monitoring Well Sites and Meteorological Observation Stations in the Study Area

Not only correspondence of location between meteorological stations and groundwater monitoring sites, but also a viable duration of data serials has to be confirmed. The data availability confirmation result is shown in Table 4.8 based on the period of precipitation observation for each station and analysis of groundwater monitoring result for each site.

Table 4.8 Result of Data Availability Examination for Tank Model Creation

WL_Station	W_Duration	Rain_Station	R_Duration	Cal_ Duration
WT-3	Aug.03 - Apr.08	Puok	Mar.03 - Dec.08	Jan.04 - Apr.08
WT-4	Mar.07 - Mar.08	Puok		Mar.07 - Mar.08
WT-5	Mar.07 - Mar.09	City	Jan.88 - Dec.08	May.07 - Dec.08
WT-6	Jul.08 - Jun. 09	Angkor Thom	Jul.00 - Dec.08	Jul.08 - Dec. 08
WT-7	Aug.03 - Jun.09	Angkor Thom Prasat Bakong		Sept.03 - Dec.08
WT-8	-	City	Jan.88 - Dec.08	-
LTa	-	City		-
LTb	Sept.03 - Jun.09	City		Sept.03 - Dec.08

(Note) WL_Station: Groundwater level monitoring well code.
W_Duration: Duration of reliable groundwater level monitoring data for each well inspected by manual observation result.
Rain_Station: Metrological observation station name.
R_Duration: Duration of observation for each metrological station.
Cal_Duration: Duration while both data of the groundwater monitoring and metrological observation are available for tank model analysis.

4-5-2 Result of Groundwater Recharge Calculation for Each Monitoring Site

Figure 4.38 to Figure 4.45 show the results of groundwater level simulation by the Tank Model in all available monitoring well sites given in Table 4.8.

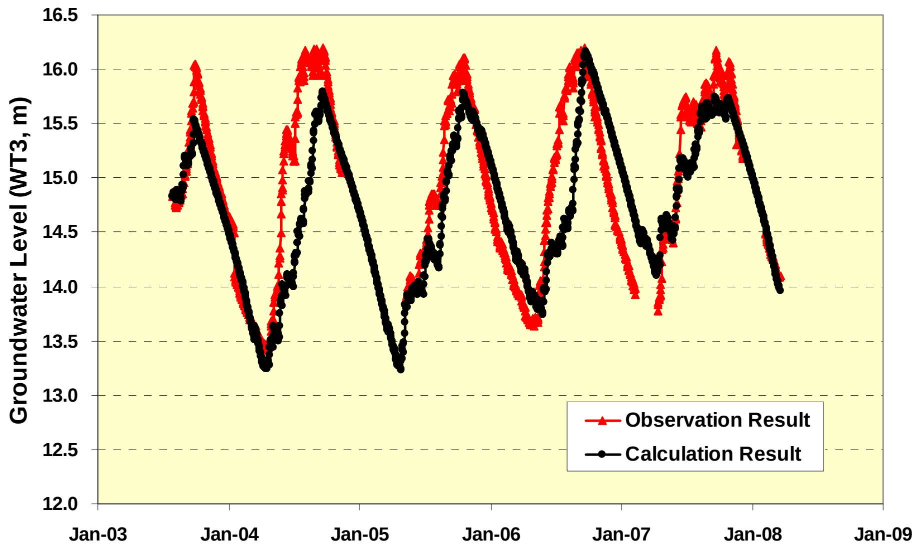


Figure 4.38 Result of Groundwater Level Simulation by Tank Model in Monitoring Site WT-3

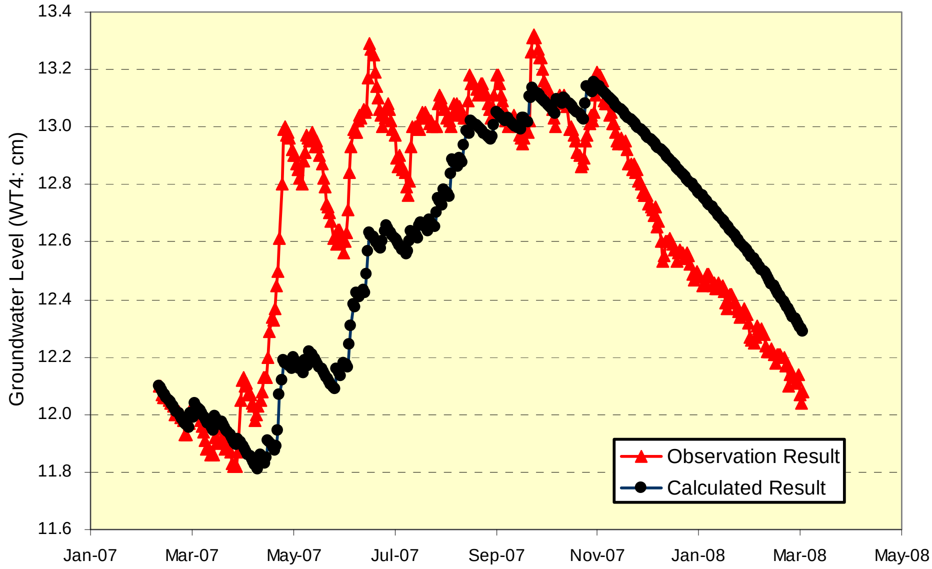


Figure 4.39 Result of Groundwater Level Simulation by Tank Model in Monitoring Site WT-4

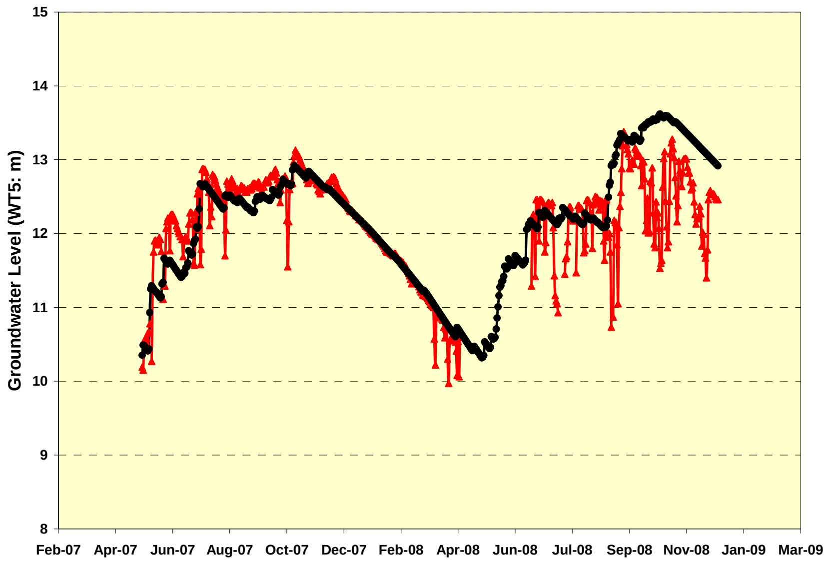


Figure 4.40 Result of Groundwater Level Simulation by Tank Model in Monitoring Site WT-5

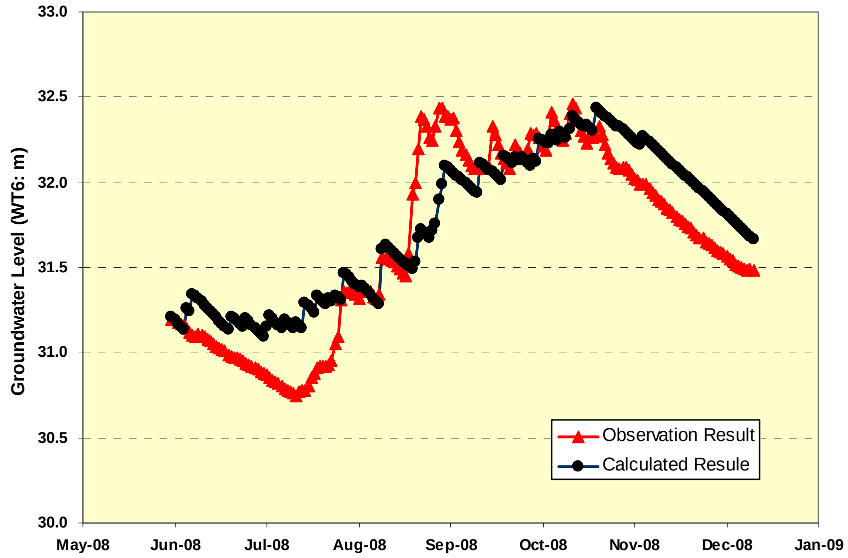


Figure 4.41 Result of Groundwater Level Simulation by Tank Model in Monitoring Site WT-6

The precipitation data at the Meteorological observation station Angkor Thom is 964 mm (corresponding to a dry year with probability of about 100 return years) in 2006, followed by fewer amounts of 557 mm (corresponding to a drier year with a probability of over 10,000 return years) in 2007. It is a very exceptional phenomenon.

Incidentally, precipitation records in 3 neighborhood meteorological observation stations were in the range of 1,415 mm to 1,640 mm in the year 2006, and 1,356 to 1,615 mm, corresponding to an ordinary or wet year. There is no doubt that the precipitation differs from station to station, however, a difference such as that between Angkor Thom and the other stations is inconceivable. Also, because the distance between the meteorological station of Angkor Thom with other stations is less than 10 km in a plain area, it is surely impossible to be an extremely dry year while all the other neighboring stations have wet or ordinary precipitation. Therefore, it is safe to say that the precipitation data for 2006 and 2007 from the meteorological station of Angkor Thom is wrong. By the way, if the data were directly used in the tank model for groundwater recharge calculation the result can not fit the observation result as shown in Figure 4.42.

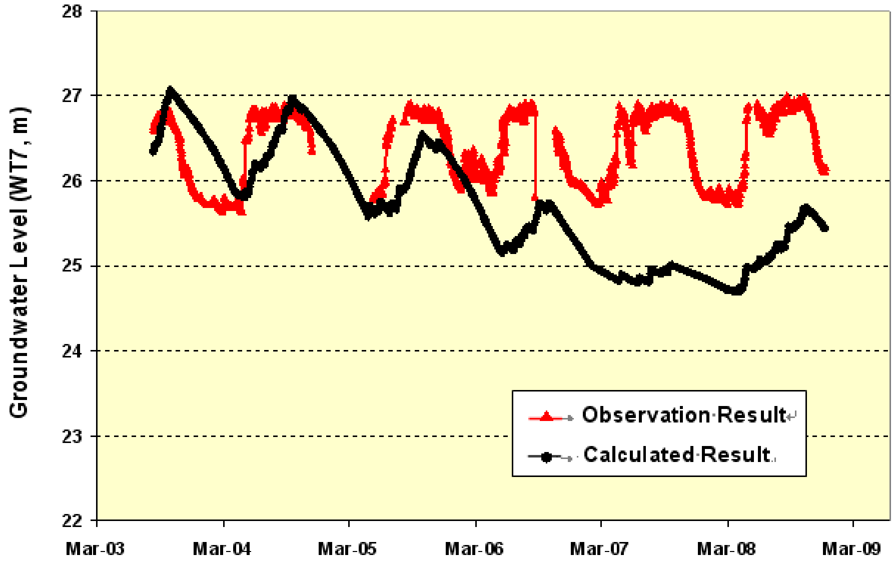


Figure 4.42 Result of Groundwater Level Simulation in Monitoring Site WT-7 by Tank Model and Corresponding Precipitation Data of the Meteorological Station Angkor Thom

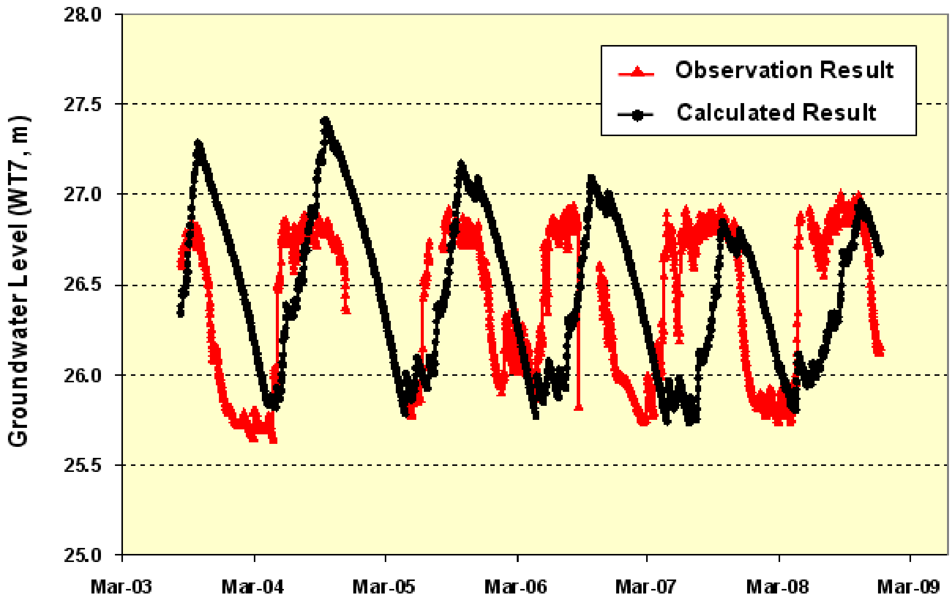


Figure 4.43 Result of Groundwater Level Simulation in Monitoring Site WT-7 by Tank Model and Corresponding Modified Precipitation of the Meteorological Station Prasat Bakong

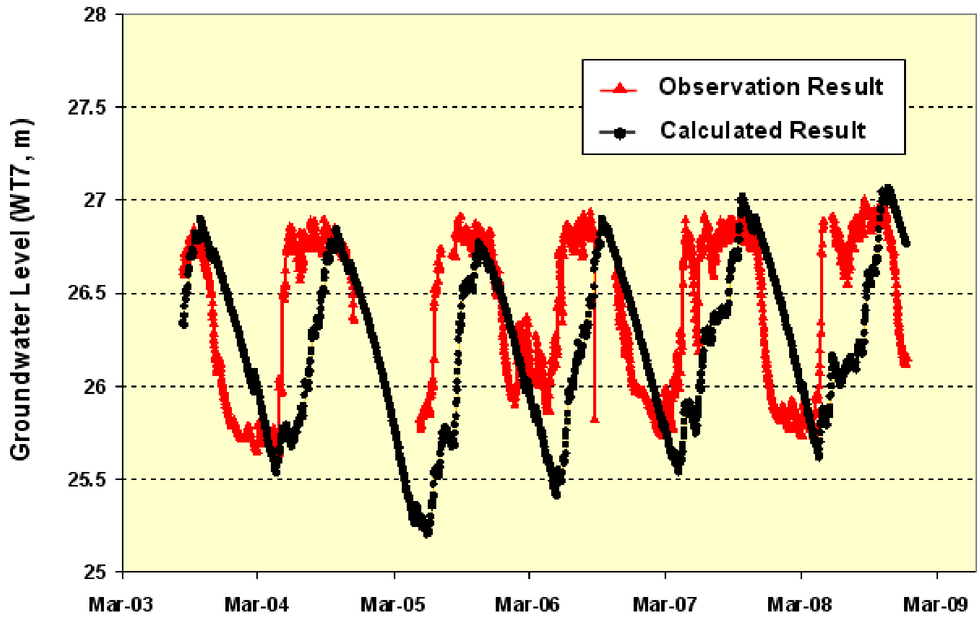


Figure 4.44 Result of Groundwater Level Simulation in Monitoring Site WT-7 by Tank Model and Corresponding Precipitation Data of the Meteorological Station Prasat

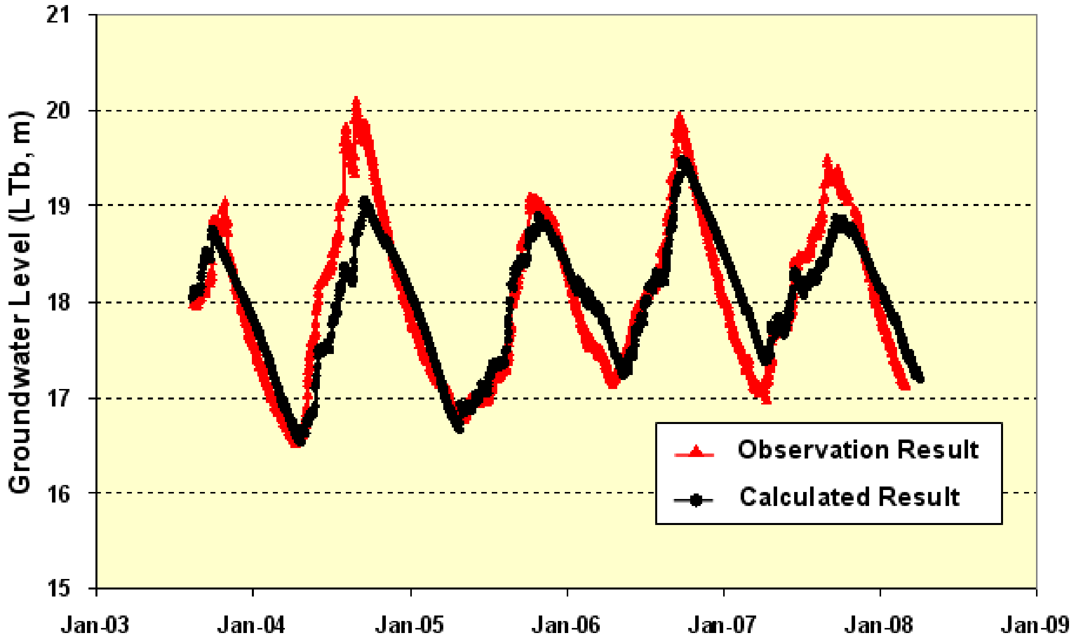


Figure 4.45 Result of Groundwater Level Simulation by Tank Model in Monitoring Site LTb

4-5-3 Summary of Groundwater Recharge Calculation

The groundwater recharge calculation results are summarized in Table 4.9 and Table 4.10.

Table 4.9 Monthly and Yearly Average Recharge for Each Station (mm)

Month	WT-3	WT-4	WT-5	WT-6	WT-7 (1)	WT-7 (2)	LTb
Jan	0.0	0.0	1.0	-	0.0	0.0	0.3
Feb	0.0	0.0	2.1	-	0.0	0.0	4.3
Mar	6.4	13.9	2.5	-	1.0	6.5	8.5
Apr	20.0	12.1	7.1	-	4.0	6.4	13.6
May	74.4	82.4	17.1	-	28.0	31.8	56.8
Jun	70.8	54.2	18.5	38.2	38.0	39.8	60.7
Jul	71.1	57.8	13.6	55.0	24.0	51.0	56.6
Aug	59.7	56.3	13.8	120.1	55.0	35.1	40.6
Sep	93.6	36.6	31.4	115.8	55.0	60.5	86.8
Oct	59.2	33.8	25.8	91.8	47.0	37.0	61.1
Nov	12.4	20.1	6.1	33.0	6.0	9.8	10.7
Dec	5.4	0.0	0.0	0.0	10.0	2.2	2.4
Yearly	**473**	**367**	**139**	**>454**	**268**	**280**	**402**

Table 4.10 Summary of Tank Model Calculation Result (mm)

Month	Precipitation			Groundwater Recharge			Evapotranspiration		
	Max.	Avrag	Min.	Max.	Avrag	Min.	Max.	Avrag	Min.
Jan	10.0	6.0	1.4	1.4	0.1	0.0	38.9	29.3	20.2
Feb	46.7	11.2	0.0	17.1	1.1	0.0	39.8	30.0	21.0
Mar	121.9	29.5	0.2	28.7	5.8	0.0	51.6	38.8	26.3
Apr	124.0	53.5	2.7	29.6	10.4	0.0	53.4	39.3	27.4
May	372.0	232.4	42.0	113.1	45.4	0.0	54.3	37.4	22.2
Jun	397.7	217.5	102.4	93.9	48.5	17.8	49.1	31.8	20.0
Jul	340.0	199.3	117.9	82.3	47.0	11.3	66.7	31.0	17.2
Aug	306.8	206.1	43.0	120.1	47.7	11.2	68.0	32.0	19.2
Sep	502.9	254.1	130.0	134.8	70.4	26.0	54.2	24.7	15.6
Oct	375.7	196.6	103.0	119.1	49.7	14.8	58.9	29.2	19.2
Nov	98.2	50.8	3.9	33.0	10.7	0.0	58.5	28.0	18.6
Dec	71.1	31.2	0.2	23.4	4.2	0.0	60.3	28.6	18.2

The annual groundwater recharge is calculated as 341 mm/year by summarizing the result of the tank model simulation. The annual groundwater recharge of the whole recharge area can be calculated by multiplying 341 mm with the recharge area of 1,277 km^2 (Refer to Figure 4.2), to get a result of 435,517,000 m^3, corresponding to a daily amount of 1,193,000 m^3.

On the other hand, the Kulen mountain range is located in the northeast side of Siem Reap, and is a part of the recharge area by hydrological classification. If there exists a relatively deep aquifer, e.g. as deep as more than 100 m, with high permeability, e.g. with hydraulic conductivity larger than 1 m/day, the recharge in Kulen cordillera would be possible to contribute for recharge to the Siem Reap area. However, due to the aquifer structure, there is no such deep aquifer with high permeability in Siem Reap; so the groundwater recharge in the Kulen Mountain area can hardly be considered as actual recharge to the groundwater in the Siem Reap area.

The groundwater recharge for the water supply area can be actually obtained from its own extent. The area of water supply service area is 552 km^2, therefore, the annual groundwater recharge can be calculated by multiplying 341 mm with 552 km^2 to get the yearly average amount of 188,320,000 m^3, corresponding to a daily amount of 516,000 m^3.

If only comparing the amount of recharge from precipitation (516,000 m^3/day) to the amount given in water supply development plan (86,300 m^3/day), it can be found that the former is about 6 times that of the latter. When groundwater is used as a source for water supply, an essential condition is to keep the groundwater withdrawal amount less than the groundwater recharge amount. Obviously, there is no problem for groundwater use just judging by this condition.

However, keeping the groundwater withdrawal amount less than the recharge amount is not the only technical standard for groundwater water utilization evaluation. The groundwater level goes up when getting recharged from precipitation and goes down when being consumed by evaporation. When considering in a time unit of years rather than days, the groundwater level neither goes up nor goes down. Namely, there is almost no fluctuation in yearly groundwater level. Moreover, when considering within the hydrologic cycle, the groundwater level can be deemed as not changing at all, even though a relative big amount precipitation recharges groundwater. That is, under natural conditions, the amount of groundwater recharge is consumed and the main groundwater consumption is clearly from evaporation or evapotranspiration. Hence, the groundwater balance can be expressed by the equation as follows:

$$\text{Recharge}_{\text{rain}} - \text{Consumption}_{\text{Evaporation}} = 0$$

Or

$$\text{Recharge}_{\text{rain}} = \text{Consumption}_{\text{Evaporation}}$$

It is unavoidable to break the natural balance of groundwater when groundwater is withdrawn for water supply. In water resources balance analysis groundwater development is also classified as groundwater consumption. On the other hand, groundwater withdrawals have almost no effect on the recharge amount in Siem Reap because the recharge amount is mainly decided by amount of precipitation. Therefore, if continuous water level drawdown would not occur, that is, a new groundwater amount balance is obtained in a hydrologic cycle; the balance equation can be expressed as follows:

$$\text{Recharge}_{\text{rain}} - \text{Consumption}_{\text{Evaporation}} - \text{Consumption}_{\text{Withdrawal}} = 0$$

Or

$$\text{Recharge}_{\text{rain}} = \text{Consumption}_{\text{Evaporation}} + \text{Consumption}_{\text{Withdrawal}}$$

Because groundwater recharge does not change when considering within the hydrological cycle, the groundwater development actually results in reducing of consumption from evaporation.

Evaporation from groundwater is not a constant amount. It depends on the evaporation amount from the ground surface and the depth of groundwater table. The amount of evaporation from groundwater at a certain depth is also affected by the type of soil or aquifer. However, for general analysis, a value of 5 m can be taken as an effective depth of evaporation from groundwater. Therefore, the groundwater level will get to about 5 m below ground surface in case the groundwater withdrawal amount equals to the recharge amount. In other words, if the whole groundwater recharge amount is used for water supply, the groundwater level will become 5m below the ground surface in the whole Siem Reap area.

The simultaneous groundwater level survey found that the groundwater level changes in different seasons, to less than approximately 1 m below the ground surface in the rainy season and 3 m in the dry season. Therefore, to take all groundwater recharge amount for groundwater development would cause average groundwater drawdown from 2 m to more than 4m in different seasons in Siem Reap. This is an unallowable situation because the degree of groundwater drawdown will surely have a negative effect on the heritage sites and the environment. Therefore, not all recharge of groundwater is available for groundwater development and all the groundwater development plan have to be evaluated by checking the extent and magnitude of groundwater drawdown caused by groundwater withdrawal.

4-6 Simultaneous Groundwater Observation

4-6-1 Groundwater Level Distribution and Change

To make clear the groundwater level distribution 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.

210 wells were visited for observation well selection. When the wells were visited, basic information was recorded such as coordinates, village name, well’s owner, type, depth, well head, and well water utilization. From the 210 wells, 155 wells were selected for groundwater level observation based on the following principals:

- The selected wells should be distributed in Siem Reap as homogenously as possible,
- The selected wells should be easy to access, and
- The selected wells should be permitted for water level observation.

To clearly grasp the groundwater level distribution, it is indispensable to confirm the ground surface elevation of all of the surveyed wells. The ground surface elevation was obtained mainly from the 1:5,000 scale topographic maps that were created by a previous JICA survey (Study of Integrated Master Plan for Sustainable Development of Siem Reap/Angkor Town in the Kingdom of Cambodia, 2005) with more than 140,000 control points in Siem Reap.

Figure 4.46 and Figure 4.47 show the results of simultaneous groundwater observations in the rainy season and dry season, respectively.

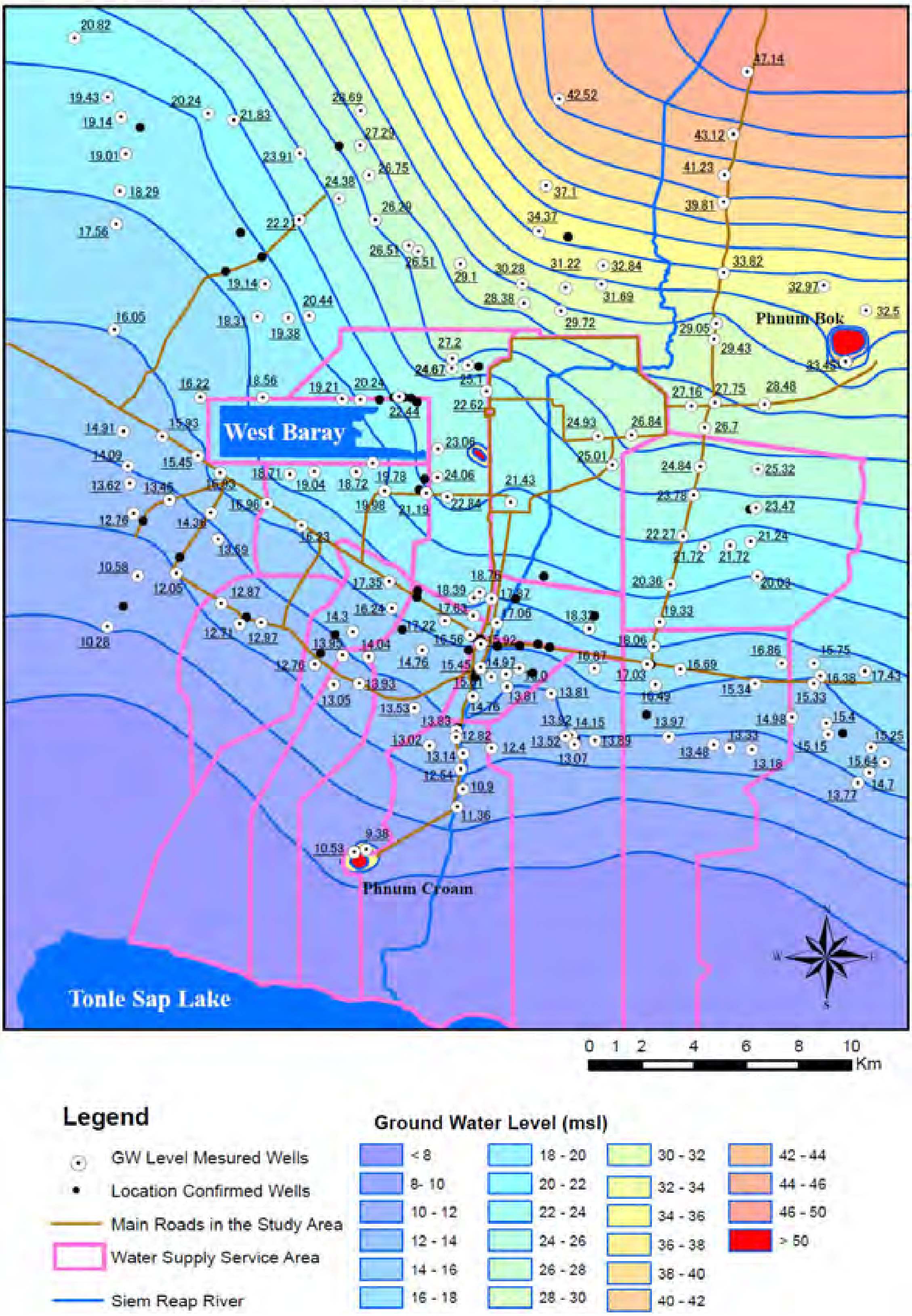


Figure 4.46 Result of Simultaneous Groundwater Observation the Rainy Season (September 2009)

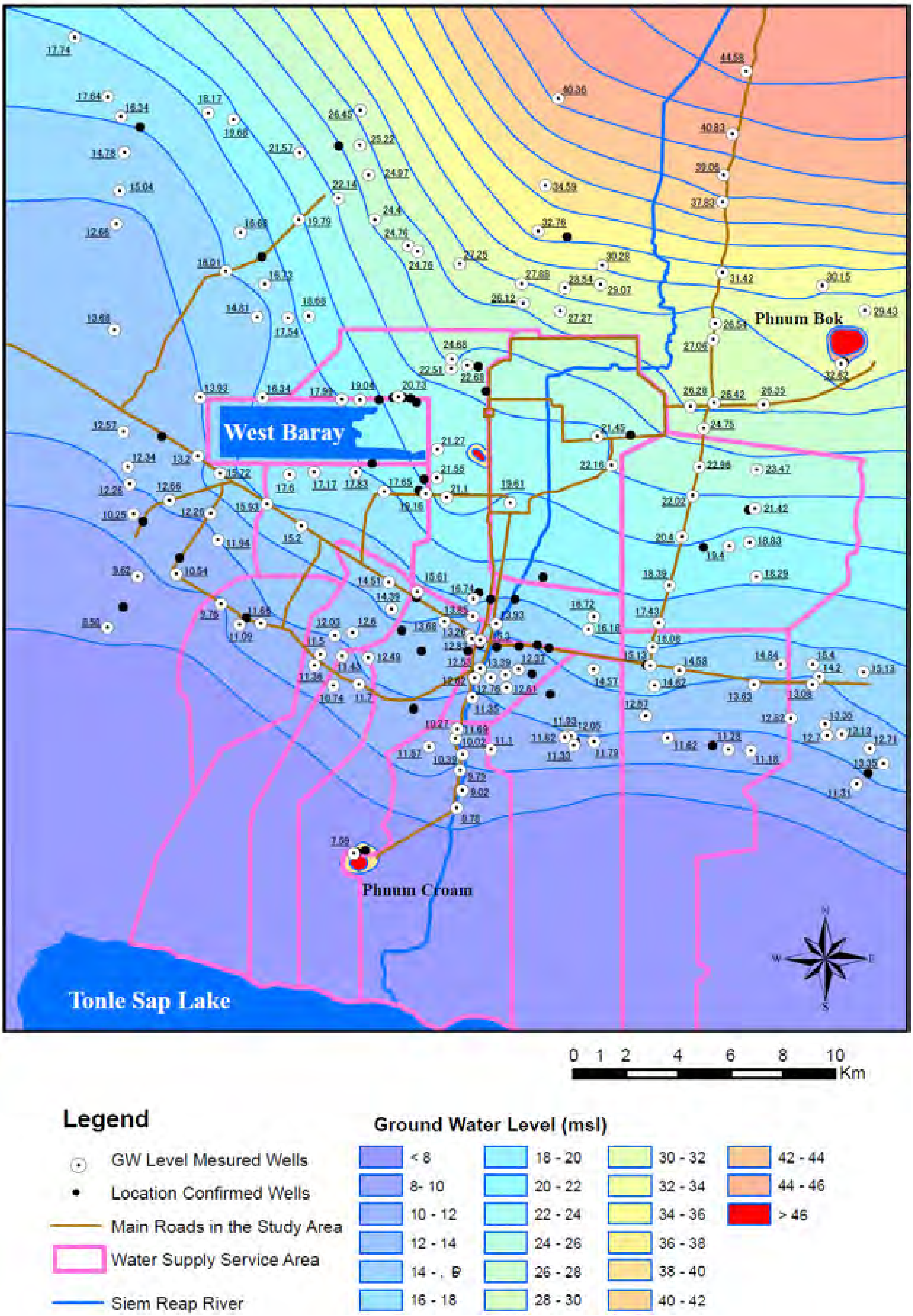


Figure 4.47 Result of Simultaneous Groundwater Observation the Dry Season (April 2010)

Figure 4.48 shows the difference of the groundwater level between the two seasons.

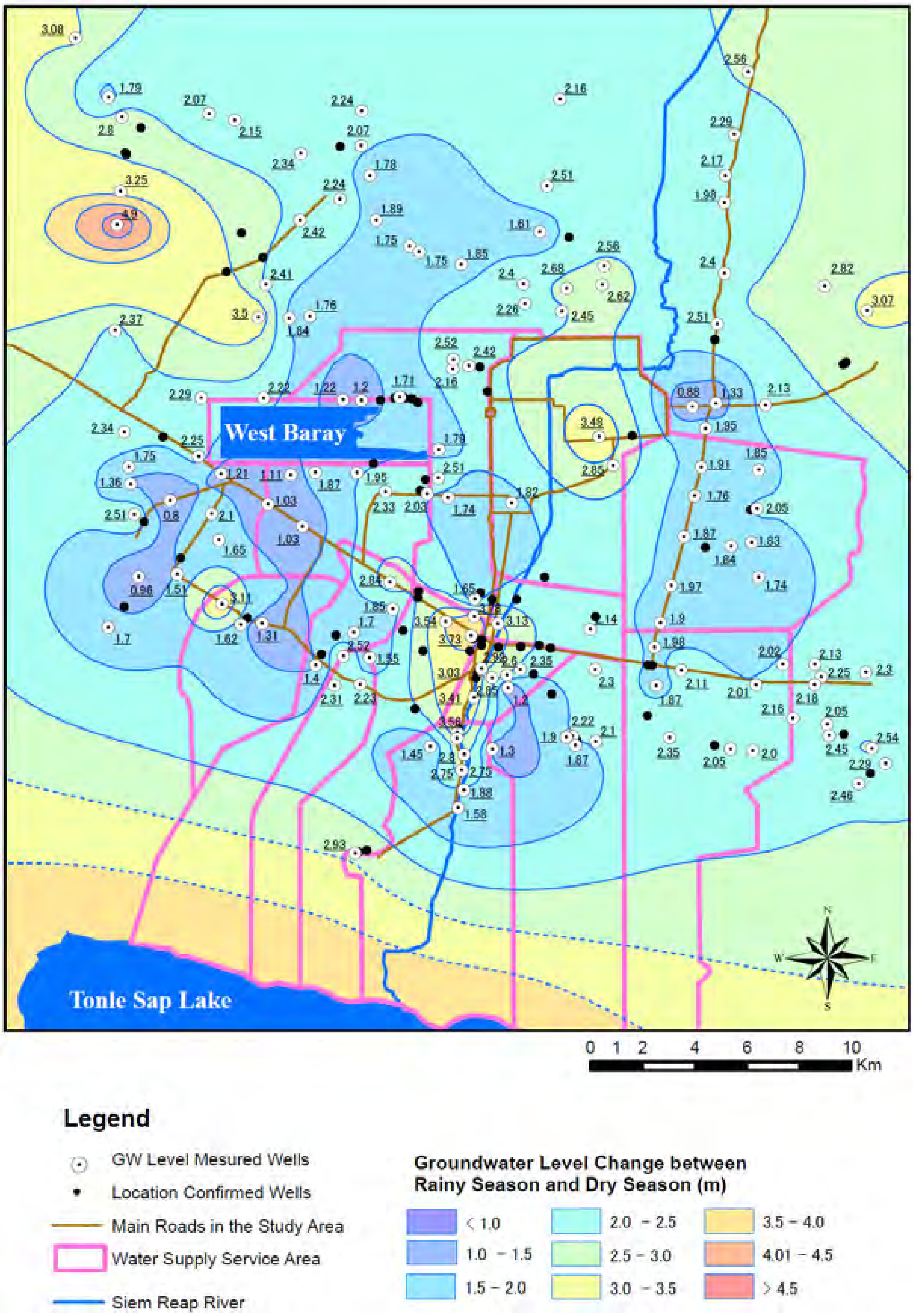


Figure 4.48 Groundwater Level Change between the Rainy (September 2009) and Dry Seasons (April 2010)

Table 4.11 and Table 4.12 give the summary results of groundwater level in the rainy and dry seasons, respectively.

Table 4.11 Summary of Groundwater Level in the Rainy Season

(Water Level Unit: m from ground surface)

Water Level	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	3-3.5	4.4.5	7-7.5
Numbers	51	57	28	11	5	1	1	1
Percentage	32.9	36.8	18.1	7.1	3.2	0.6	0.6	0.6

In the rainy season, groundwater level changes from 0.2 m to 7.4 m. About 95 % of surveyed wells have a groundwater level less than 2 m, and the average value is 0.88 m in depth from the ground surface. This result indicates a very high conformity of groundwater table distribution with topography in Siem Reap.

It is common knowledge in hydrogeology that the distribution of groundwater level is generally gentler than topography, because groundwater water can flow from high level place to low level place; even though the change of groundwater recharge amount may be negligible in a small area. However, the flow direction and amount depends on not only difference of water level but also the aquifer structure and aquifer parameters. Considering this common knowledge and the result of simultaneous groundwater observation survey together, the following conclusions can be reached:

Groundwater flow in Siem Reap is slow under natural conditions. In other words, the affect of recharge from precipitation and consumption from evaporation to groundwater level fluctuation is much bigger than that of groundwater flow in natural condition.

Table 4.12 Summary of Groundwater Level in the Dry Season

(Water Level Unit: m from ground surface)

Water Level	**Numbers**	**Percentage**	**Water Level**	**Numbers**	**Percentage**
1 - 1.5	2	1.3	4.5 - 5	5	3.3
1.5 - 2	9	5.9	5 - 5.5	3	2
2 - 2.5	34	22.4	5.5 - 6	1	0.7
2.5 - 3	47	30.9	6 - 6.5	1	0.7
3- 3.5	23	15.1	6.5 - 7	1	0.7
3.5 - 4	17	11.2	8.5 - 9	1	0.7
4 - 4.5	7	4.6	> 13	1	0.7

Two purposes were set for the simultaneous groundwater observation in the dry season. To make clear the groundwater level distribution in dry season and make clear the groundwater change between the rainy and dry seasons. Therefore, all wells used for groundwater level observation in the rainy season were taken as target wells for the observation in the dry season. However, 2 wells available for water level observation in the rainy season have dried up in the dry season. And one well is unavailable for water level observation because the well belongs to a hotel and was in pumping when twice visitations in different days. Therefore, total as 152 wells were taken for groundwater level observation in the dry season.

In the dry season, groundwater level changes from 1.2 m to more than 13 m. One well near hill Phnom Bok with a well depth of 13 m dried up, from which it can be ascertained that the water level to is deeper than 13 m from ground surface, but the exact water level cannot be measured. From the observation in the dry season, it can be found that the majority of surveyed wells have groundwater level between 1.5 m and 5 m, and the average value is 3.1 m in depth from ground surface.

Table 4.13 shows the statistics of the water level change between the two seasons. Nearly 90 percent of wells have a groundwater level change between 1 and 3.5 m and the average value is 2.5 m.

Table 4.13 Summary of Groundwater Level Change between Rainy and Dry Seasons

(Water Level Change Unit: m)

Water Level Change	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	3.5-4	>4
Numbers	4	14	44	50	22	8	5	5
Percentage	2.6	9	28.4	32.3	14.2	5.2	3.2	3.2

As shown in Figure 4.46 and Figure 4.47, it can be found that even though groundwater level changes between rainy and dry seasons, the water table distribution has the same pattern in both seasons. That is, groundwater table distribution is basically determined by topography. From Figure 4.48, it can be found that even though the pattern of the water table is the same in both rainy and dry seasons, the groundwater level changes in an irregular shape. All the following factors can be considered as affecting the groundwater level change:

- Amount of evaporation or evapotranspiration,
- Distance of wells to rivers and lakes (ponds),
- Water level change in rivers and lakes (ponds),
- Change of topography and then the change of hydraulic gradient,
- Structure and permeability of aquifers, and
- Amount of groundwater use.

To make all of the above factors clear, for example to obtain soil profiles for all of the surveyed wells, is quite difficult in this study and for almost all similar investigations. However, the results indicate that when the hydrological analysis and groundwater simulation is conducted, all of the above factors need to be taken into consideration as much as possible. And all these factors are specified in the groundwater simulation model in as much detail as possible by using all available data and analysis results.

Even though it is difficult to clarify the main factors and also to explain properly the difference in water level change between the two seasons for the whole study area, the fact that there is high water level drawdown during the dry season in the town area is not at all difficult to explain. Relatively more wells are used for the observation in the town area so that the reliability of the water level survey result in this area can be assured even if there is the occasional abnormality. . All surveyed wells showed larger water level change than the average value of 2.5 m, and the majority of surveyed wells showed a change larger than 3 m.

A lot of private wells for big groundwater users like hotels and guest houses are used for groundwater withdrawal in the town area. Not only the number of wells, but also many wells have pumps installed. Therefore, the greatest amount of groundwater development is concentrated in the town area. This would be the reason for heavier groundwater level drawdown in the town area than most other areas in Siem Reap.

4-6-2 Groundwater Level Observation in Previous JICA Study (2000)

In the study on water supply system for Siem Reap region in Cambodia (2000), 79 wells including groundwater water monitoring wells with automatic observation logs have been used for monthly groundwater level observation from Feb. 1998 to Nov. 1999. Average of the monthly water level fluctuation in these wells and the monthly precipitation fluctuation in the meteorological station of Siem Reap City are shown in Figure 4.49.

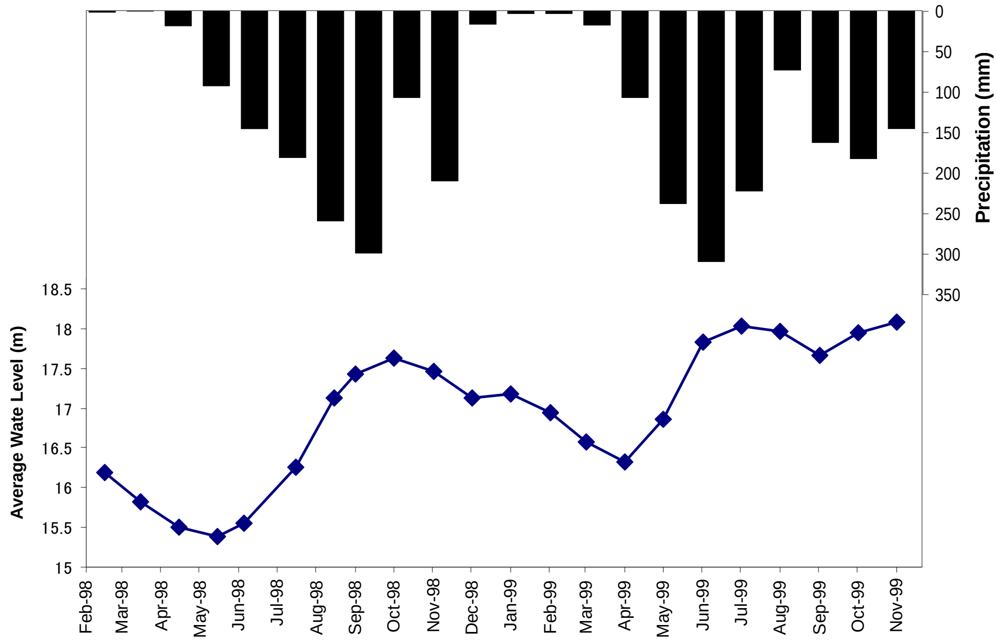


Figure 4.49 Relation of Precipitation and Average Groundwater Level
Precipitation data source: Siem Reap City Station
Groundwater level data source: 79 observation wells

An obvious tendency of groundwater level going up within the two years can be found from the figure, because the yearly precipitation increases from 1,328 mm in 1998 to 1,460 mm in 1999.

This relation indicates the fact that groundwater level changes, not only with the alternation of seasons, but also the total precipitation amount in each year. That is, in an extremely dry year, the groundwater level will be drawn down much more than in an ordinary or rainy year.

The figure also shows that the lowest or the highest groundwater level may occur in different months in a year. The water level was the lowest in May and the highest in October in 1998, and the lowest in April and the highest in November in 1999. This fact indicates that even if the water level were compared in the same month for different years, it is still difficult to ascertain how the groundwater changed between those two years.

To compare the results of simultaneous groundwater level survey between this study and the study on water supply system for Siem Reap region in Cambodia (2000), the location all wells are plotted in the Figure 4.50.

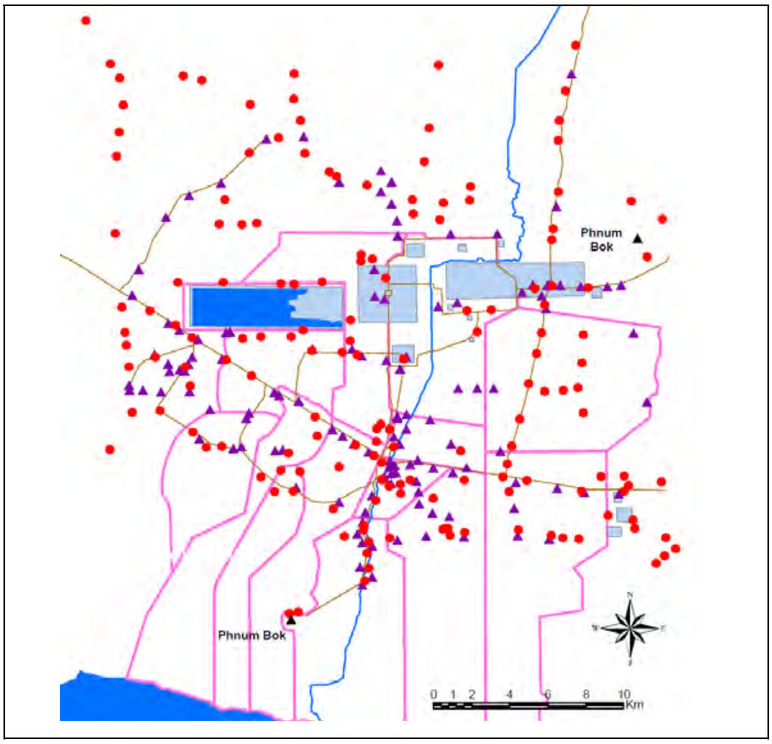


Figure 4.50 Location of Wells Used for Simultaneous Groundwater Level Observation in the Study on Water Supply System for Siem Reap Region in Cambodia (2000) and This Study.

Red circle marker: wells used in this study.
Purple triangle marker: wells used in the previously study.

Within the nearly two years continuously groundwater level observation in monthly units, the highest groundwater level appeared in November 1999 and the lowest in May 1998. Water level distributions in these two months are shown in Figure 4.51 and Figure 4.52. And the water level change between these two months is shown in Figure 4.53.

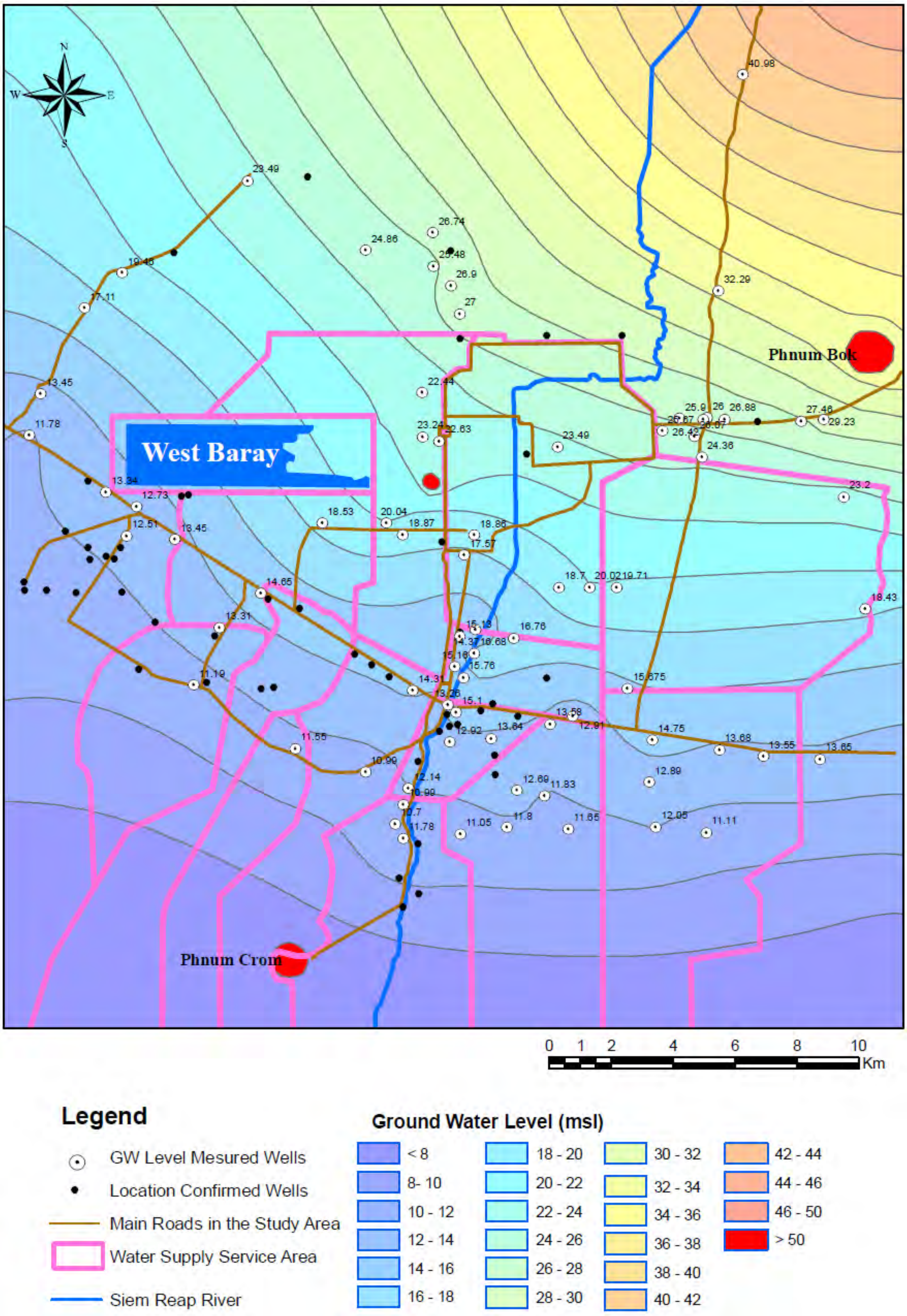


Figure 4.51 Distribution of the Highest Groundwater Level in the Study on Water Supply System for Siem Reap Region in Cambodia (2000) in November 1999

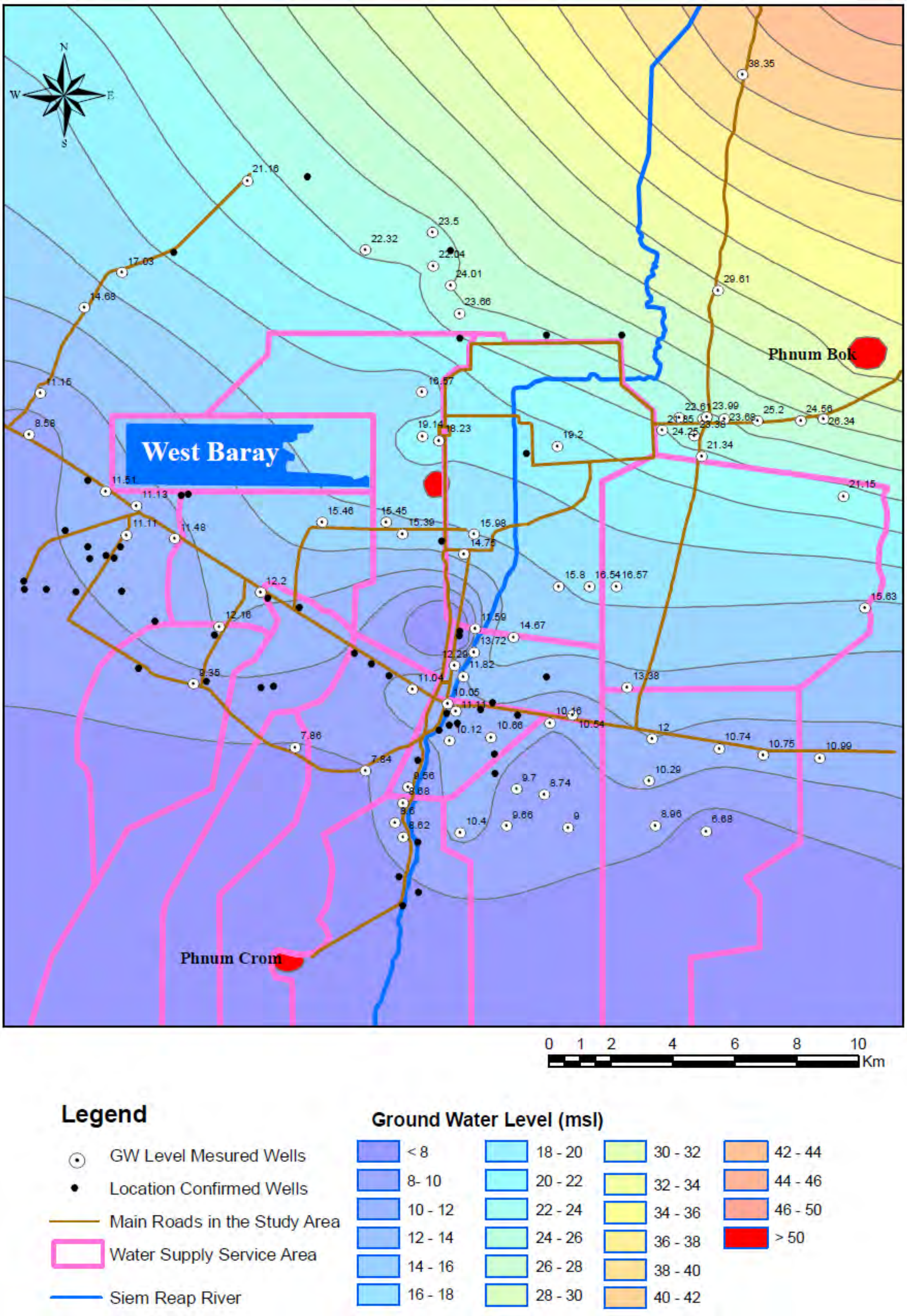


Figure 4.52 Distribution of the lowest Groundwater Level in the Study on Water Supply System for Siem Reap Region in Cambodia (2000) in May 1998

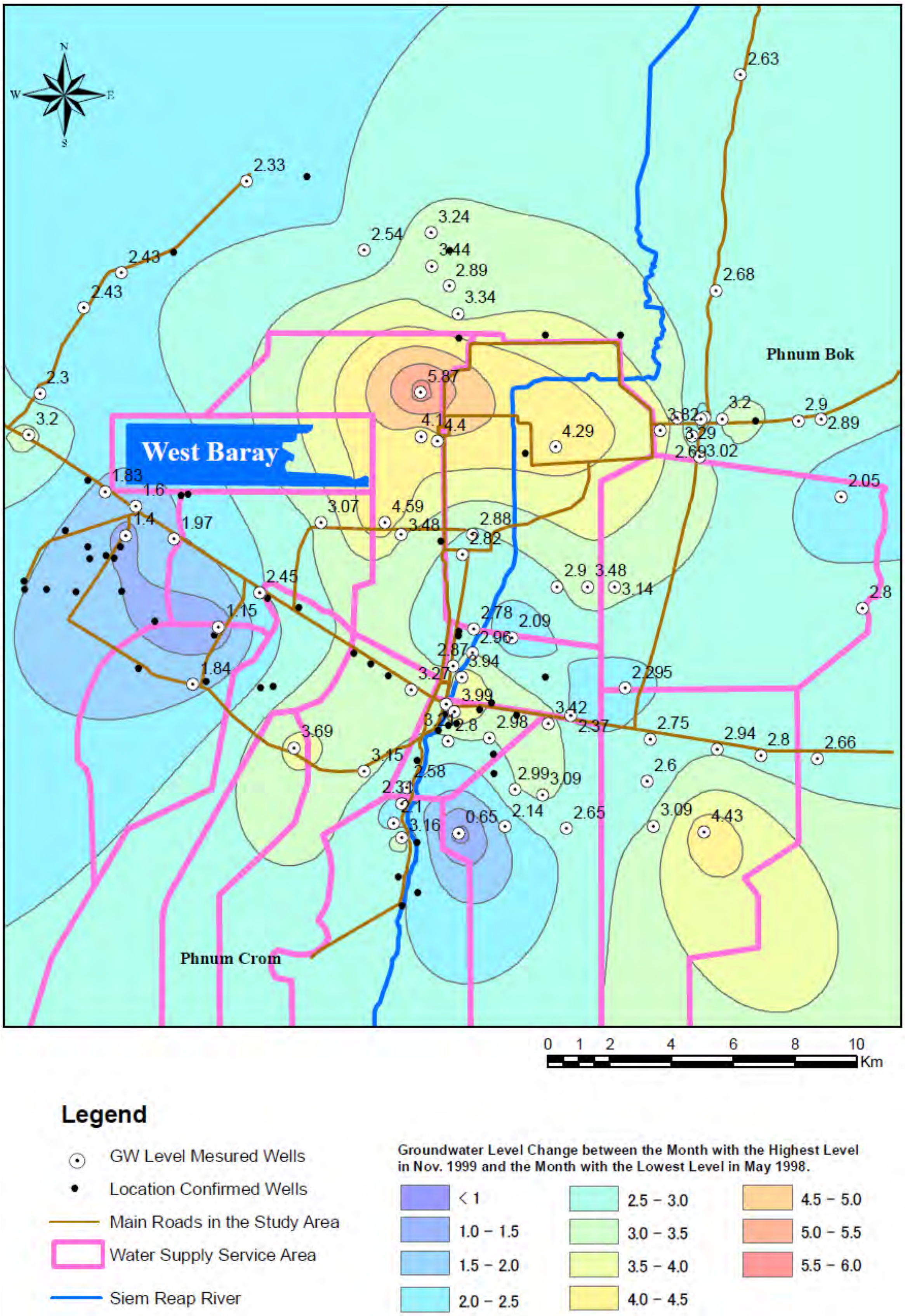


Figure 4.53 Groundwater Level Change between the Highest Month (November 1999) and the Lowest Month (May 1998) in the Study on Water Supply System for Siem Reap Region in Cambodia (2000)

4-6-3 Comparison of Groundwater Observation Result

As mentioned above, a lot of factors can affect groundwater level change, and some occasional factors, for example, a large and temporary groundwater withdrawal, may cause a temporarily large change to the groundwater level in an observation well. But this kind of change should not be taken as the general tendency of groundwater level fluctuation. Therefore, the more wells available for analysis the higher reliability that can be ensured of the analysis results.

From Figure 4.50 it can be found that in both JICA studies, this study and the study on water supply system for Siem Reap region in Cambodia (2000), relatively more wells along National road No.6 and the road from heritage Angkor Wat to Tonle Sap Lake were selected for groundwater level observation. All wells within 1km of the two main roads in Siem Reap were extracted for water level change comparison in both studies, as shown in Figure 4.54.

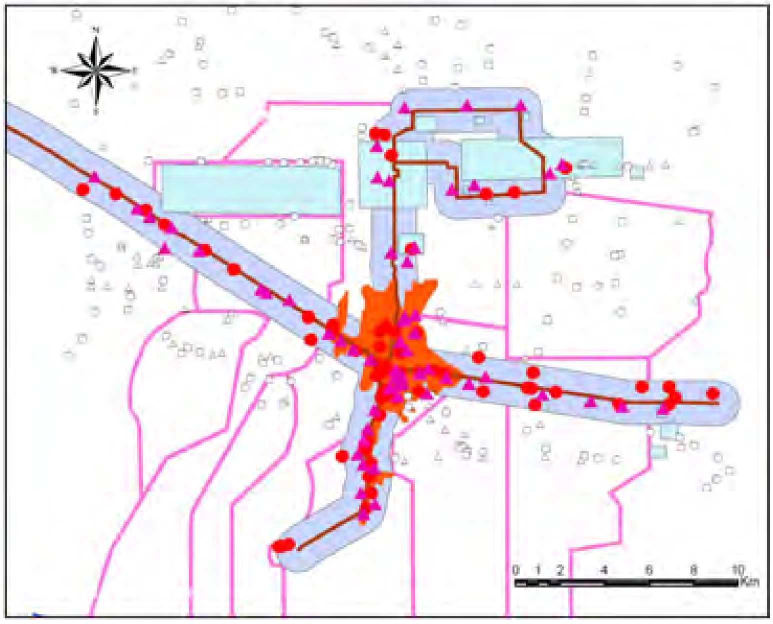


Figure 4.54 Location Map of Selected Wells for Water Level Observation Result Comparison

White circles: Wells used for groundwater level survey in this study.
White triangles: Wells used for groundwater level survey in previous study.
Red circles: Wells selected from this study for the comparison.
Pink triangles: Wells selected from the previous study for the comparison.
Light blue zone: 1km zone from the two main roads in Siem Reap.
Light cyan features: main heritage sites in Siem Reap.
Brown zone: town area in Siem Reap.

About half of total used wells, 59 wells, from the previous study, and about 1/3, 65 wells, from this study, were selected.

4-6-3-2 High Groundwater Level Season

Groundwater level fluctuates with the alternation of seasons. The highest groundwater level in a year appears in October or November. Of the total of 65 selected wells, as shown in Figure 4.54, 50 wells were actually used for groundwater level measurement in the rainy season at the end of September 2009. The average water level below ground surface is 1.58 m with a range from 0.2 to 5.12 m.

The corresponding water level observation result from 34 available wells in the previous study is summarized in the table below.

Table 4.14 Comparison of Water Level in Rainy Season by Wells along Main Roads in Siem Reap

Time	Sept_09	Sep_98	Oct_98	Nov_98	Sep_99	Oct_99	Nov_99
Average (m)	1.58	1.57	1.32	1.39	1.2	0.84	0.61
Maximum (m)	5.12	6.83	5.88	5.79	5.21	4.21	3.13
Minimum (m)	0.2	0.1	0	0.08	-0.06	-0.44	-0.49

(Remark) The value in the table gives the water level below the ground surface.

Comparing to the water level of this study with the results from previous study in 1999, it is obvious that the water level in 2009 is lower than that in 1999. However, 2 wells from the 34 available showed minus values of water level from ground surface in September 1999. That means water levels in these 2 wells were over the ground surface. And the number of this kind of well increased to 12 in October and 13 in November. About one third of observation wells with the groundwater level over the ground surface should not be considered as a normal situation. Actually, the precipitation data showed that the difference of precipitation in the two years of 1998 and 1999 is only about 100 mm. This difference of precipitation amount is not enough to explain the difference in average water level of about 0.37 m* to 0.78 m* in corresponding months in 1998 and 1999. (Note, 0.37 m* = 1.57 m (1998/9) – 1.2 m (1999/9); 0.78 m* = 1.39 m (1998/10) – 0.61 m (1999/10))

On the other hand, when the groundwater level in September is compared between 1998 and 2009, the values of average water level were almost the same to show no larger difference of groundwater level in rainy season between these two years.

(Note,

4-6-3-3 Low Groundwater Level Season

Of the total of 65 selected wells, as shown in Figure 4.54, 52 wells were actually used for groundwater level measurement in the dry season. The average water level below ground surface is 3.97 m, with a range from 1.73 m to 9.12 m

The corresponding water level observation result from 33 available wells in the previous study is summarized in the table below.

Table 4.15 Comparison of Water Level in Dry Season in Wells along Main Roads in Siem Reap

Time	Apr_09	Apr_98	May_98	Apr_99	May_99
Average (m)	3.97	3.48	3.48	2.7	2.28
Maximum (m)	9.12	8.52	8.52	9.22	7.4
Minimum (m)	1.73	0.99	0.99	0.65	-0.05

(Remark) The value in the table gives the water level below the ground surface.

Except one figure, the maximum value of groundwater level below ground surface in April 1999, for all of the compared figures, the largest values can be found in the dry season of 2009. The fact indicates the groundwater level in the dry season of 2009 is lower than the water level in the dry seasons of 1998 and 1999.

As shown in Figure 4.48, a relatively larger groundwater drawdown can be clearly ascertained in the town area by comparing the groundwater level in the rainy and dry seasons. This is considered a result of a high groundwater use in the town area by many private wells. This consideration can also be used for explaining the fact of relatively larger groundwater level drawdown in 2009 when compared with the years of 1998 and 1999.

4-6-3-4 Result Comparison in Town Area

The analysis above shows the possibility of effect of groundwater use for groundwater level change in the town area. To check the water level change in the town area, all wells in different studies in the town area have been extracted as shown in Figure 4.55.

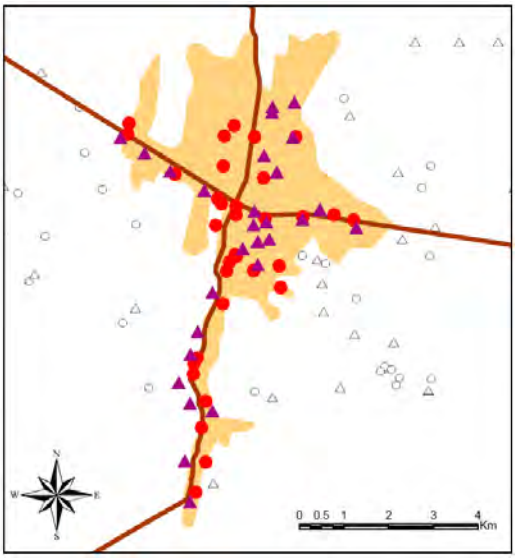


Figure 4.55 Location Map of Selected Wells in Town Area in Siem Reap for Water Level Observation Result Comparison

White circles: Wells used for groundwater level survey in this study.
White triangles: Wells use for groundwater level survey in previously study
Red circles: Wells selected from this study for the comparison (33 wells)
Pink triangles: Wells selected from the previous study for the comparison (28 wells).
Yellow colored zone: Town area in Siem Reap.

Of the 33 selected wells, which were visited in this study, 23 wells were used for groundwater level measurement in the rainy season and 25 wells in the dry season. Of the 28 wells shown in the map for previous study, 13 wells have data available for this comparison. All the available data are summarized in different season, and the results are shown in Table 4.16 and Table 4.17.

Table 4.16 Comparison of Water Level in Rainy Season in Town Area

Time	Sept_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 (m)	5.12	3.51	3.1	3	3.26	2.9	2.32
Minimum (m)	0.2	0.1	0	0.3	0.23	-0.28	-0.41

(Remark) The value in the table gives the water level below the ground surface.

As shown in Table 4.14, it has been confirmed that no significant difference can be found between April 2009 and April 1998, from the result of over 33 wells used in this study and the previous study. However, Table 4.16 shows obvious difference between water levels in the rainy seasons of this study and the previous study. The smallest difference in average water level is 0.22 m, nearly 13 % of the average water level in this study. And for the other months the difference are as big as from 0.43 m* to 1.03 m. That is, compared to the observation result in 1998 and 1999, the groundwater level in 2009 got down in a range from 0.22 m* to 1.03 m*. (Note, 0.43 m* = 1.63 m (2009/9) – 1.2 m (1998/10); 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))

Table 4.17 Comparison of Water Level in Dry Season in Town Area

Time	Apr_09	Apr_98	May_98	Apr_99	May_99
Average (m)	4.19	3.5	3.5	2.5	2
Maximum (m)	7.4	5	5.1	4.6	4.81
Minimum (m)	2.6	2.35	2.25	1.46	0.82

(Remark) The value in the table gives the water level below the ground surface.

Both Table 4.15 and Table 4.17 show obvious difference in water level between April 2009 and corresponding months in 1989 and 1999. However, the difference is larger when only wells in town area are used for comparison than the case when all wells near the main roads used for comparison. That is, the groundwater level drawdown in town area is clearly larger than other area in Siem Reap because of a lot of private wells are centralized in town area for relatively big amount of groundwater use.