Chapter 4.
Hydrological Conditions in Siem Reap

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4-1 River Basin Division in Water Supply Area

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.

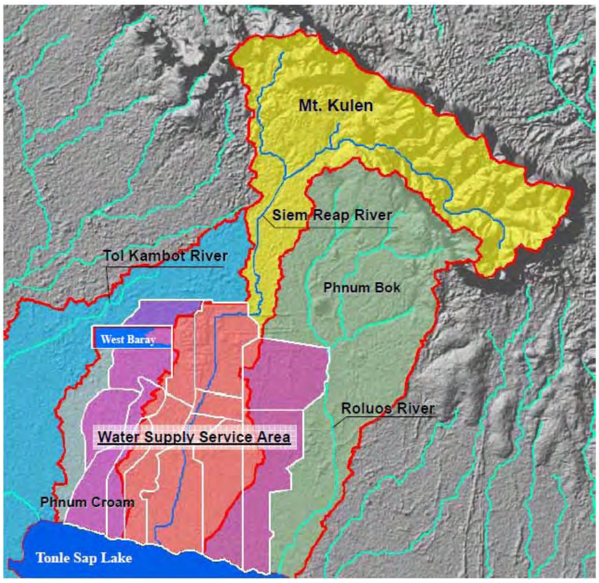


Figure 4.1 The Water Supply Service Area and Relevant River Basins

As shown in the map above, 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.

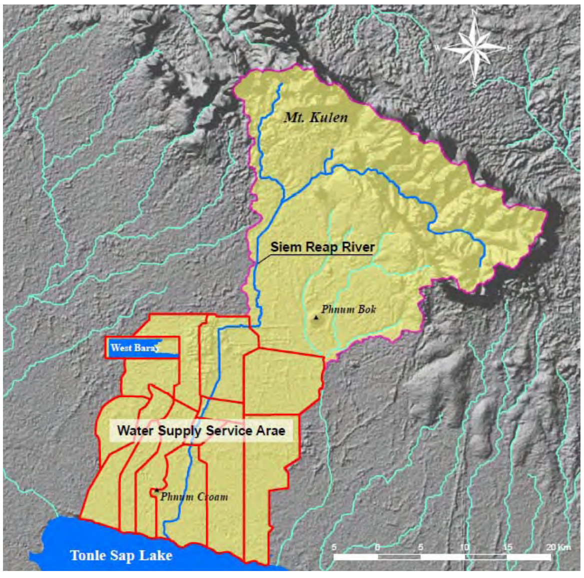


Figure 4.2 Recharge Area of the Water Supply Service Area

The recharge area of the water supply service area is shown in the map above. The total recharge area of the water supply area is 1,277 km^2, of which 552 km^2 is 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. 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 plain area like Siem Reap, the water exchange amount between rivers and groundwater is generally small. The amount of groundwater flow out to Tonle Sap Lake is also small. Therefore, the precipitation and evaporation can be taken as the most important two components for water balance analysis in the study area.

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 as shown in the chart below.

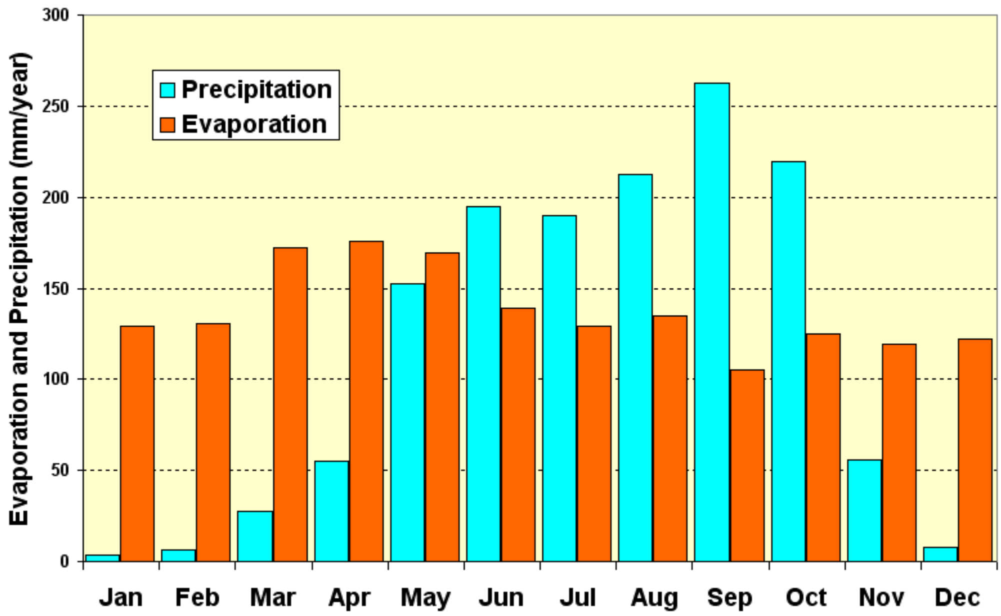


Figure 4.3 Distribution of Monthly Precipitation and Evaporation in the Study Area
The graph was created by summarizing observation result in the meteorological observation station Siem Reap City from 1988 to 2008.

4-3 Available Meteorological Data

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

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). 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 wells. Therefore, the manual observation was started by SRWSA to be used for examination of automatic observation results.

4-4-2 Inspection of Groundwater Monitoring Result

(1) Monitoring Site WT-3

The following figure shows the original monitoring data obtained from WT-3. Except some periods of missing data and obvious observation errors, periodic groundwater level fluctuation is clearly shown by the figure.

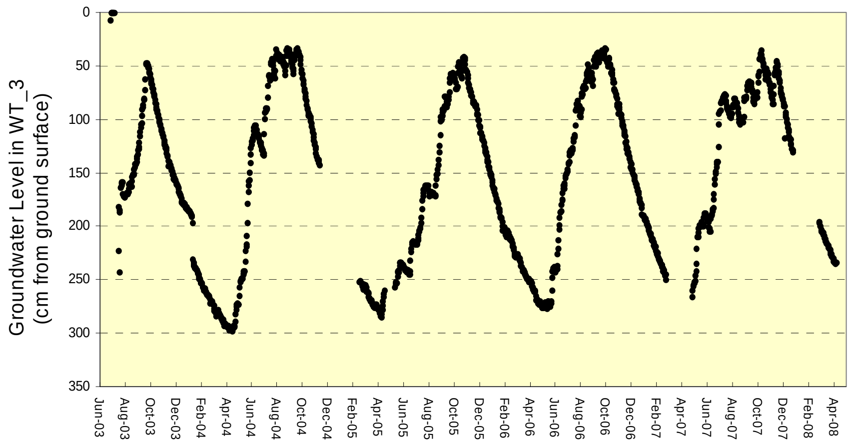


Figure 4.4 Observation Result of Groundwater Level Fluctuation (WT-3)

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 4.5.

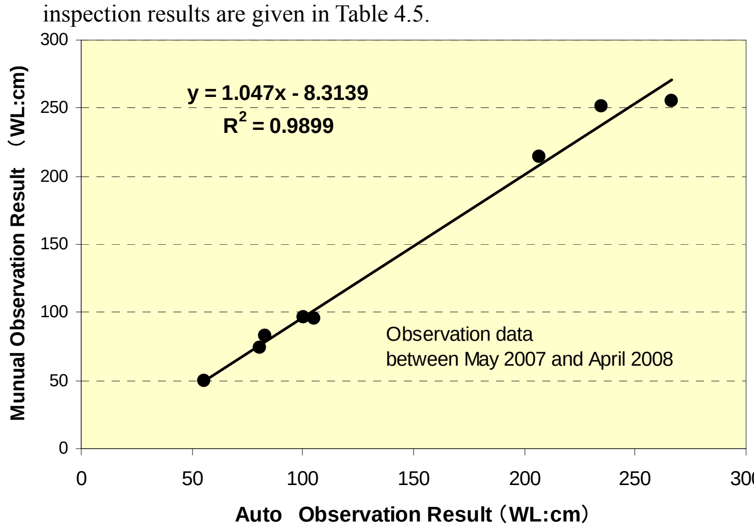


Figure 4.5 Examination of Groundwater Level Observation Data (WT-3)

Based on the result shown in the figure above, 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

The following figure shows the original monitoring data obtained from WT-4. Compared to the observation results from monitoring well WT-3, the result from monitoring well WT-4 shows abnormal fluctuation in groundwater levels.

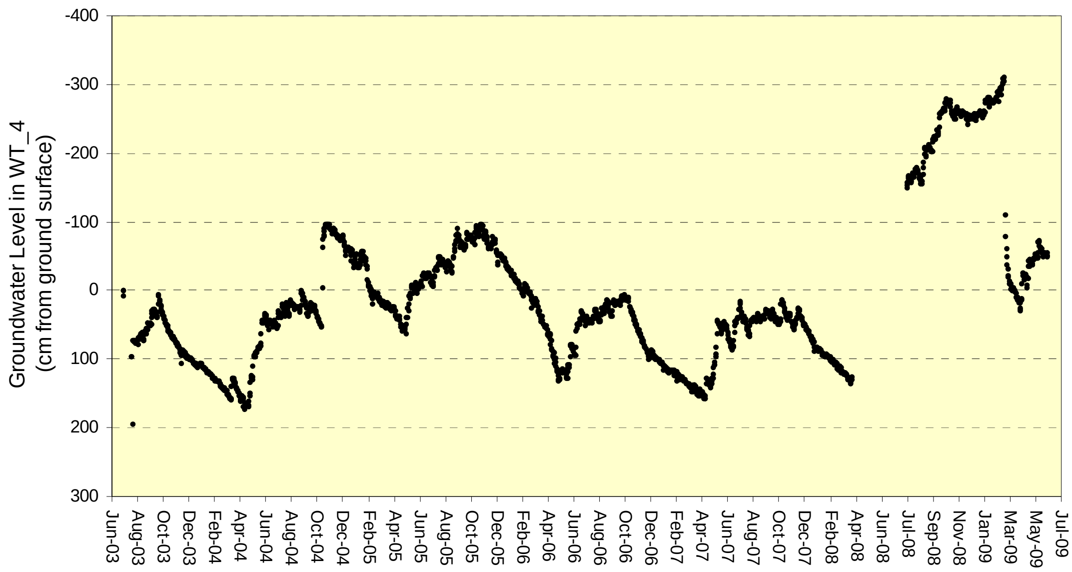


Figure 4.6 Observation Result of Groundwater Level Fluctuation (WT-4)

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 4.5.

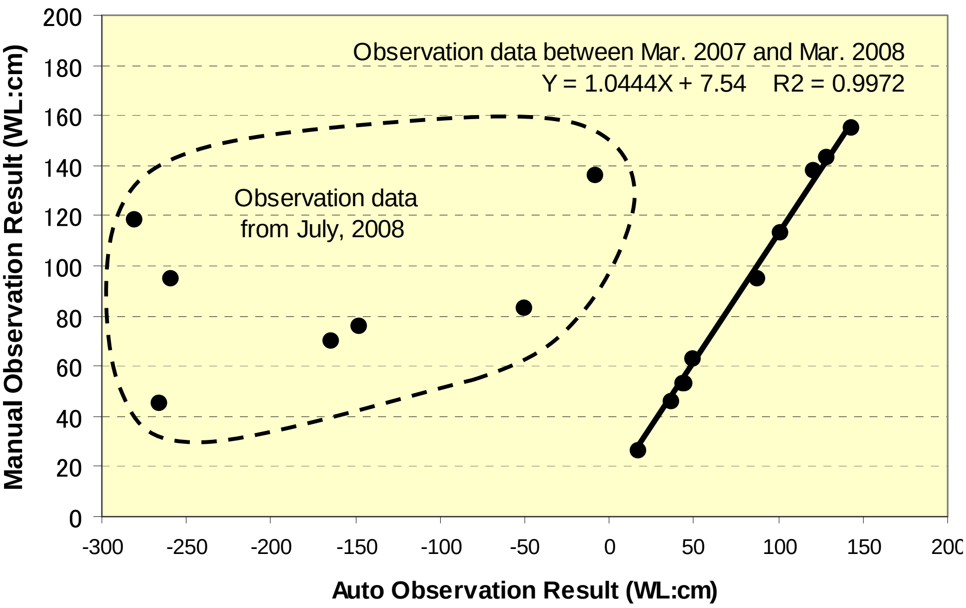


Figure 4.7 Examination of Groundwater Level Observation Data (WT-4)

As shown in the figure above, 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

The following figure shows the original monitoring data obtained from WT-5. The data of WT-5 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.

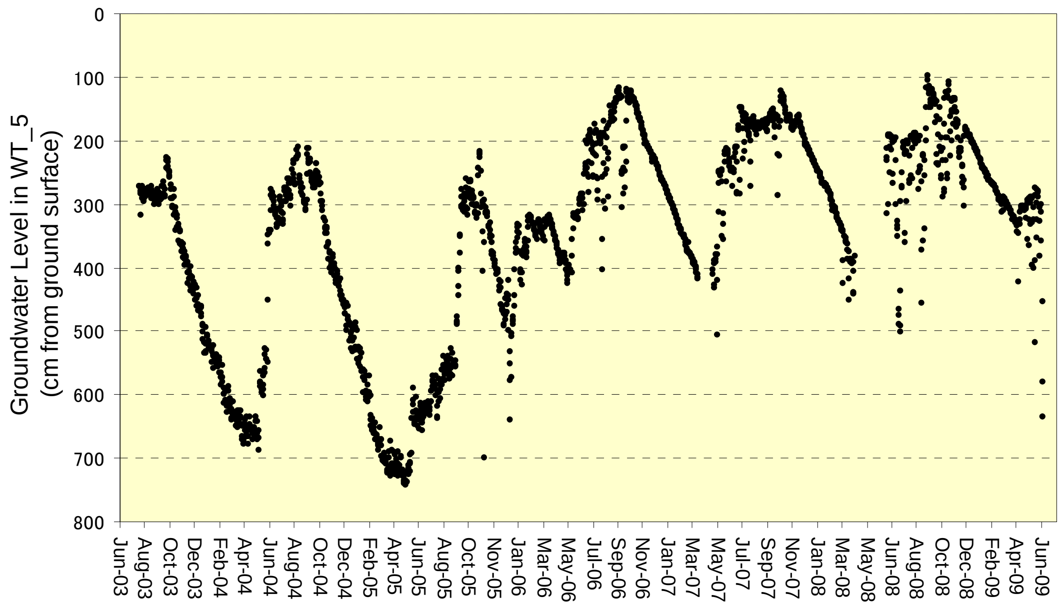


Figure 4.8 Observation Result of Groundwater Level Fluctuation (WT-5)

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 4.5.

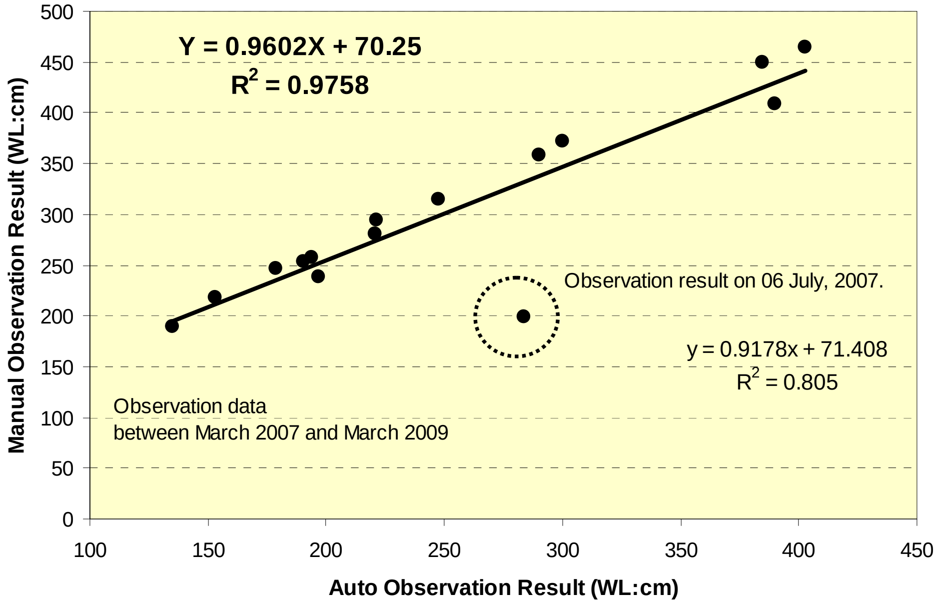


Figure 4.9 Examination of Groundwater Level Observation Data (WT-5)

As shown in the figure above, 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

The following figure shows the original monitoring data obtained from well WT-6. The water level fluctuates from 9 m above ground surface to 3 m below the ground surface. It is clear that the result of groundwater level of 9 m over ground surface is not true.

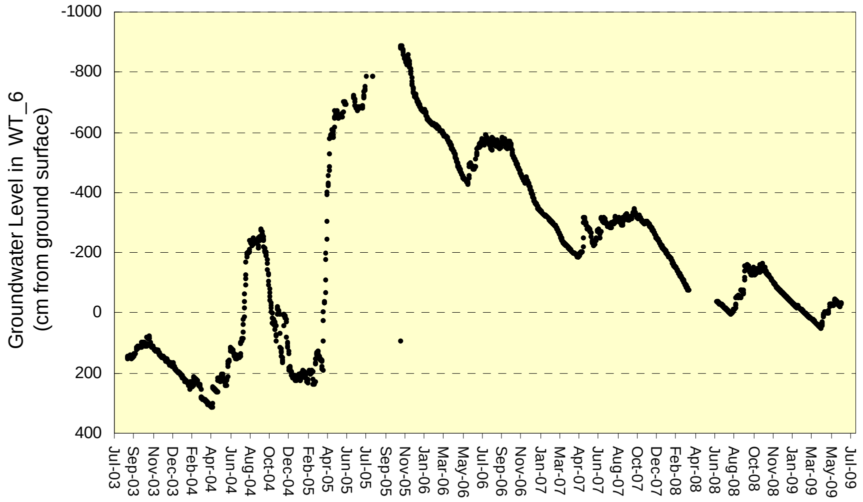


Figure 4.10 Observation Result of Groundwater Level Fluctuation (WT-6)

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 4.5.

As shown in the figure below, the result of inspection indicates that the reliable data duration for

WT-6 is limited from July 2008 to June 2009.

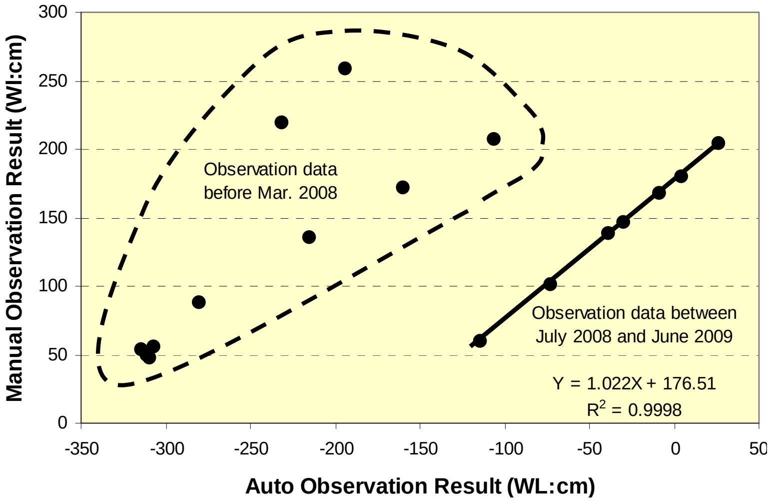


Figure 4.11 Examination of Groundwater Level Observation Data (WT-6)

(5) Monitoring Site WT-7

The following figure shows the original monitoring data obtained from WT-7. Groundwater level in monitoring well site WT-7 is sometimes above ground surface. However, a photo in Figure 4.13 shows that the groundwater level was about 10 cm above the ground surface, when the well site was checked in September 11, 2009. 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 correctly. The figure shows a relatively regular groundwater level fluctuation pattern, except some obviously erroneous data.

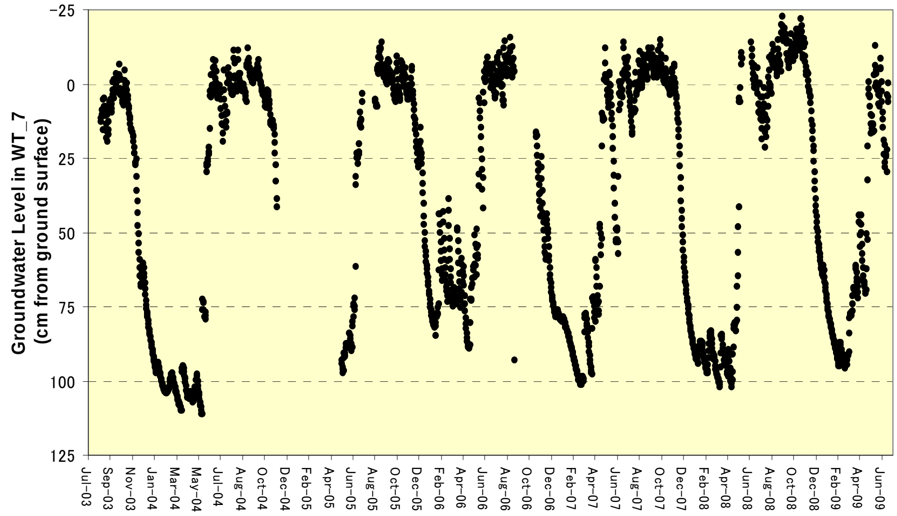


Figure 4.12 Observation Result of Groundwater Level Fluctuation (WT-7)

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 4.5.

Figure 4.13 Photograph of the Observation Cabin of Monitoring Site WT-7

A high correlation can be seen in the following figure between the two data sets over whole corresponding observation period. Because Figure 4.12 showed the regular groundwater level fluctuation in this site, all of the results of WT-7 can be considered as available.

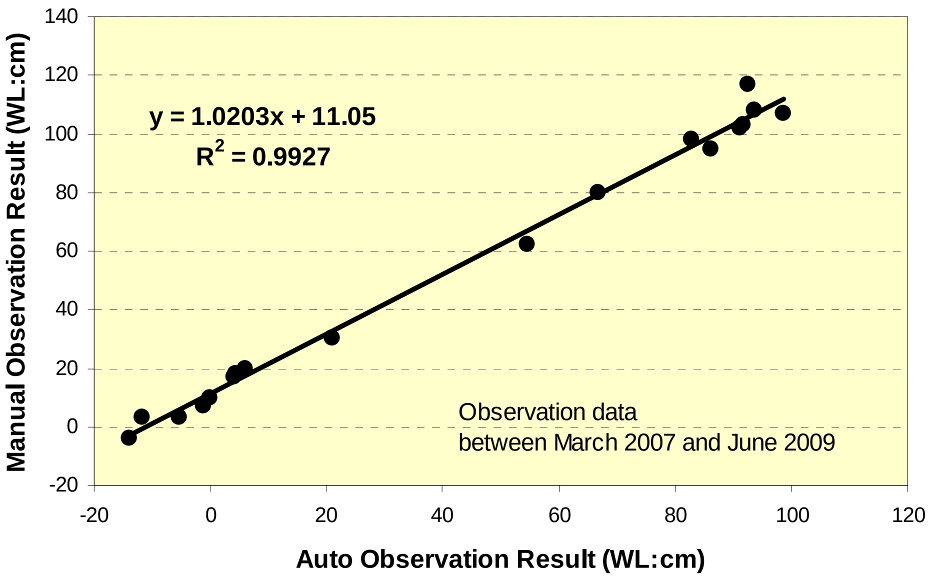


Figure 4.14 Examination of Groundwater Level Observation Data (WT-7)

(6) Monitoring Site WT-8

The following figure shows the original monitoring data obtained from 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.

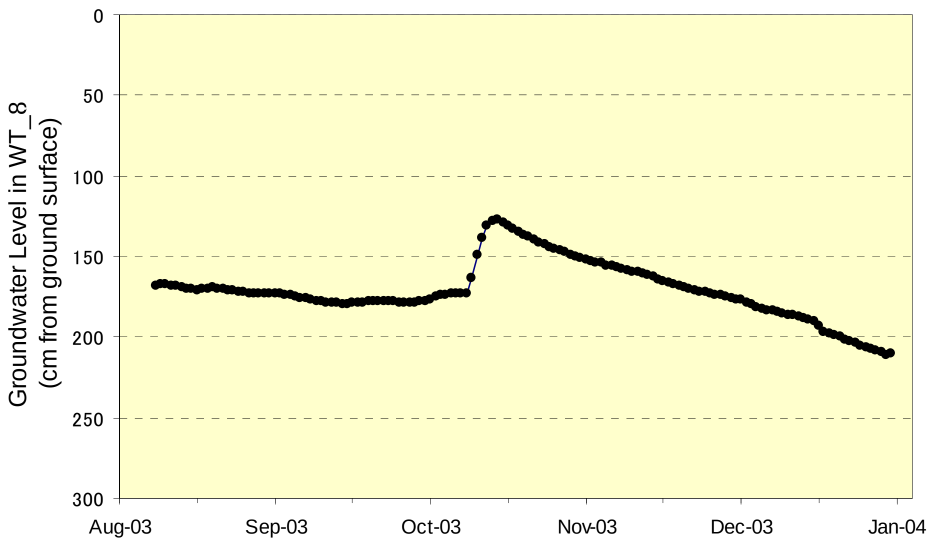


Figure 4.15 Observation Result of Groundwater Level Fluctuation (WT-8)

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 4.5.

(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. The following figure shows the original monitoring data of groundwater levels for the deep and shallow aquifers in the site of LTa.

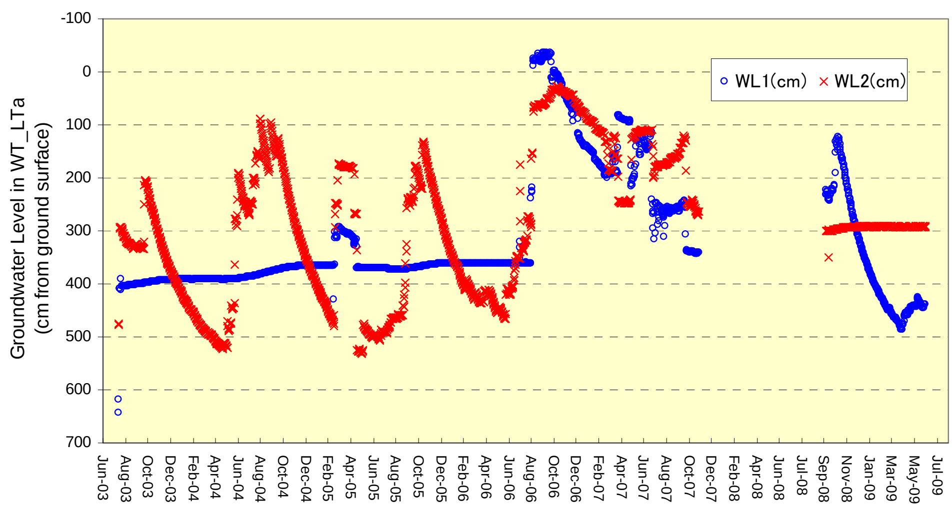


Figure 4.16 Observation Result of Groundwater Level Fluctuation (LTa)

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 4.5.

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 fluctuation pattern of the shallow aquifer and deep aquifer becomes exactly opposite, showing the problem of contrary connection of sensors and data logs.

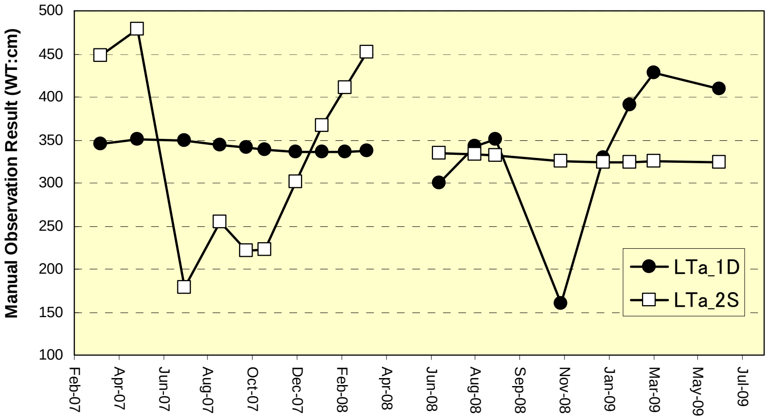


Figure 4.17 Manual Observation Result in Monitoring Site (LTa)

As shown in the figure above, 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 two data sets still gives no acceptable correlation as shown in the following 2 figures. Therefore, the groundwater monitoring data in well site of LTa should be considered as unavailable for analysis.

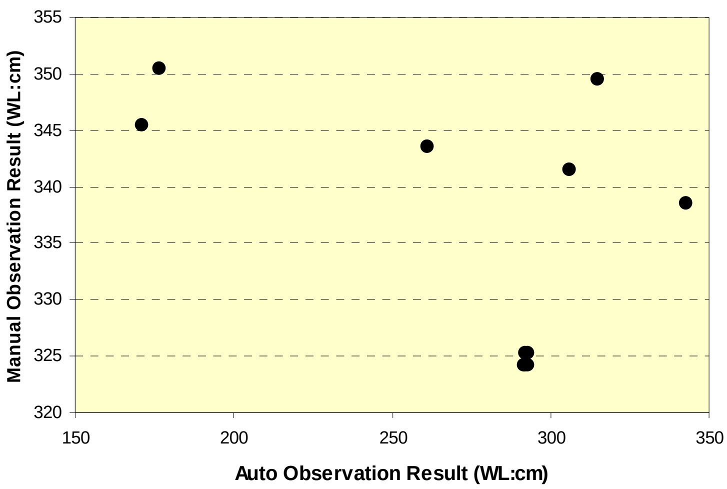


Figure 4.18 Examination of Groundwater Level Observation Data (LTa; Deep Aquifer)

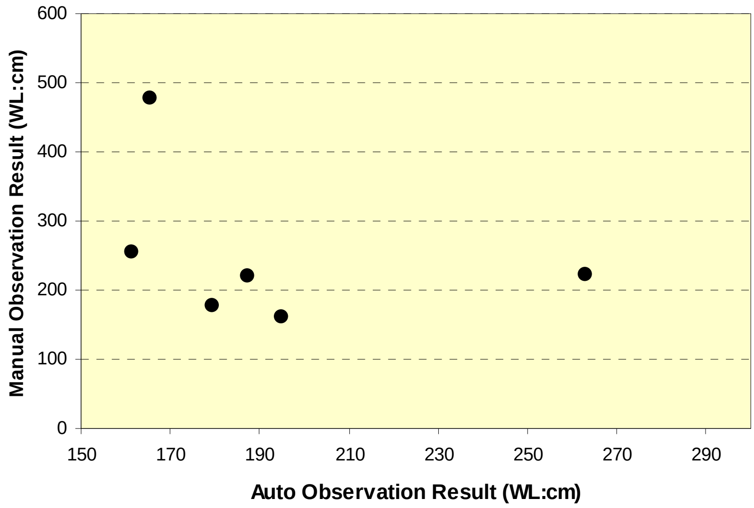


Figure 4.19 Examination of Groundwater Level Observation Data (LTa; Shallow Aquifer)

(8) Groundwater Level Monitoring Site LTb

Two wells were also constructed in site LTb for groundwater level and land displacement observation in the shallow and deep aquifers, respectively. The following figure shows the original monitoring data of groundwater levels for the deep and shallow aquifers in the site.

Relatively high correlations can also be found from Figure 4.21 and Figure 4.22 for confirmation of reliability of the groundwater level observation results in the two aquifers. All data in this site of LTb can be considered as reliable for groundwater analysis.

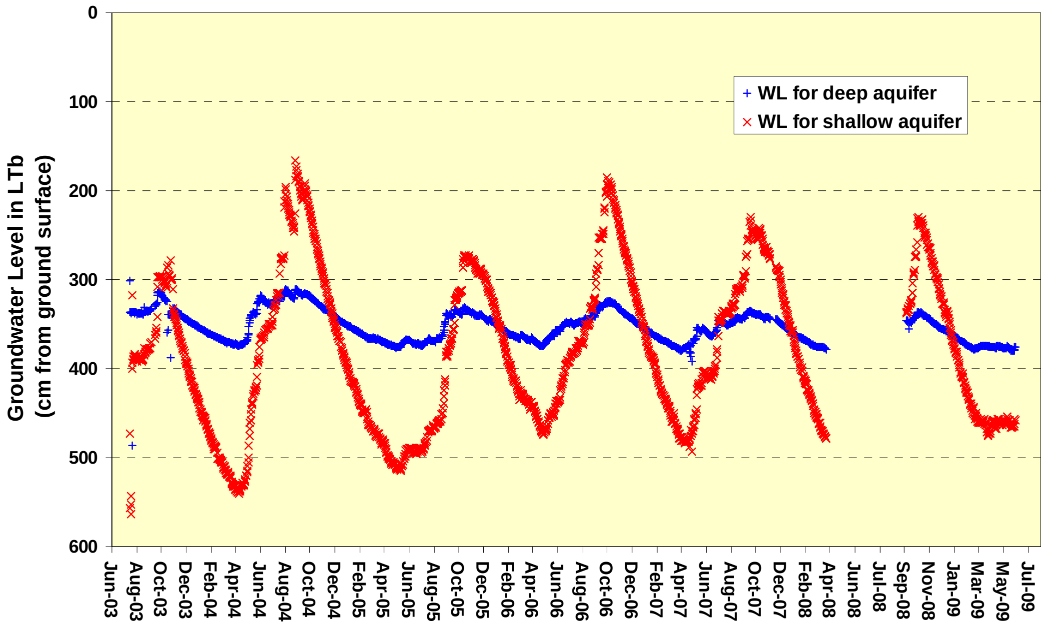


Figure 4.20 Observation Result of Groundwater Level Fluctuation (LTb)

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 4.5.

The following conclusions can be reached from the examination of groundwater fluctuations results shown in the figure above.

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.

2) The water level difference between the two aquifers

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.

Water flows from a higher to a lower place. Hence, if the groundwater flows between the shallow aquifer and deep aquifer, the groundwater flow direction will change as: 1) Flowing downward from the shallow aquifer to the deep aquifer in the rainy season, and 2) Flowing upward from the deep aquifer to the shallow aquifer in the dry season.

3) The water level fluctuation range:

As shown in Figure 4.20, 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.

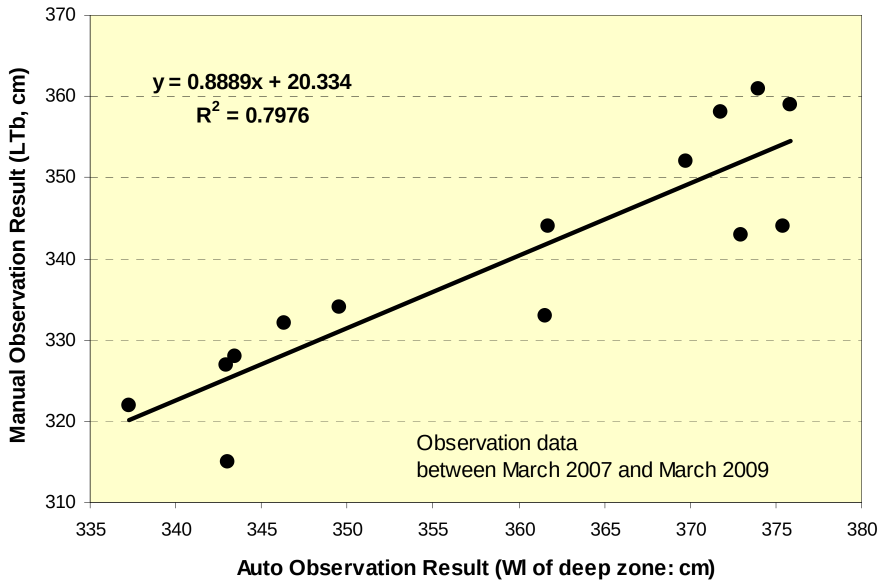


Figure 4.21 Examination of Groundwater Level Observation Data (LTb; Deep Aquifer)

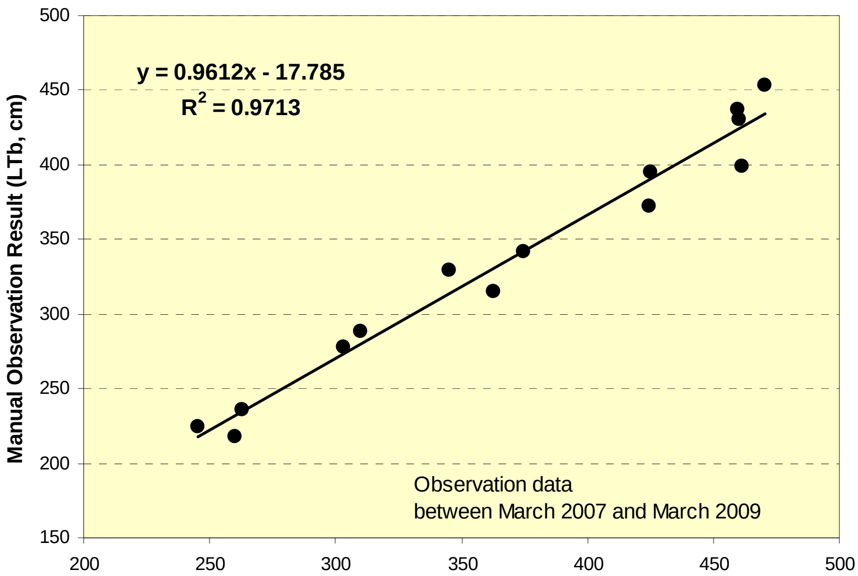


Figure 4.22 Examination of Groundwater Level Observation Data (LTb; Shallow Aquifer)

4-4-3 Result of Land Displacement Monitoring

1) Result of Land Displacement Observation in Site of LTa

The following figure shows the original monitoring results of land displacement for deep and shallow aquifers of the monitoring site LTa.

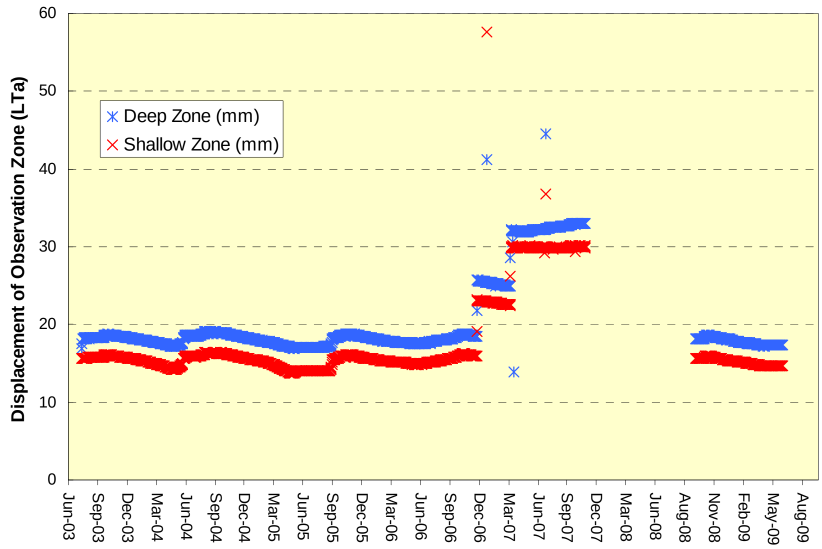


Figure 4.23 Land Displacement Observation Result in LTa

Except the obvious error observation data from November 2006 to July 2008, the observation results show the following points:

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

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

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

To confirm the tendency of land displacement within the circulations of seasonal fluctuation, the monthly average displacement value was calculated. As shown in the table below, examination by the available data results in a maximum displacement range of 18.96 - 17.06 = 1.9 (mm) for the deep aquifer.

Table 4.1 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.

The maximum land displacement in the shallow aquifer is 16.31 - 13.86 = 2.45 (mm) as shown in the table below.

Table 4.2 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 above two Tables are compared, the result seems abnormal. When land displacement is observed in both shallow and deep aquifer in the same location, generally, land displacement in the deep aquifer is larger than in the shallow aquifer, or at least the same as 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.

The following figure shows the yearly average of land displacement in monitoring site of LTa. With merely 6 years observation, 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.

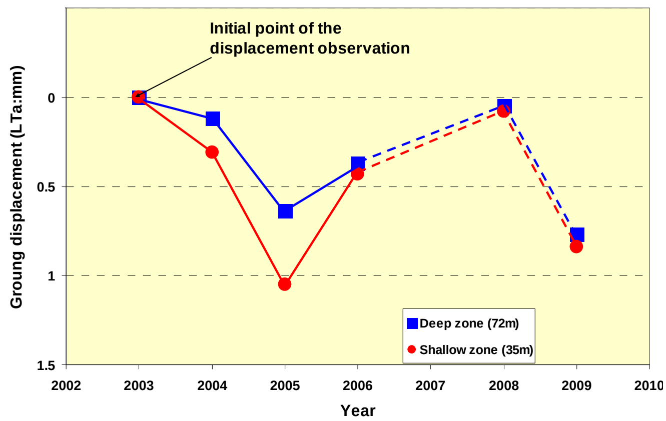


Figure 4.24 Yearly Average of Land Displacement in LTa

2) Result of Land Displacement Observation in Well of LTb

The following figure shows the original monitoring results of land displacement in LTb. The observation in LTb started from July 2003. 6 years 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.

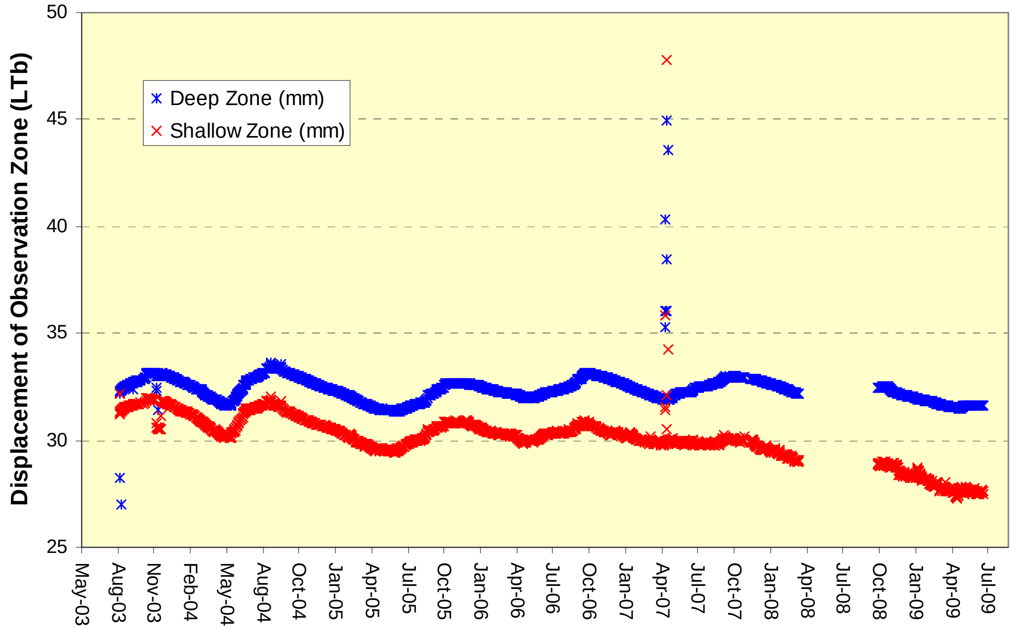


Figure 4.25 Land Displacement Observation Result in LTb

Monthly average of land displacement in the deep and shallow aquifers are calculated and shown in Table 4.3 and Table 4.4, respectively.

Table 4.3 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 4.4 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.

The following figure shows the yearly average value of land displacement in monitoring site of LTb. 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 buildings, 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.

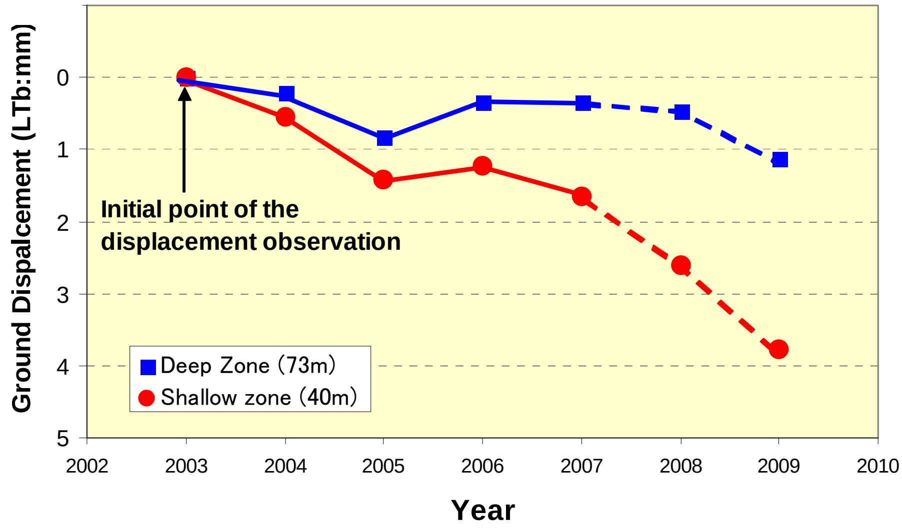


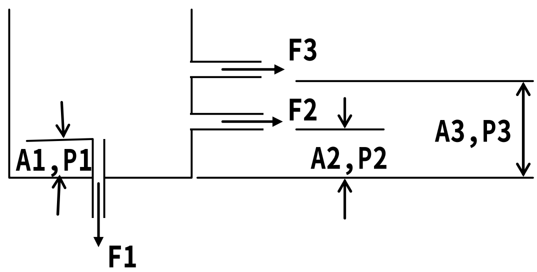
Figure 4.26 Yearly Average of Land Displacement in LTb

4-5 Groundwater Recharge Analysis

4-5-1 Examination of Data Availability

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.

Of many methods for groundwater recharge analysis, the tank model can be considered as a practical method with a fairy high accuracy, when the amounts of precipitation and evaporation are directly linked to the groundwater level fluctuation by tank model. By using the tank model, the recharge and consumption amount of groundwater will be possibly calculated as the result of comprehensive affection of all the relative factors. The basic concept of the tank model is shown in the figure below.



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 4.27 Concept of the Tank Model

The correspondence of meteorological observation stations and groundwater monitoring sites is shown in Figure 4.28.

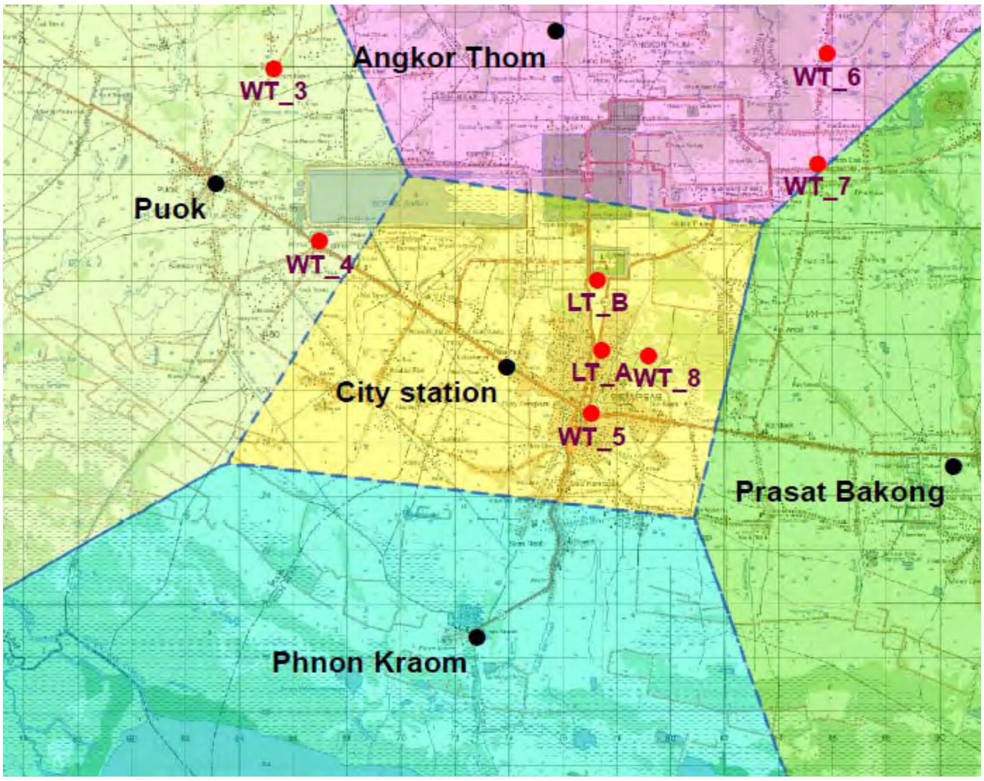


Figure 4.28 Locations of Groundwater Monitoring Well Sites and Meteorological Observation Stations in the Study Area

The data availability confirmation result is shown in the table below.

Table 4.5 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

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 4.29 to Figure 4.34 show the results of groundwater level simulation by the Tank Model in all available monitoring well sites given in Table 4.5.

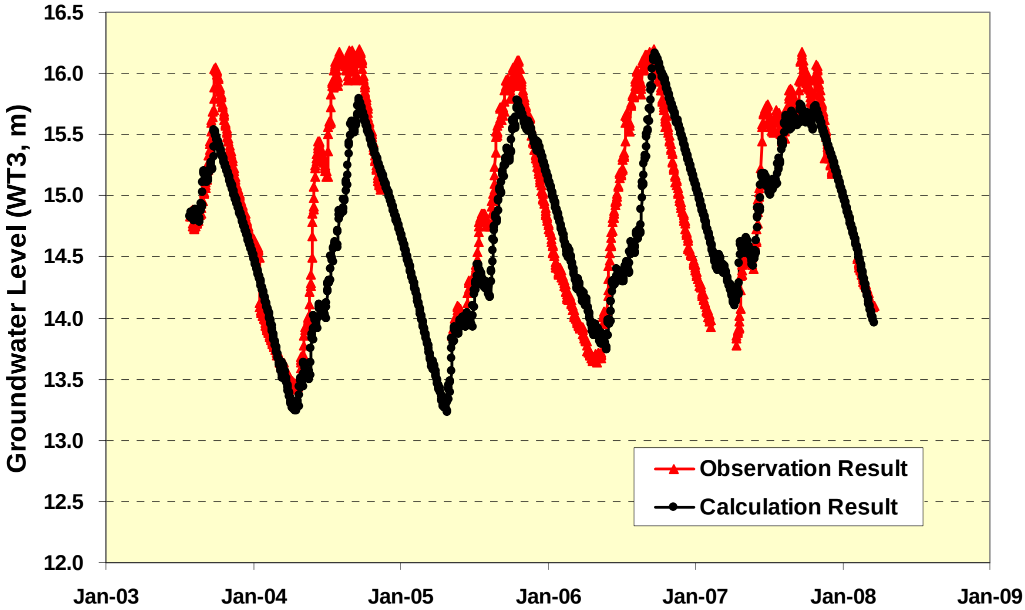


Figure 4.29 Result of Groundwater Level Simulation by Tank Model (WT-3)

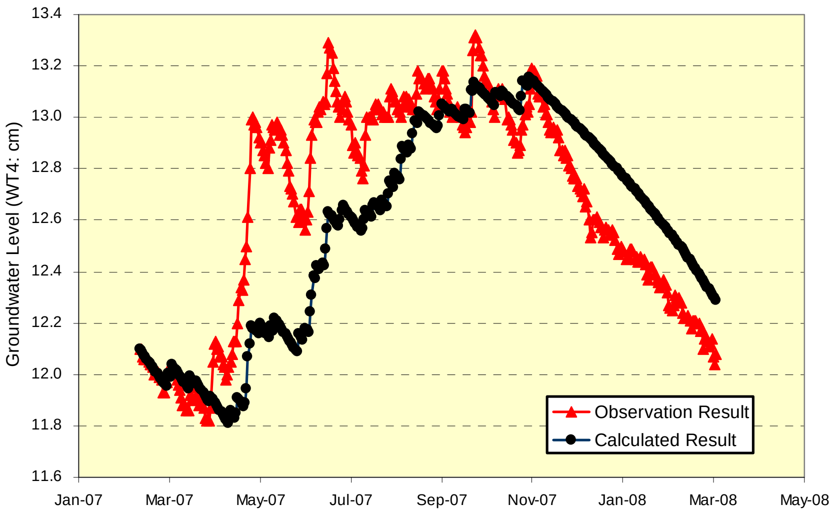


Figure 4.30 Result of Groundwater Level Simulation by Tank Model (WT-4)

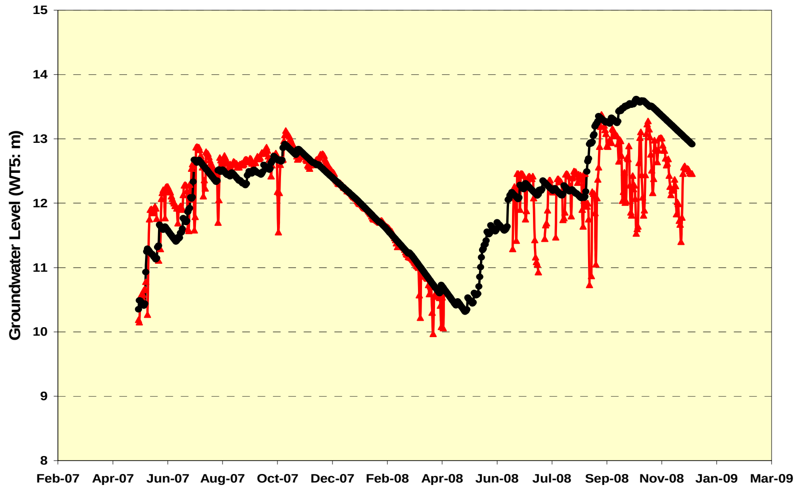


Figure 4.31 Result of Groundwater Level Simulation by Tank Model (WT-5)

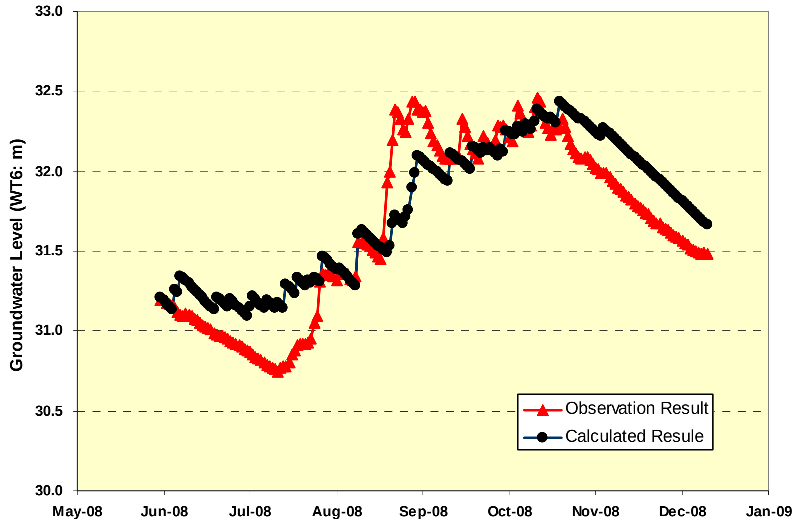


Figure 4.32 Result of Groundwater Level Simulation by Tank Model (WT-6)

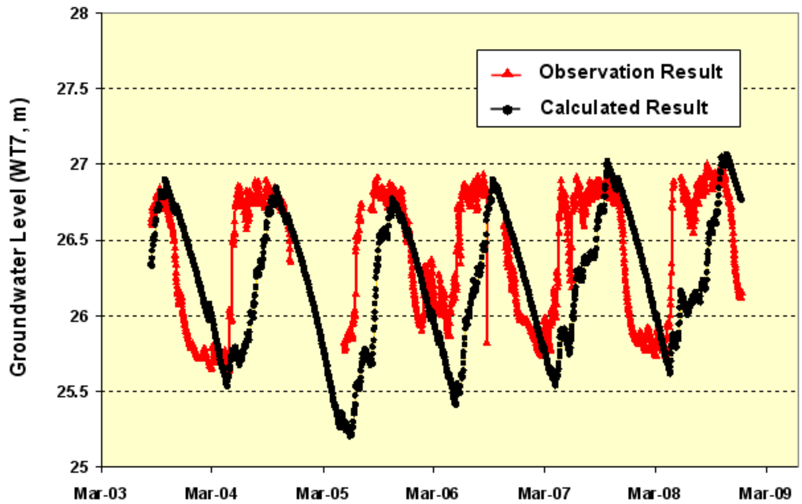


Figure 4.33 Result of Groundwater Level Simulation (WT-7)

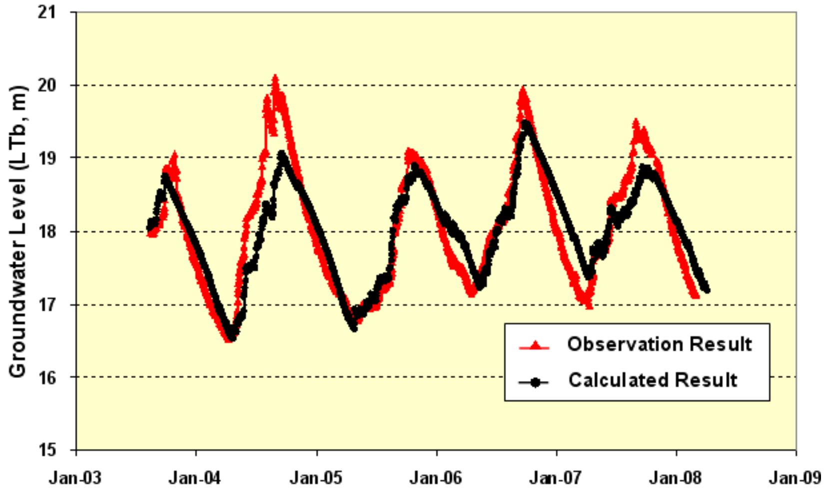


Figure 4.34 Result of Groundwater Level Simulation by Tank Model (LTb)

4-5-3 Summary of Groundwater Recharge Calculation

The groundwater recharge calculation results are summarized in the following 2 tables.

Table 4.6 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 4.7 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 average annual groundwater recharge is 341 mm/year. The annual groundwater recharge of the whole recharge area, three river basins (refer to yellow colored area in Figure 4.2) is 435,517,000 m^3, corresponding to a daily amount of 1,193,000 m^3.

On the other hand, There is no deep aquifer with high permeability in Siem Reap; so the groundwater recharge amount water supply service area should 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. However, 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.

Evaporation from groundwater depends on many factors as the evaporation amount from the ground surface, the depth of groundwater table, the type of soil or aquifer, and so on. 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 whole Siem Reap area in case the groundwater withdrawal amount equals to the recharge amount.

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 season of September 2009 and dry seasons of April 2010. The similar groundwater level distribution has been confirmed from the twice groundwater level survey. Figure 4.35 shows the results of simultaneous groundwater observations in the rainy season. Figure 4.36 shows the difference of the groundwater level between the two seasons.

A high water level drawdown during in dry season can be found from Figure 4.36. A lot of private wells for big groundwater users like hotels and guest houses are used for groundwater withdrawal 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

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.

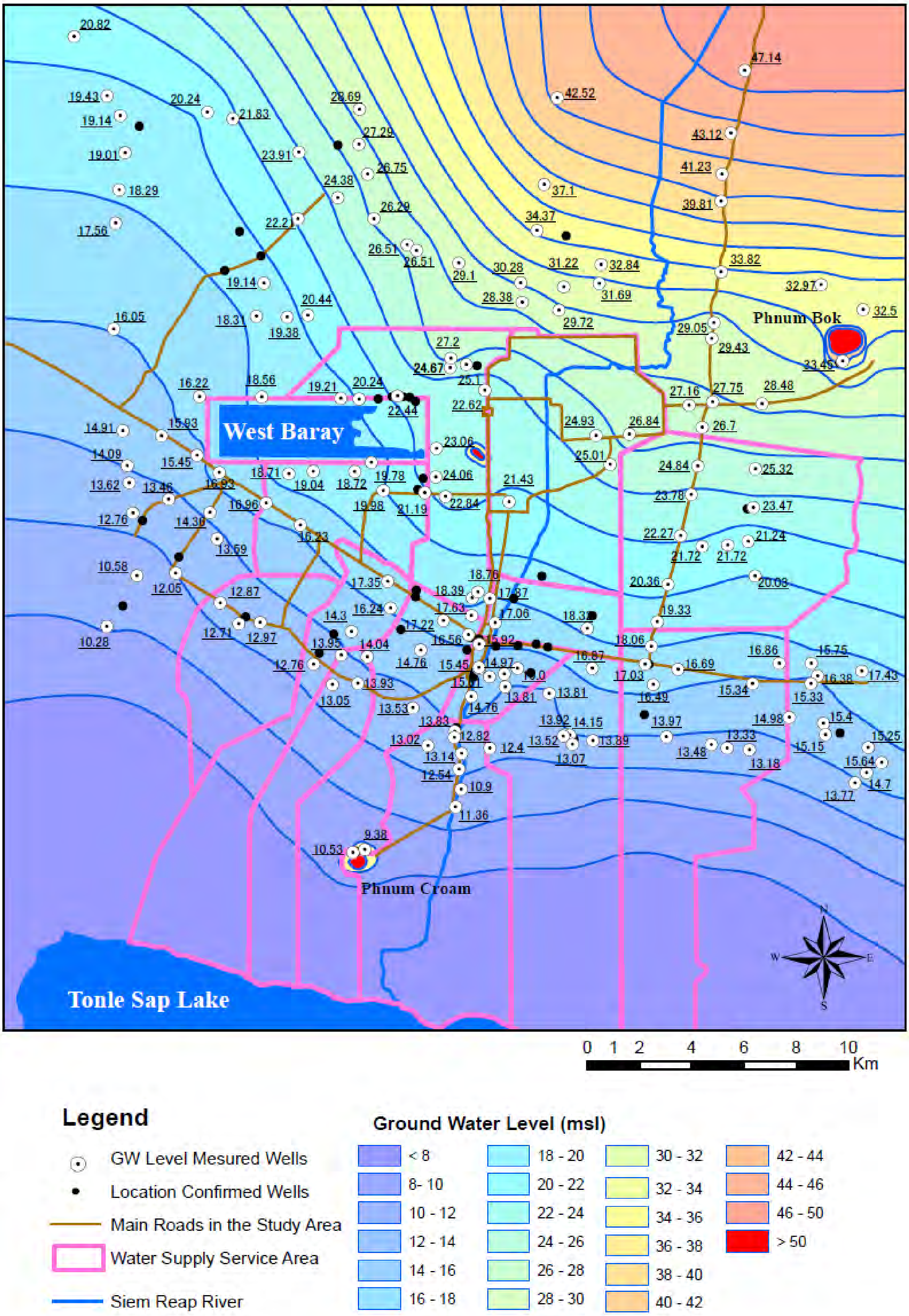


Figure 4.35 Result of Simultaneous Groundwater Observation the Rainy Season (September 2009)

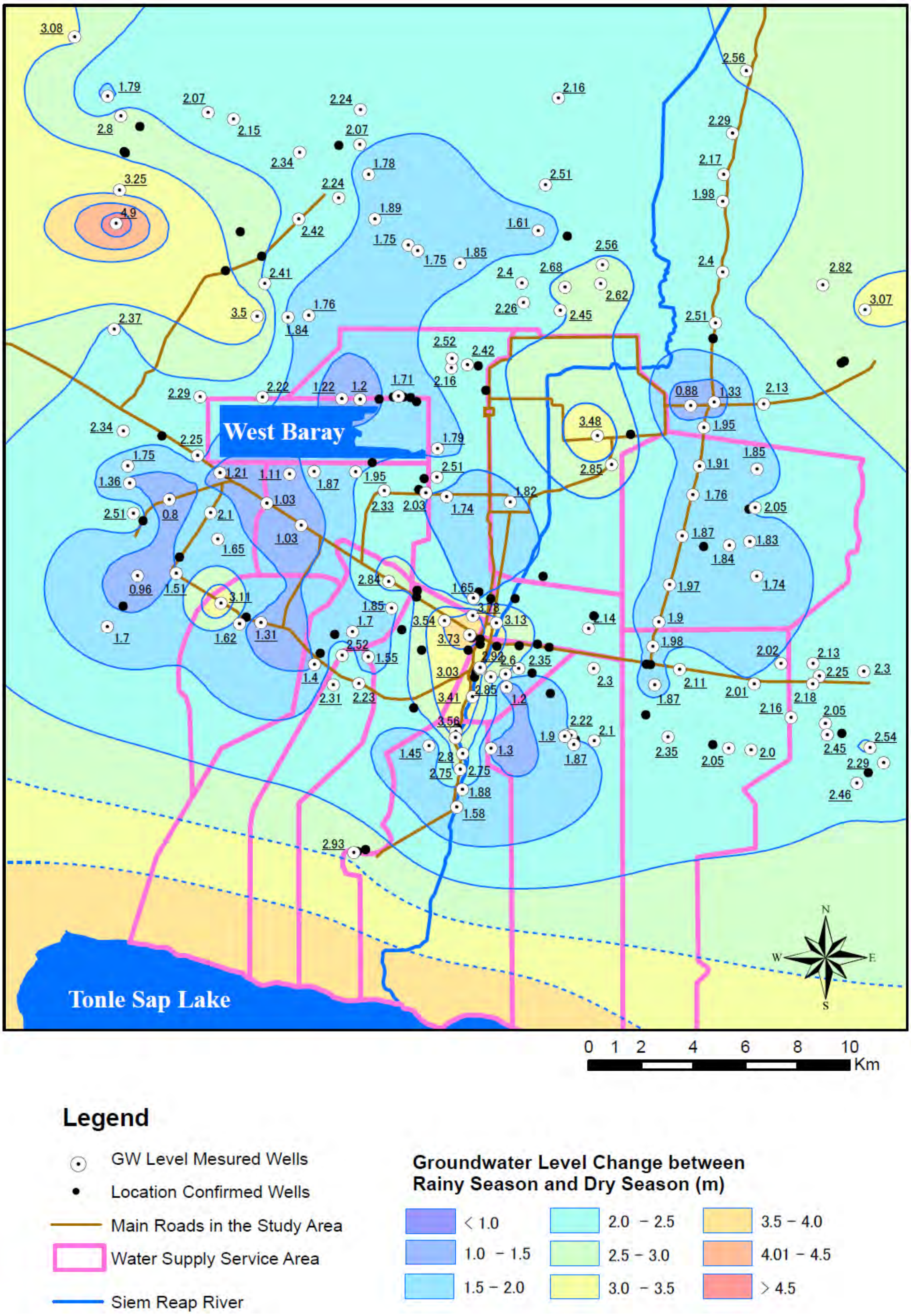


Figure 4.36 Groundwater Level Change between the Rainy (September 2009) and Dry Seasons (April 2010)

4-7 Comparison of Groundwater Level Observation Result

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.

4-7-1 High Groundwater Level Season

The water level in rainy reason in both JICA studies is summarized in the table and figure below. The water level in 2009 is lower than that in 1999, but almost the same as it in 1998.

Table 4.8 Comparison of Water Level in Rainy Season by Wells along Main Roads

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.

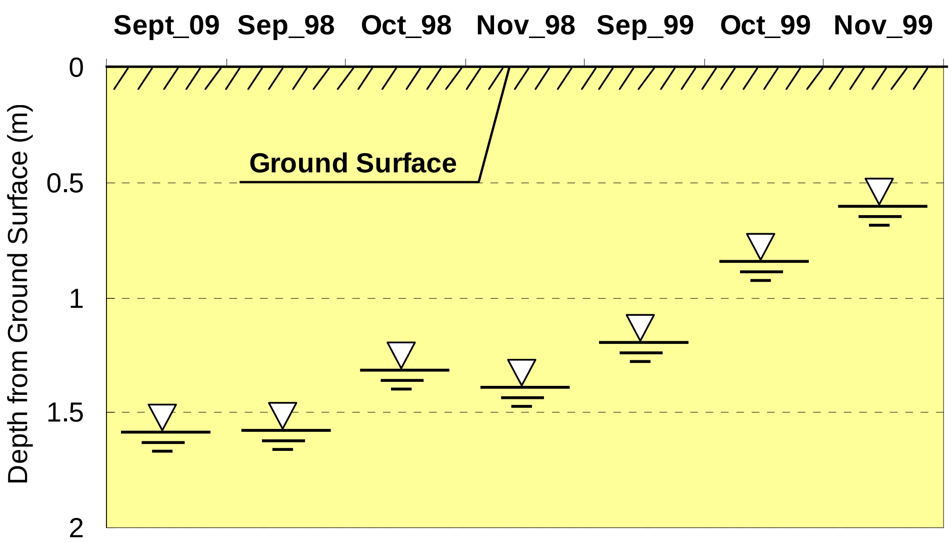


Figure 4.37 Comparison among Average Water Levels in Rainy Season by Wells along Main Roads

4-7-2 Low Groundwater Level Season

The water level in dry season of this survey (April 2009) is lower than the water level in all corresponding months in the dry seasons of 1998 and 1999.

Table 4.9 Comparison of Water Level in Dry Season in Wells along Main Roads

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.

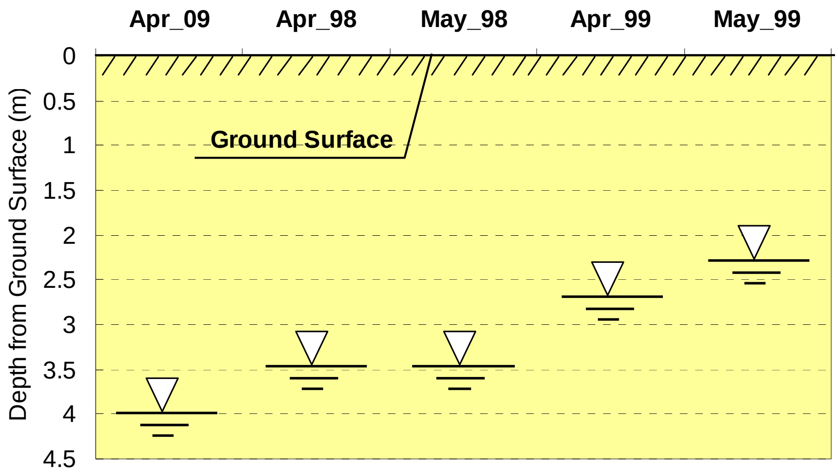


Figure 4.38 Comparison among Average Water Levels in Dry Season by Wells along Main Roads

4-7-3 Result Comparison in Town Area

To check the water level change in the town area, all wells in different studies in the town area have been extracted. 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 extracted from the previous JICA study, 13 wells have data available for this comparison. All the available data are summarized in different season, and the results are shown in the following tables and figures.

Table 4.10 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.

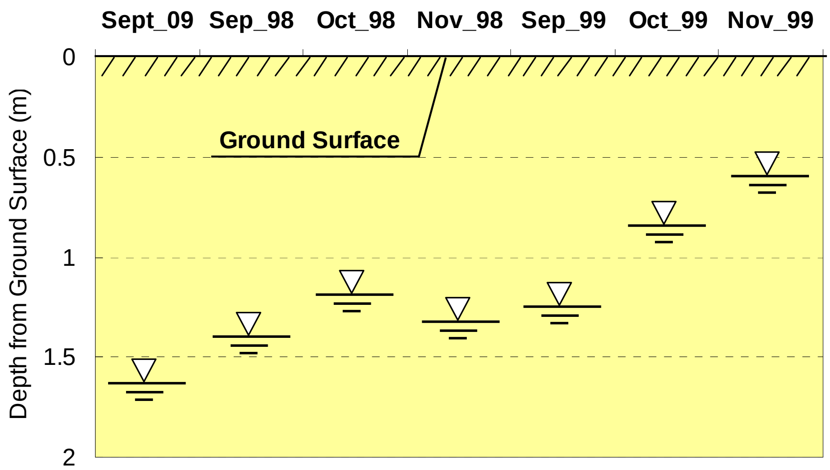


Figure 4.39 Comparison among Average Water Levels in Rainy Season in Town Area

Table 4.10 shows obvious difference between water levels in the rainy seasons of this study and the previous study. 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. 0.22 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 4.11 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

Remark: the value in the table gives the water level below the ground surface.

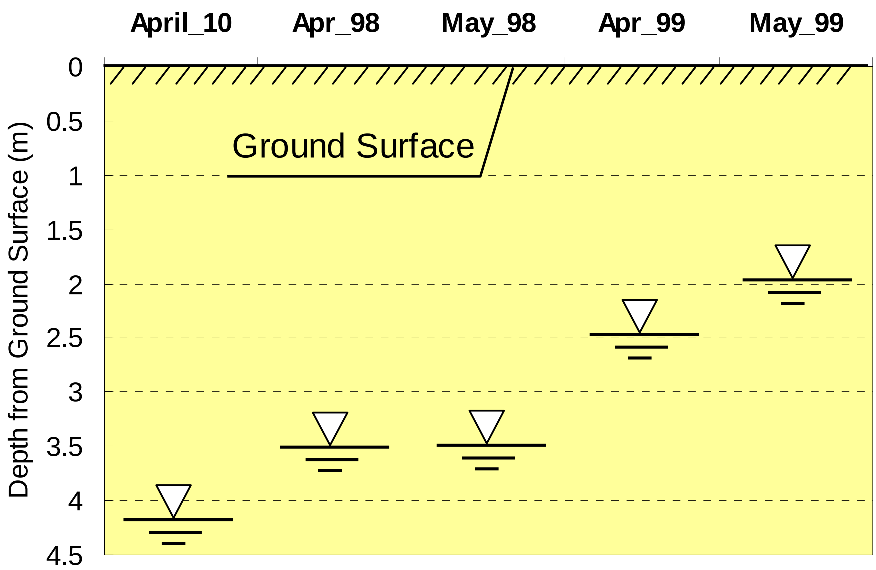


Figure 4.40 Comparison among Average Water Levels in Dry Season in Town Area

Both Table 4.10 and Table 4.11 show obvious difference in water levels between September 2009 (April 2010) 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.

Chapter 5.
Groundwater Simulation

Chapter 5. Groundwater Simulation

Simply considering from the groundwater recharge amount of 516,000 m^3/day, that is about six times the estimated water demand of 86,300 m^3/day in 2030. Hence, in case of available groundwater development amount evaluation from the viewpoint of balance between withdrawal and recharge, the value of 516,000 m^3/day can be taken as the potential amount for groundwater development.

However, not only the balance between groundwater recharge and withdrawal, but also the effect of groundwater development such as increasing of pumping volume in the future and selection of development areas 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.

As having been mentioned in Chapter 4, 4-5-3 Summary of Groundwater Recharge Calculation, because the lack of deep and high permeability aquifer in Siem Reap, if all the recharge amount of 516,000 m^3/day were used for water supply, the groundwater level will fall to 5m below the ground surface in the whole Siem Reap area. The water demand is about one sixth of the recharge amount. Therefore average groundwater level drawdown in the whole water supply service area would be smaller than 5 m. However, it is unavoidable to cause groundwater drawdown when groundwater withdrawal. And the magnitude of groundwater drawdown might be larger than 5 m in and around well's field.

5-1 Distribution of Heritages in Siem Reap

Siem Reap is a world famous place because there are lots of heritage sites in the area. The well known heritage sites are Angkor Wat, Angkor Thom and West Baray. As shown in Figure 5.1, a lot of other heritage sites are also very important in Siem Reap including East Baray, Bakong, and so on.

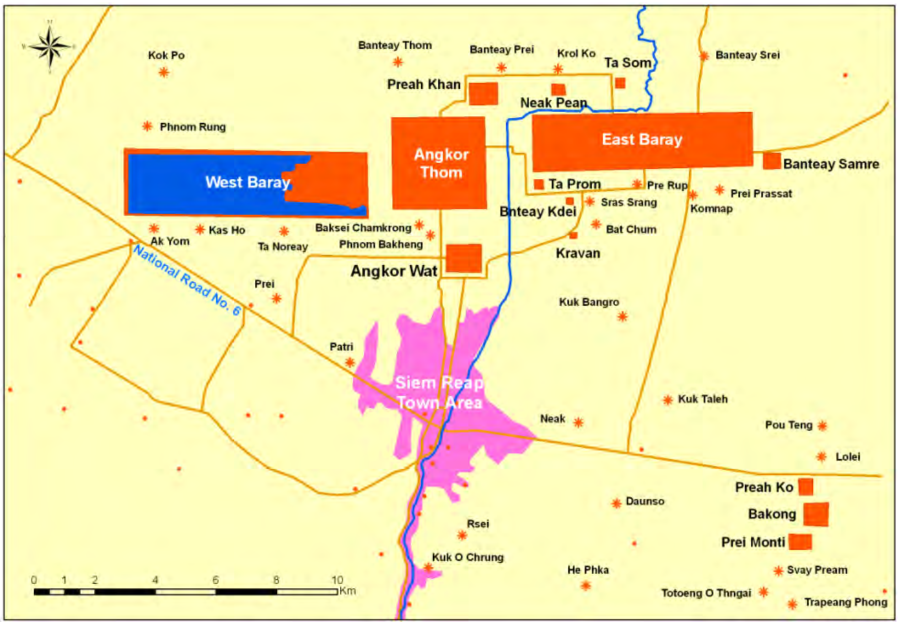


Figure 5.1 Distribution Map of Main Heritage Sites in Siem Reap

5-2 Groundwater Simulation Model Structure

There is not deep, thick and high permeability aquifer in Siem Reap. Therefore, when groundwater is used for water supply, not only does the daily production amount have to be limited to about 1,000 m^3/day/well to avoid large drawdown of groundwater level in localized well-fields, but also the groundwater level drawdown in regional area has to be evaluated earnestly.

This study has reviewed several water supply system expansion plans such as (1) supply plan covering a part of water demand by groundwater and considering KTC project which uses a part of (irrigation) canal water from West Baray, (2) groundwater development plan covering all the water demand, (3) surface water development plan of Tonle Sap Lake. The effect of these plans is evaluated by a groundwater simulation model created on the basis of geological and hydrogeological survey results and other relative surveys.

A model domain is determined on the basis of considering features of groundwater in Siem Reap, available data and simulation purpose as shown in Figure 5.2.

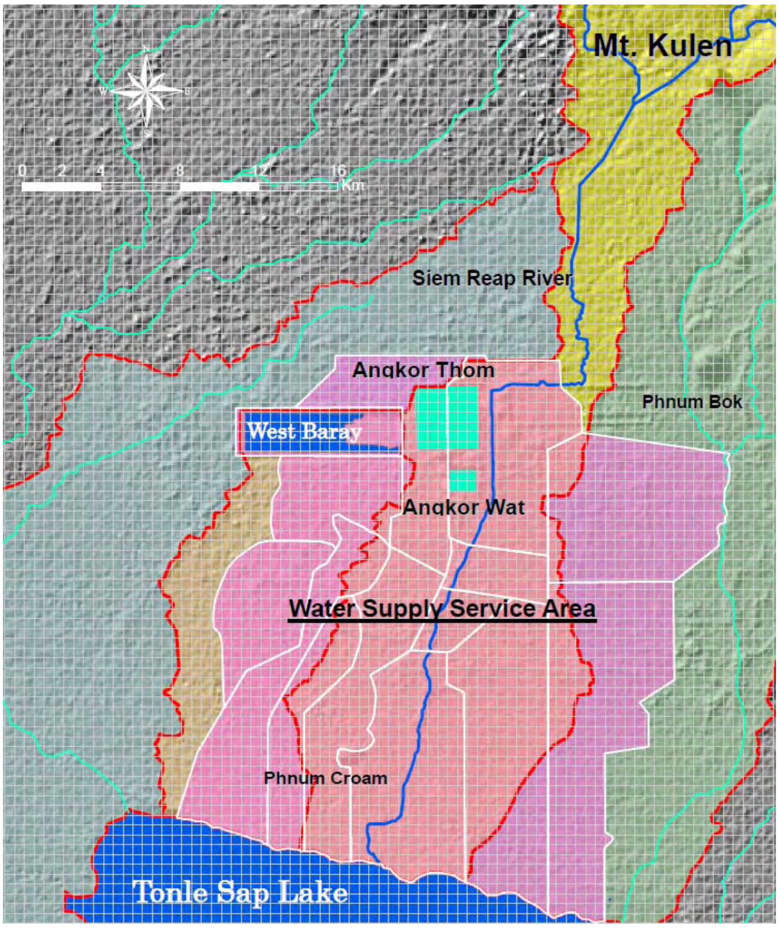


Figure 5.2 Groundwater Simulation Model Domain

5-2-1 Model Domain

As shown in Figure 5.2, the model domain covers an extent, as follows, in coordinate system of WGS84, UTM zone 48 north:

- Easting: 354000 – 393000 (39 km)
- Northing: 1460500 – 1507000 (46.5 km)
- Total coverage area ＝39×46.5 ＝1,813 km^2

The model is created using the most world famous groundwater simulation program, Modflow. Modflow is developed by the USGS (the U.S. Geological Survey) and the source code can be freely downloaded from the web page of USGS. Modflow uses groundwater simulation method of finite difference method. This method requests to specify the model domain as a rectangle shape and divide the model domain into small rectangle shape grids. The same as model domain specification, grid division is based on the consideration of precision of the model, available data for parameter specification, efficiency of input data creation and output data acquisition extraction, and so on.

- Grid Size: 500 m ×500 m
- Number of rows: 93
- Number of columns: 78
- Number of cells: 7,254

Layer Specification

Based on pumping test results of a previous JICA study (the Study on Water Supply System for Siem Reap region in Cambodia, 2000) and the water level observation results in land displacement monitoring sites LTa and LTb (refer to Chapter 4, section 4-4), it has been revealed that aquifers in Siem Reap can be separated into two ones: shallow aquifer and deep aquifer. Between the two aquifers exists an aquiclude.

On the other hand, in the shallow aquifer, many cells should be taken as constant water head boundary because of the surface water features located in those cells. Existence of these surface water features does not only affect the groundwater level in its vicinity, but also plays an irreplaceable role in the protection of the heritage sites. Therefore, these water features are specified into the model domain to make the model fit the situation in Siem Reap as much as possible.

To ensure the model convergence and make model parameter specification fit the real groundwater use situation in Siem Reap, the shallow aquifer is separated into two layers in the model; and then model domain is separated into 5 model layers as follows.

Layer 1: 10 m thickness for constant head boundary of Tonle Sap Lake; 6 m thickness for other constant head boundary cells; 5 m above bottom of layer 2 for all head computed cells.

Layer 2: from the bottom of layer 1 to the bottom of Quaternary aquifer.

Layer 3: Aquiclude

Layer 4: Deep Aquifer

Layer 5: Basement rock

5-2-2 Boundary Condition Specification

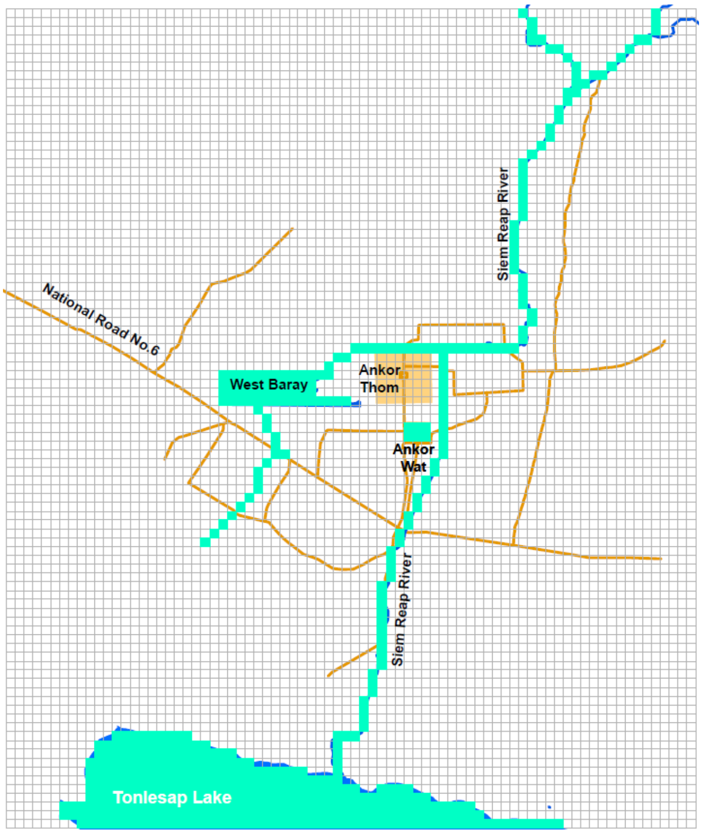


Figure 5.3 Specification of Constant Head Boundary

Constant water head boundary shown in Figure 5.3 includes:

- Siem Reap River
- Angkor Wat moat
- West Baray (man-made lake) and its channels for water conveyance in its upstream and downstream sides
- Tonle Sap Lake

5-2-3 Elevation Specification

The topography data, a 1:5,000 topography map created in a previous JICA survey (Integrated Master Plan for Sustainable Development of Siem Reap/Angkor Town in Kingdom of Cambodia; 2005), was used for elevation specification in the urban and surrounding areas. For other areas slightly further from the urban area, the elevation specification is based on 90 m mesh DEM data SRTM from the USNASA.

Specification of the bottom of each layer in the model depends on the test boring data and geophysical survey results in the Study on Water Supply System for Siem Reap Region in Cambodia (2000).

Figure 5.4 and Figure 5.5 show examples of vertical (North - South) and horizontal (East - West) sections in the groundwater simulation model domain.

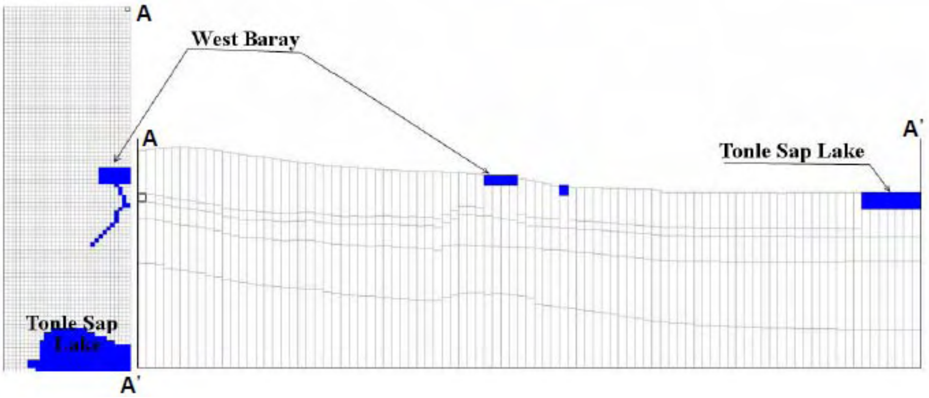


Figure 5.4 Example of Vertical Section in North – South Direction.

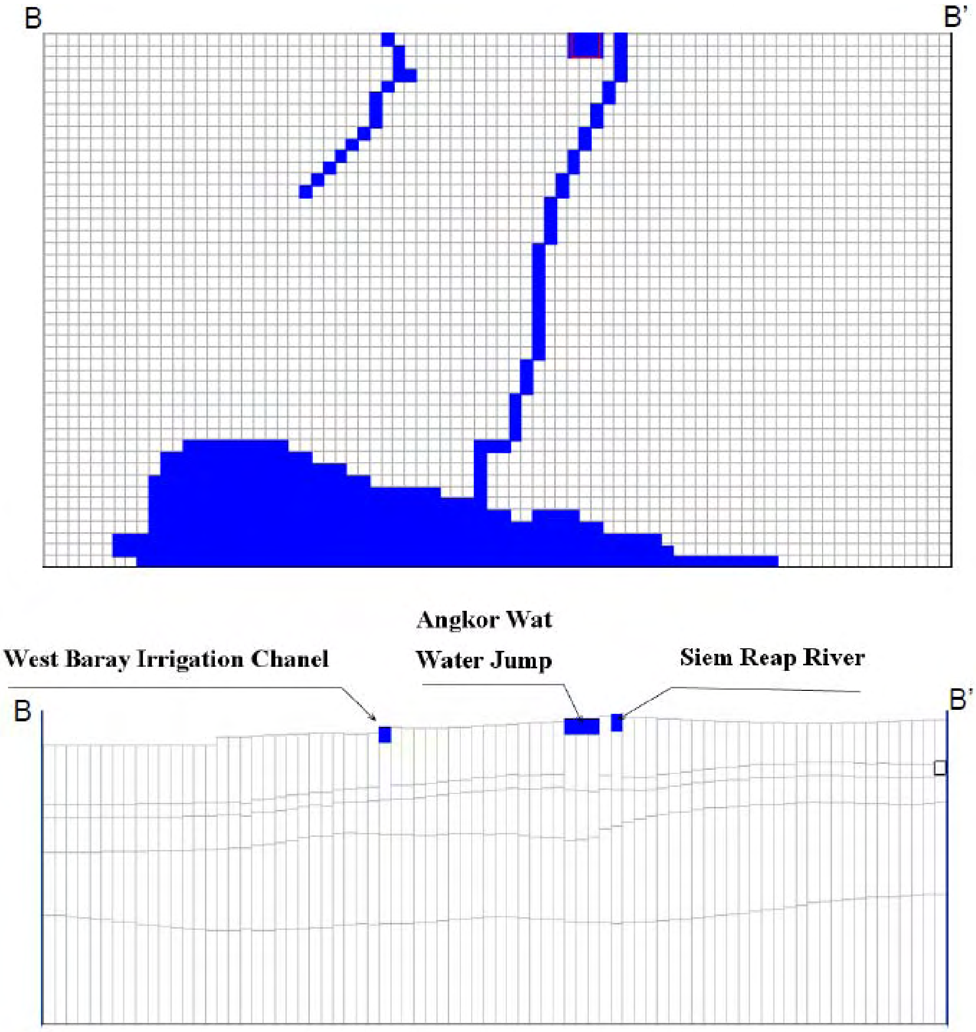


Figure 5.5 Example of Vertical Section in East – West Direction

5-3 Specifications of Parameters

5-3-1 Hydraulic Conductivity

Hydraulic conductivities are specified for each layer as follows based on the pumping test results of the Study on Water Supply System for Siem Reap Region in Cambodia (2000):

- Layer 1 & layer 2: Shallow Aquifer
  Lithofacies: Clayey sand or sand or clay of silty sand, mainly silty sand.

  0.05 to 35.5 m/day, 11.95 m/day on average

- Layer 3: Aquiclude
  Lithofacies: Clayey sand or sandy claystone or clayey sandstone or silty stone or sandy stone; mainly clayey sand.

  0.002 to 0.1m/day, 0.0077m/day on average

- Layer 4: Deep Aquifer
  Lithofacies: Clayey sandstone or sandy claystone silty stone or clay stone, mainly clayey sandstone

  0.012 to 4.03 m/day, 1.21 m/day on average

- Layer 5: Basement Rock
  Lithofacies: Sandstone or shale or tuff, mainly sandstone

  0.00005 m/day

5-3-2 Storage Coefficient (dimensionless)

- Layer 1 to layer 3: 0.000005
- Layer 4: 0.00005
- Layer 5: 0.0005

5-3-3 Effective Porosity (dimensionless)

- 0.15 for all layers

5-3-4 Specific Yield (dimensionless)

- Layer 1: 0.05 to 0.17; 0.095 on average
- Layer 2 to layer 5: 0.15

5-4 Model Calibration - Steady Flow Simulation

The basic method for model stability or convergence examination is to conduct steady flow calculation. This is because in some cases, some simulation results can be obtained even though the model actually does not converge. The steady flow calculation result of the Siem Reap groundwater simulation model is shown in Figure 5.6.

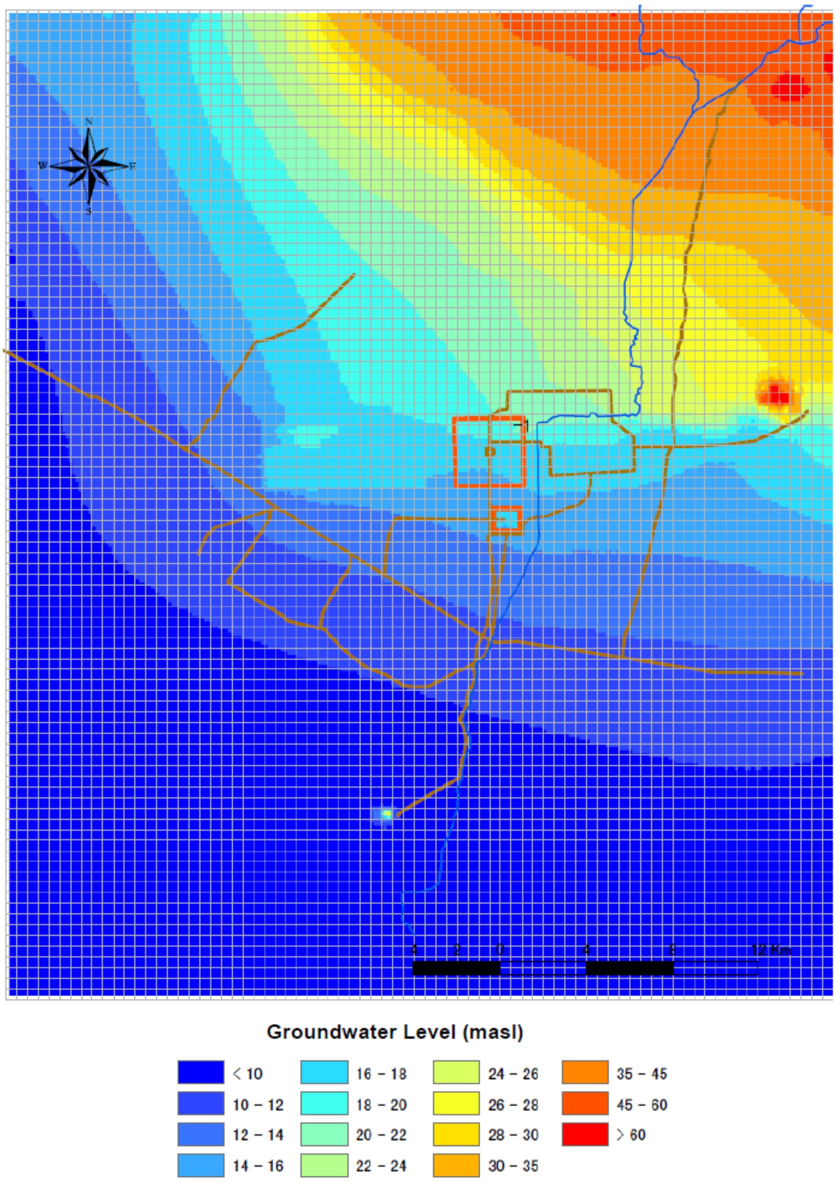


Figure 5.6 Result of Steady Flow Simulation

As shown in Figure 5.6, the steady flow simulation result fits the simultaneous groundwater observation result properly, so that both convergence and conformity of the Siem Reap groundwater simulation model can be confirmed.

5-5 Model Calibration - Transient Flow Simulation

The transient flow simulation was conducted after the steady flow calculation for model calibration by using the SRWSA production records and other relative parameters. A calculation span of three years is set from 2006, the year the SRWSA production wells began operation, to the end of 2008.

5-5-1 Amount of Groundwater Use

Not only SRWSA production wells, but also a lot of private wells are being used for water supply to hotels, guest houses and other utilities. The result of the daily per capita water use estimation was used to specify the groundwater withdrawal amount in the urban area. And the result of estimation is based on the survey of well inventory creation.

The specification of monthly groundwater withdrawal for the 3 years of the simulation span in SRWSA existing production well sites and private well areas are shown in Figure 5.7. And the location of well cells is shown in Figure 5.9.

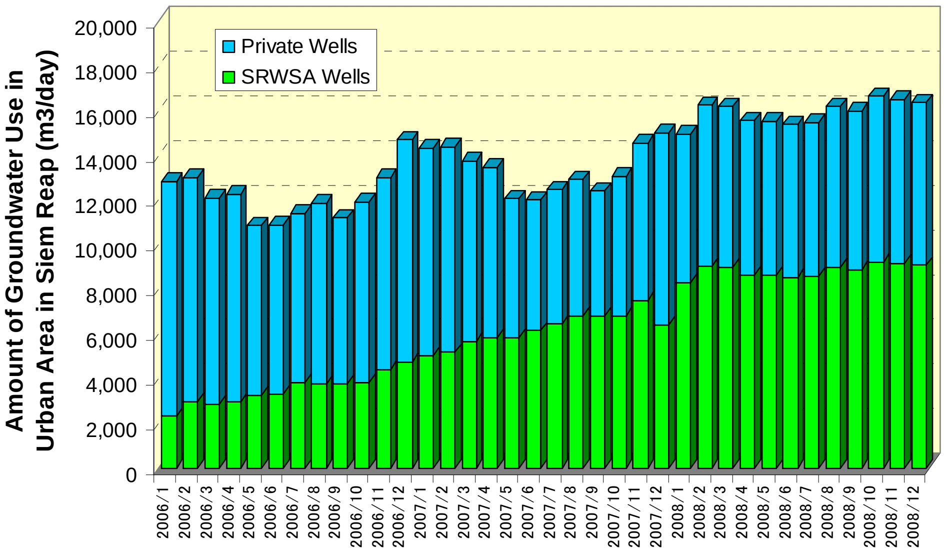


Figure 5.7 Production Amount of SRWSA Existing Wells and Private Wells in Urban Area in Siem Reap from 2006-2008

5-5-2 Precipitation, Evaporation, Groundwater Recharge and Consumption

The monthly precipitation, evaporation, groundwater recharge and consumption are summarized in Figure 5.8.

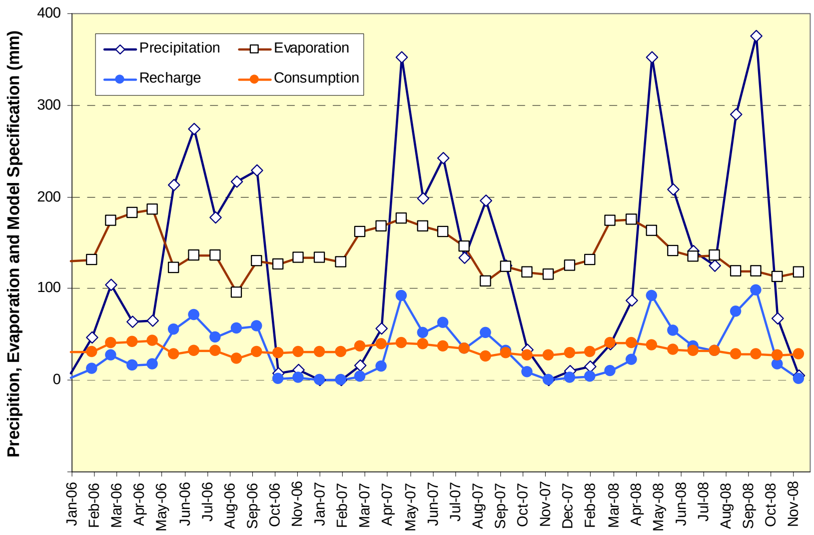


Figure 5.8 Observed Precipitation, Evaporation, Specified Groundwater Recharge and Consumption

5-5-3 Result of Transient Flow Simulation

For transient flow result checking, 5 provisional observation wells (shallow wells: calculation point) were specified in the cells of central part of the urban area (OBW_1), central part of SRWSA existing production well sites (OBW_2), and newly planned production well sites (OBW_8 to OBW_10) as shown in Figure 5.9.

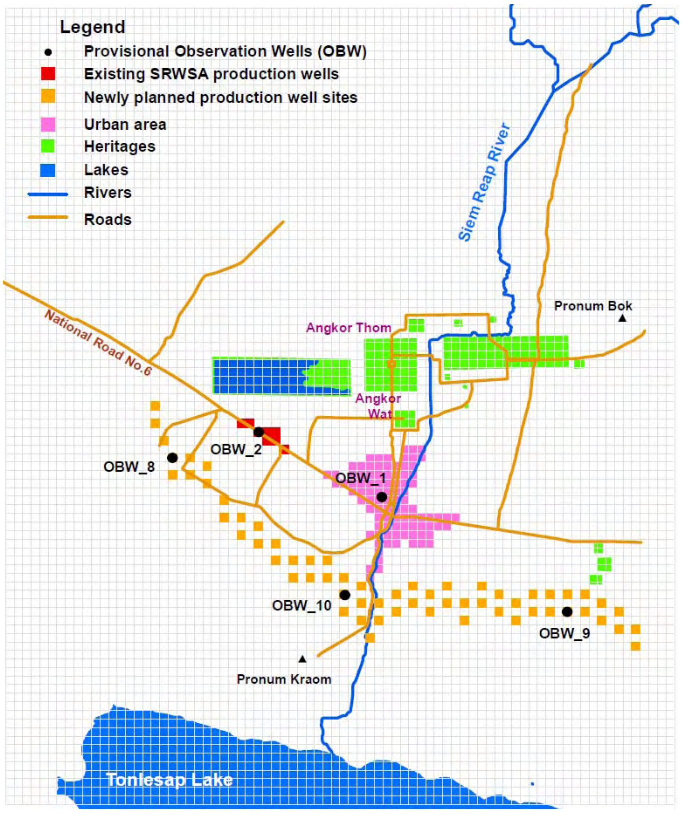


Figure 5.9 Location of Provisional Observation Wells (5 Shallow Wells) and Well Cells

The result of monthly groundwater level fluctuation by the transient flow calculation for the 3 simulation years (2006 to 2008) is shown in Figure 5.10.

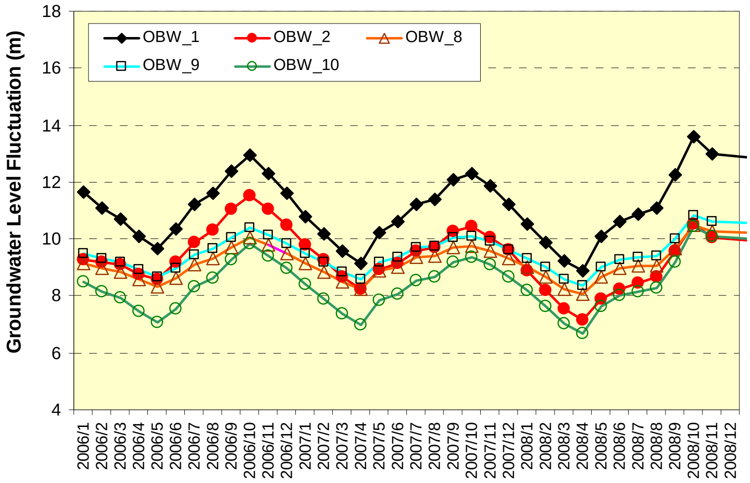


Figure 5.10 Groundwater Level Fluctuation in the Specified Observation Wells (5 Shallow Wells) in the Last 3 Years (2006-2008)

The following facts can be found from the result of the transient flow simulation.

The pattern of the seasonal fluctuation of groundwater level coincides with the result in groundwater monitoring results.

The effect of recharge and consumption of groundwater was correctly calculated. The groundwater level decreased slightly in 2006 because of relatively few recharges during the year. For the rainier years of 2007 and 2008 the groundwater level changed to the tendency of recovering.

5-6 Model Specification for Groundwater Prediction

5-6-1 Purpose and Basic Consideration of Groundwater Simulation

The purpose of this study aims to formulate a plan for ensuring domestic water supply up to the year 2030. Therefore, the simulation span for groundwater level prediction is set as 22 years from 2009 to 2030.

The evaluation of the effect of groundwater development should not be simply conducted by averaging the relative factors. Under natural conditions, groundwater level fluctuated following the seasons. The precipitation in Siem Reap area changes year by year. In case an extreme dry year appears in the year with the highest water demand, the highest groundwater level drawdown will happen, and then the biggest effect to the heritage sites would be caused.

5-6-2 Station Selection for Precipitation Probability Calculation

Of 5 meteorological observation stations which rainfall data were collected, the Siem Reap City observation station is located near the center of Siem Reap area and its rainfall data are taken into account to be representative values in the survey area. Thus, the station's observation data were used for precipitation probability calculation. The data were collected from the City

Station and database of WMO (World Meteorological Organization, observation station number: 48966000). In the periods of 10 years of (1951 – 1960) and 9 years of (1962 – 1970) and 29 years of (1982 – 2010) which correspond to the period of a total of 48 years, precipitation observation data were used for the analysis.

5-6-3 Methods and Results of Probability Analysis

4 kinds of methods were used for probability analysis.

- Normal distribution method
- Log-normal distribution method
- Log-Pearson Type III distribution method (the standard method of national agencies for hydrological analysis in the US)
- Plotting Position method

Figure 5.11 shows the probability curve obtained by Log-Pearson Type III analytical method combined with plots obtained from Plotting Position method (Hazen).

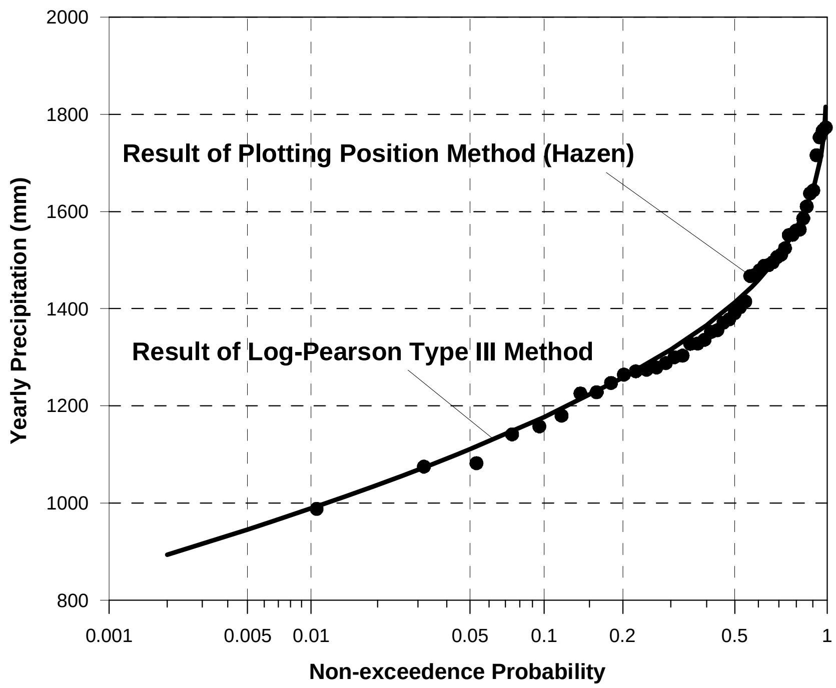


Figure 5.11 Probability Curve of Precipitation in Siem Reap City Meteorological Station

5-6-4 Specification of External Factors

External factors for Siem Reap groundwater simulation model include precipitation, evaporation amount, and water level fluctuation in rivers and lakes (constant head boundary).

5-6-4-1 Specification of Precipitation, Evaporation, Groundwater Recharge and Consumption

The specifications of precipitation, evaporation, groundwater recharge, and consumption by evaporation was summarized in Figure 5.12.

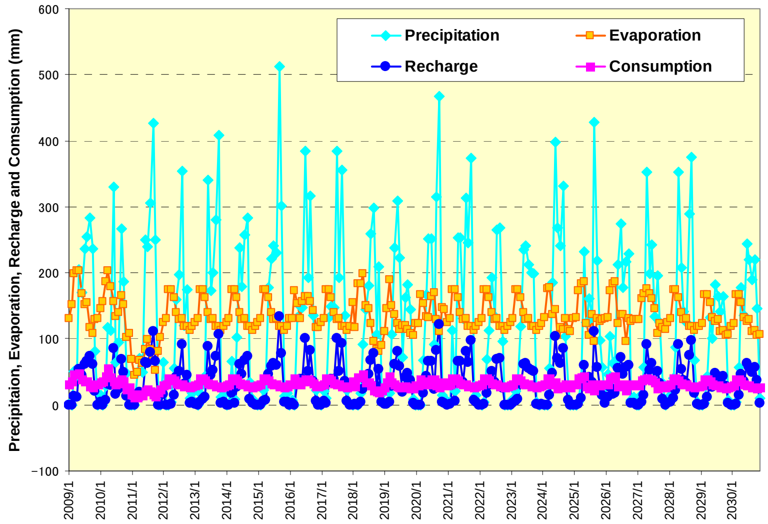


Figure 5.12 Specification of Groundwater Recharge and Consumption for the Simulation Span 2009 -2030 Based on the Observation Data from 1989 to 2008 and Probability Analysis Result with a Return Year of 50

5-6-4-2 Specification of Water Head for Constant Head Boundary

The specification of monthly river level fluctuation for the 22 simulation years is shown is based on the hydrologic observation result and shown in Figure 5.13.

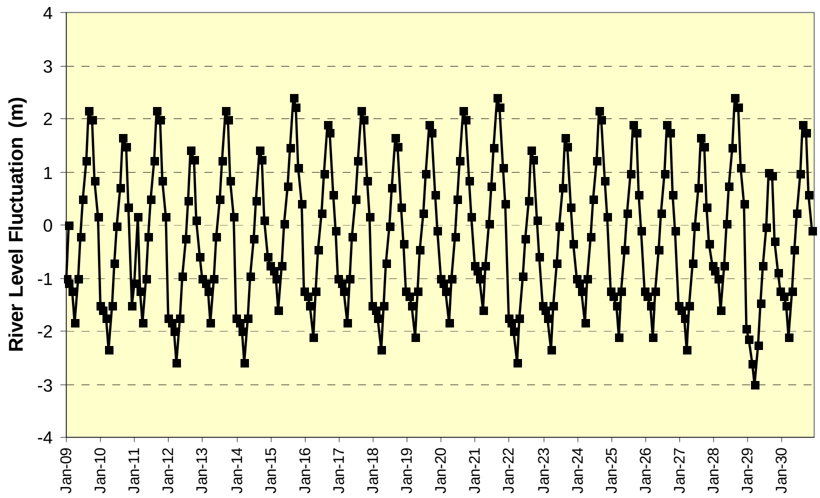


Figure 5.13 Specification of River Level Fluctuation

The specification of Tonle Sap Lake water level is based on Tonle Sap water level observation result and shown in Figure 5.14.

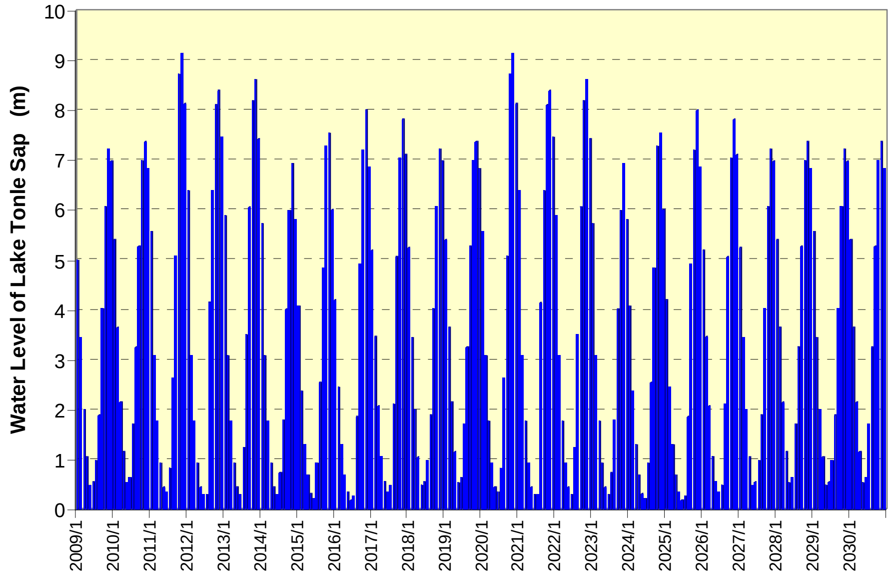


Figure 5.14 Specification of Tonle Sap Lake Water Level Fluctuation

5-6-5 Specification of Internal Factors- Scenario Specification

Scenario 1: Comparison Object Case

Two kinds of groundwater level drawdown data are needed for examination, the drawdown under natural conditions and the drawdown whereby groundwater has been developed. Therefore, scenario1 is set to include all the external factor specifications given above, but without groundwater use. (Natural condition without any groundwater use)

Scenario 2: Continue Groundwater Use at the Present Amount

At present, groundwater is the main source for water supply in Siem Reap. Scenario 2 is set to keep the present groundwater use (Average 22,176 m^3/day) until the target year of 2030.

{Total withdrawal volume = average 22,176 m^3/day: (SRWSA wells' extraction volume = 9,000 m^3/day) + (private wells' extraction volume)}

Scenario 3: Use Groundwater as the Only Source for Water Supply

Water demand has been estimated increasing year by year, to be 86,300 m^3/day by 2030. Continuing to use groundwater as the only source for water supply is one of the options in water supply expansion plans. Therefore, a scenario is set by using only groundwater to meet the water demand by 2030 and the new water supply facility is supposed to be complete in 2016.

{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)}

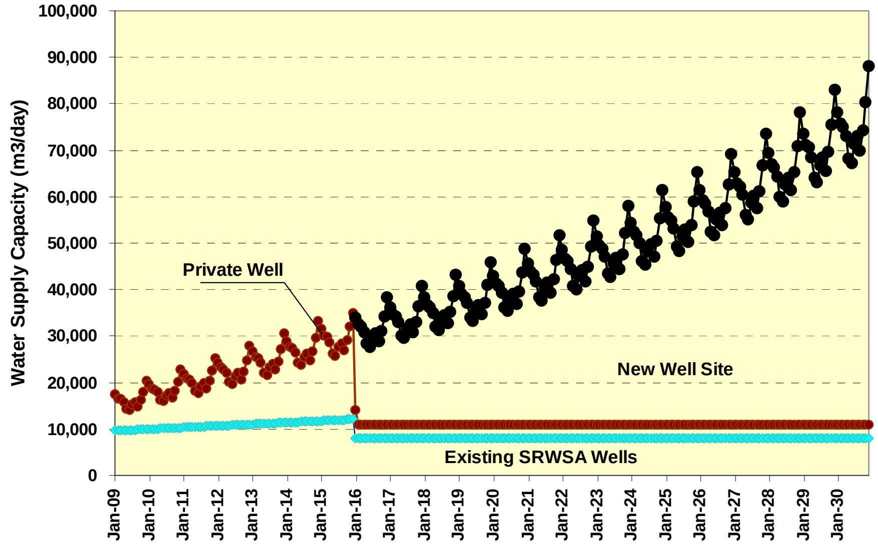


Figure 5.15 Establishment Plan (Scenario 3) of New Water Supply Facility which is supplied by Groundwater Source (New facility is planned to complete in 2016.)
(After completion of new water supply facility in 2016, most of private wells connect to new facility supplied by new production wells.)

As shown in Figure 5.16, 64 new production wells for scenario 3 are designed to be a little higher than 10 m contour line (pink color line in the figure).

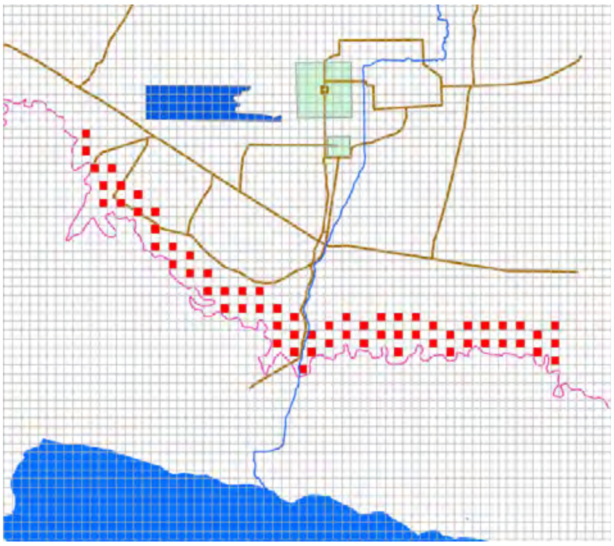


Figure 5.16 Location of New Production Wells for Scenario 3

In scenario 3, production of groundwater can be divided into 3 sectors; existing SRWSA production wells, private wells in urban area and new production.

Scenario 4 and 5: Water Supply Development Plan

For water supply expansion, a project of KTC has been taken into consideration. The main content of the KTC project is to increase water supply capacity by amount of 17,000 m^3/day, using surface water from West Baray irrigation channel. Taking this project into consideration, a water supply development plan has been created as shown in Figure 5.17.

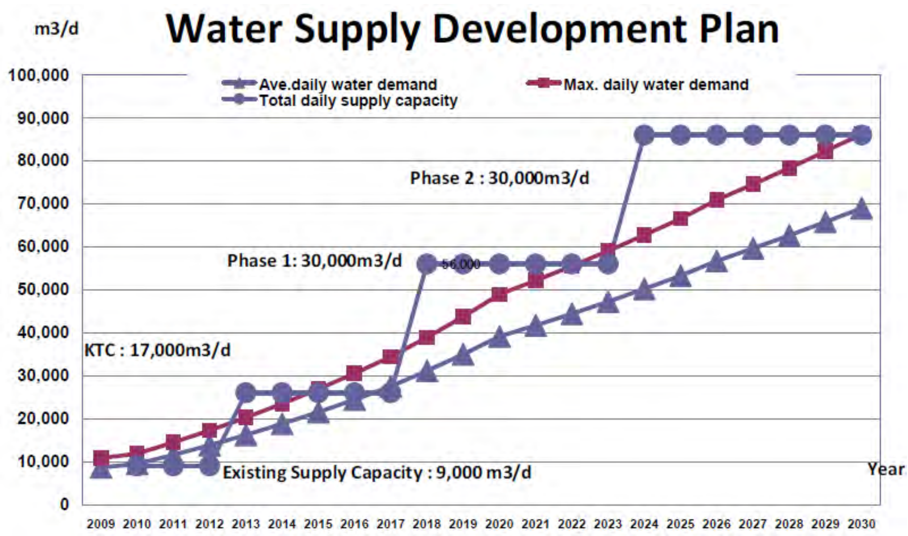


Figure 5.17 Water Supply Development Plan

In the water supply development plan shown in Figure 5.17, average daily water demand and maximum daily water demand are projected. According to each predicted value, groundwater extraction volumes were estimated.

Scenario 4 corresponds to average daily water demand and Scenario 5 relates to maximum daily water demand.

In scenario 3, total water supply amount can be divided into 3 water sectors (SRWSA water sources, private wells, and new production wells), but in scenario 4 and 5 water supply capacity has to be divided into 4 water sectors including KTC project.

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)}

According to the division of capacity increasing in water supply development plan, 30 new wells are considered for each phase, and the designed production capacity for each well is 1,000 m^3/day. The location of new wells for each phase and the location of provisional observation wells for simulation result extraction are shown in Figure 5.18.

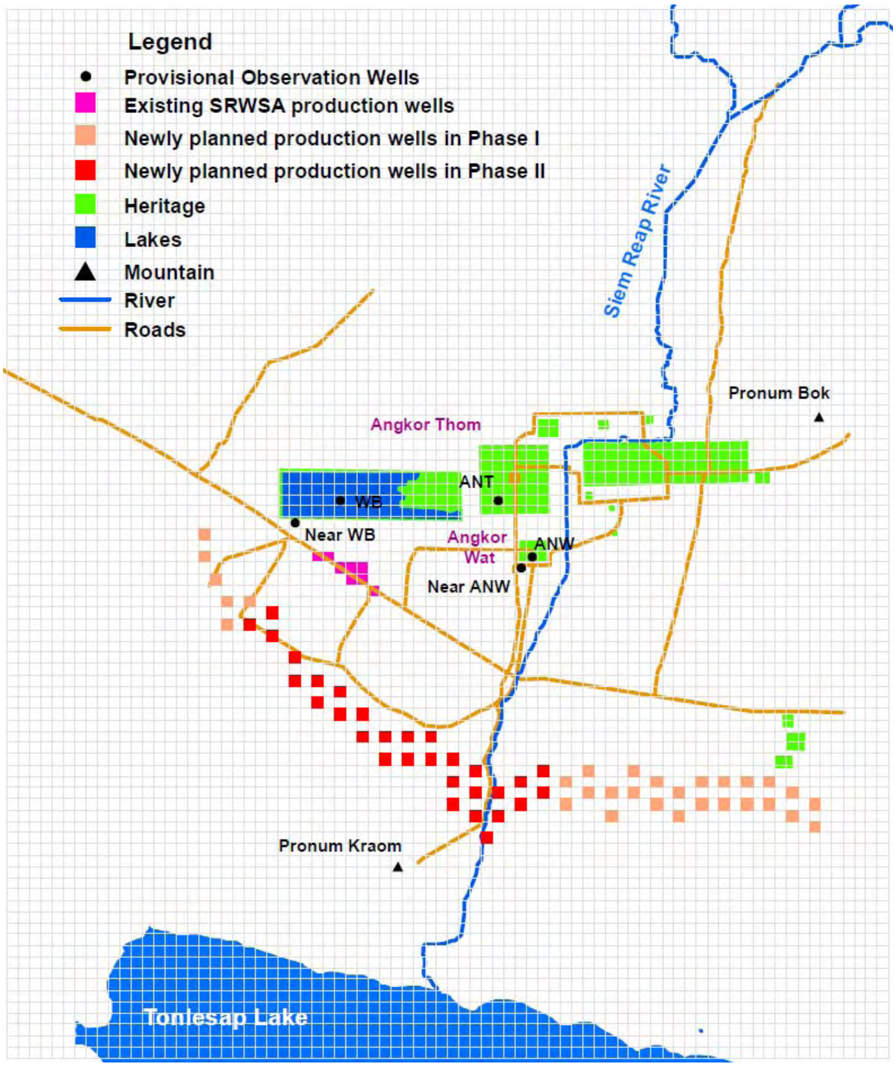


Figure 5.18 Specified New Production Wells and Provisional Observation Wells (5 Deep Wells) for Examination of Effect to the Heritage Sites in Each Simulation Scenario

Location of provisional observation wells

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

Scenario 6: Don't Build New Wells on the East Side of Siem Reap River

Scenario6 was created by the plan with no new wells constructed near the heritage group of Bakong to examine the effect of groundwater drawdown in case of stopping further groundwater development after Phase I.

{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: Using Surface Water as Water Supply Source to Reduce Groundwater Withdrawal

The plan in consideration is to complete new facilities for surface water use by 2016. After the new facilities are complete, all groundwater utilization in the urban area will be prohibited, except SRWSA existing wells. (Total withdrawal volume = SRWSA wells' extraction volume = 9,000 m3/day)

5-6-6 Specification of Provisional Observation Wells

In process of model calibration, 5 provisional observation wells (shallow wells, calculation points) are specified in shallow aquifer for simulation result summarizing and extraction as shown in Figure 5.9. For summarizing and extracting simulation results in deep aquifer in and near the heritage sites, these 5 provisional observation wells (deep wells, calculation points) are specified under and near the heritage sites of Angkor Wat, Angkor Thom and West Baray as shown in Figure 5.18. (Thus, a total of 10 provisional wells were specified: shallow wells, no.1, no.2, no.8, no.9, no.10; deep wells, ANW: under Angkor Wat, Near ANT: near Angkor Wat, ANT: under Angkor Thom, WB: under West Baray, Near WB: near West Baray)

5-7 Simulation Results

5-7-1 Water Level Fluctuation in Provisional Observation Wells

As a total 10 provisional observation wells have been specified in the model. Groundwater level fluctuations in the 10 provisional observation wells are summarized in the following 10 figures.

Provisional Observation Well No.1 (Central Part of Siem Reap; shallow aquifer)

The largest groundwater level drawdown is about 2 m in scenario 3, which has the biggest groundwater withdrawal amount.

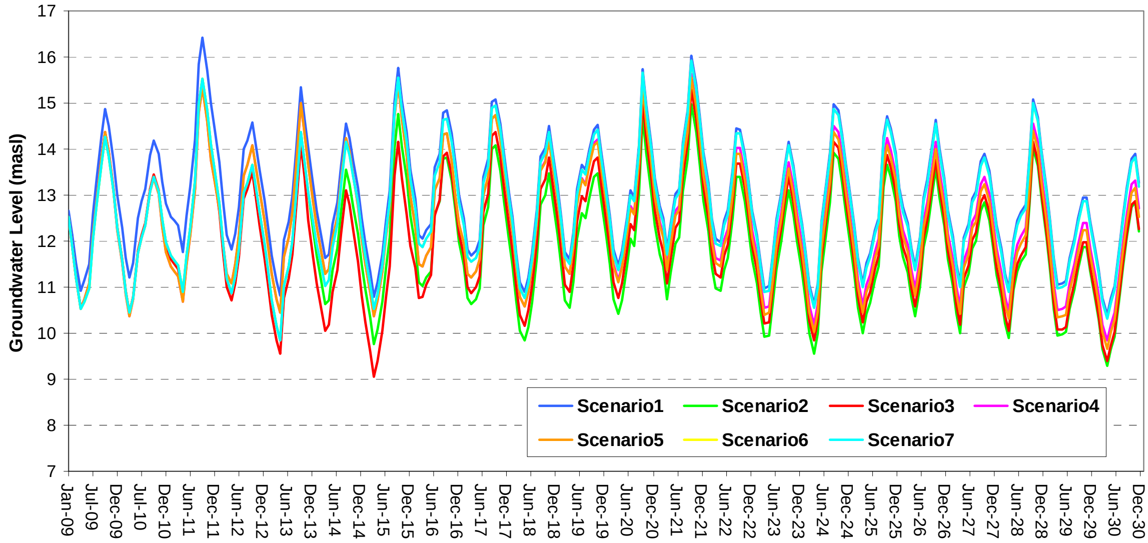


Figure 5.19 Water Level Fluctuation of Provisional Observation Well No.1 (Central Part of Siem Reap City, Shallow Aquifer)

Provisional Observation Well No.2 (Central Part of existing SRWSA production wells; shallow aquifer)

The largest groundwater level drawdown is about 4 m from scenario 3 as shown in the figure below.

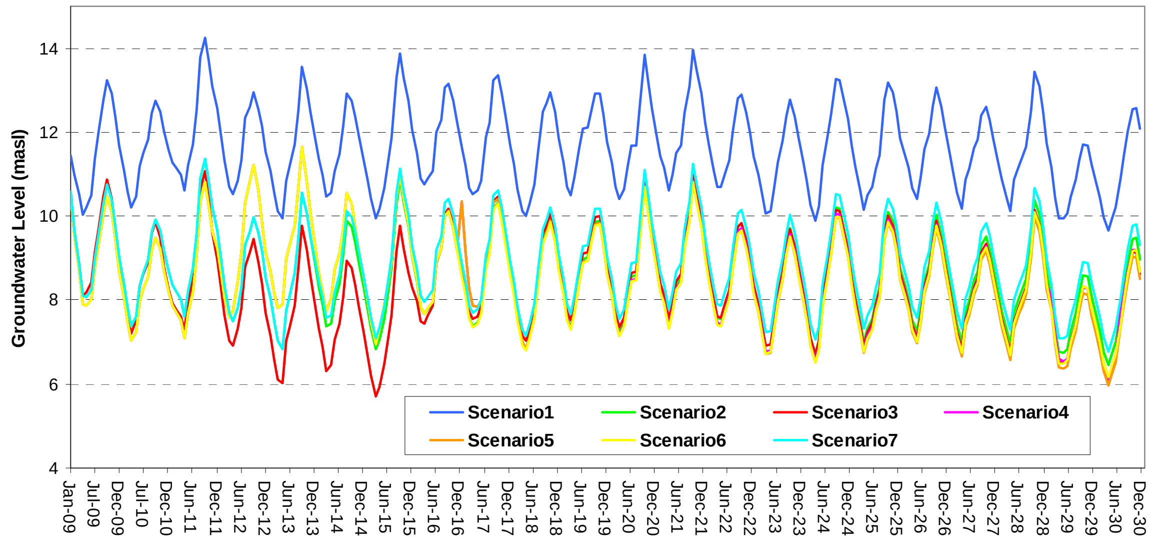


Figure 5.20 Water Level Fluctuation of Provisional Observation Well No.2 (Central Part of Existing SRWSA Wells, Shallow Aquifer)

Provisional Observation Well No.3 (Near Angkor Wat; deep aquifer)

The nearest groundwater withdrawal site to the provisional observation well is the urban area of Siem Reap. The greatest groundwater production amount from urban area private wells is set in scenario 3 in 2015, and then a downward tendency can be found in the provisional observation well in a seasonal fluctuation.

In scenario 3, the new water supply facilities is specified to be completed in 2016, and then most of groundwater withdrawal in urban area private wells will be largely reduced by shifting to new wells for new water supply system, which are designed near Tonle Sap Lake, further from the provisional observation well than the private wells in the urban area. This reducing of groundwater withdrawal in urban area results in groundwater level recovery until 2026.

However, following an increase of groundwater withdrawal amount in new wells for new water supply system, the affected area from new well site will expand and eventually reach the site of the provisional well. The effect of groundwater withdrawal from new wells to the water level in the observation well can be found in 2027, as shown in Figure 5.21. A new drawdown tendency is shown in the figure from 2027 to 2030. The lowest groundwater level appears from scenario 2 and scenario 3 in May of 2030. This is the last month of dry season of 2029; which is specified as a dry year with a probability of 50 return years. Compared with the water level under natural conditions, the water level in scenario 2 and 3 will go down to a similar value as about 0.7 m.

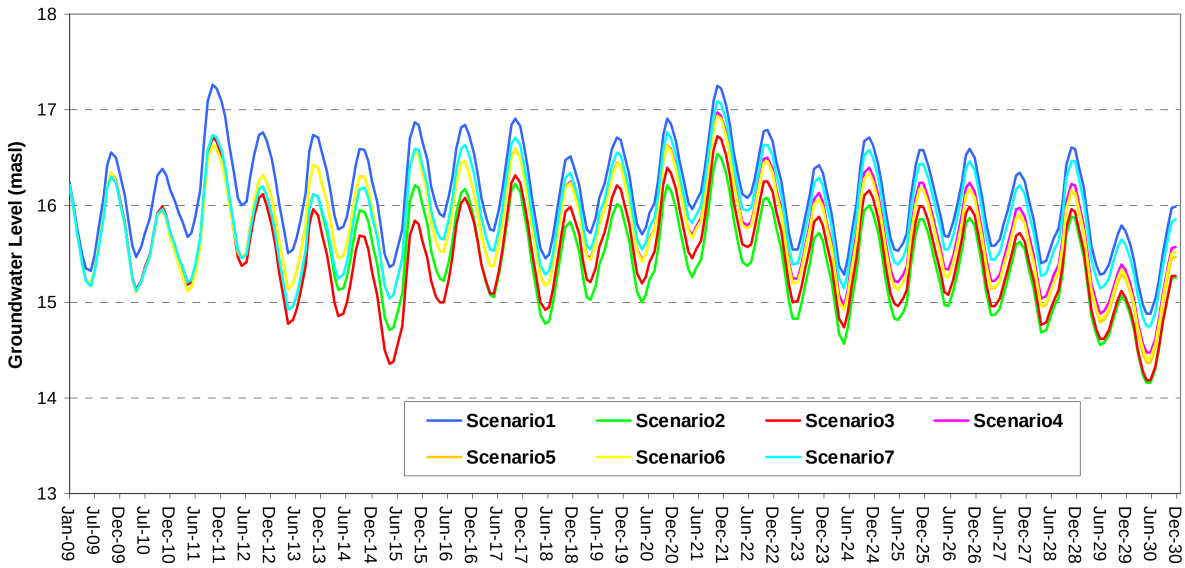


Figure 5.21 Water Level Fluctuation of Provisional Observation Well No.3 (Near Angkor Wat, Deep Aquifer)

Provisional Observation Well No.4 (Near West Baray; deep aquifer)

The maximum groundwater level drawdown appears in May of 2030, from scenario 3, which is specified to use groundwater only for all water supply in Siem Reap. Compared with the natural condition, the water level drawdown in scenario 3 is as much as more than 3 m. For scenario 4 and 5 the maximum groundwater level drawdown appears in the same period as scenario3, but the degree of drawdown is about 2.3 m and 2.8 m, because difference of production amount specification according the water supply development plan.

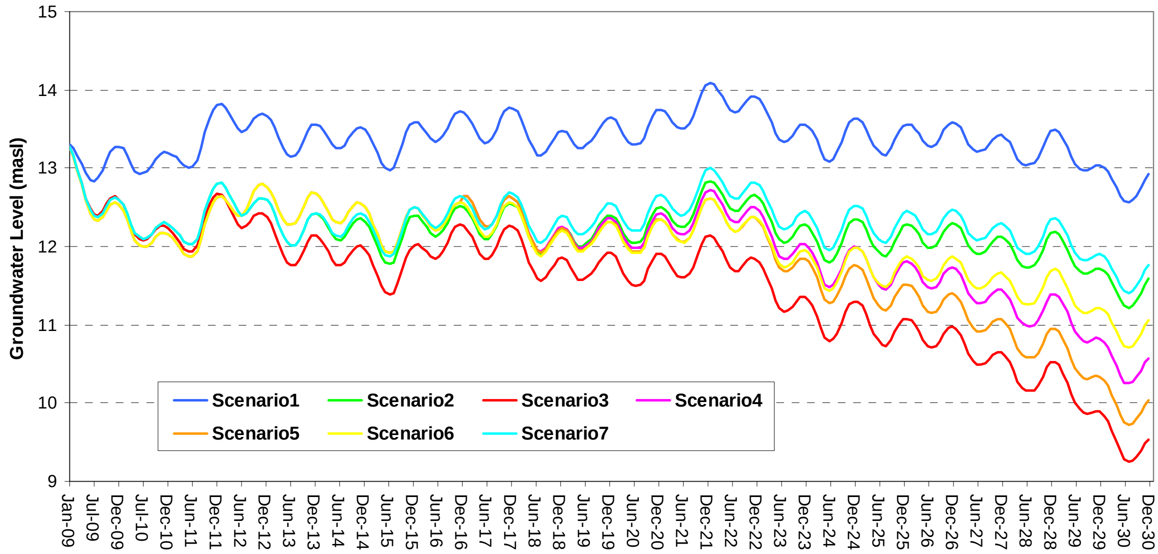


Figure 5.22 Water Level Fluctuation of Provisional Observation Well No.4 (Near West Baray; Deep Aquifer)

Provisional Observation Well No.5 (Under West Baray; deep aquifer)

The maximum groundwater level drawdown is different. In provisional observation well no.4, the maximum groundwater level drawdown is as much as more than 3 m, and in no.5 the maximum drawdown is near 2 m.

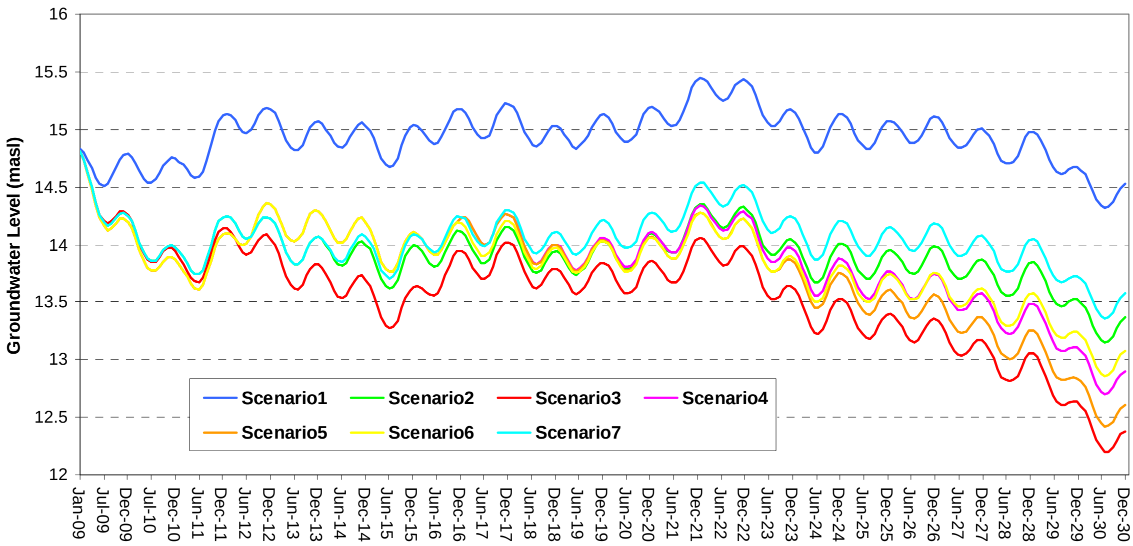


Figure 5.23 Water Level Fluctuation of Provisional Observation Well No.5 (Under West Baray, Deep Aquifer)

Provisional Observation Well No.6 (Under Angkor Thom heritage site; deep aquifer)

Compared with the natural condition, the water level drawdown for different scenarios changes from 0.2 m to 0.7 m, according to different groundwater withdrawal amount specifications.

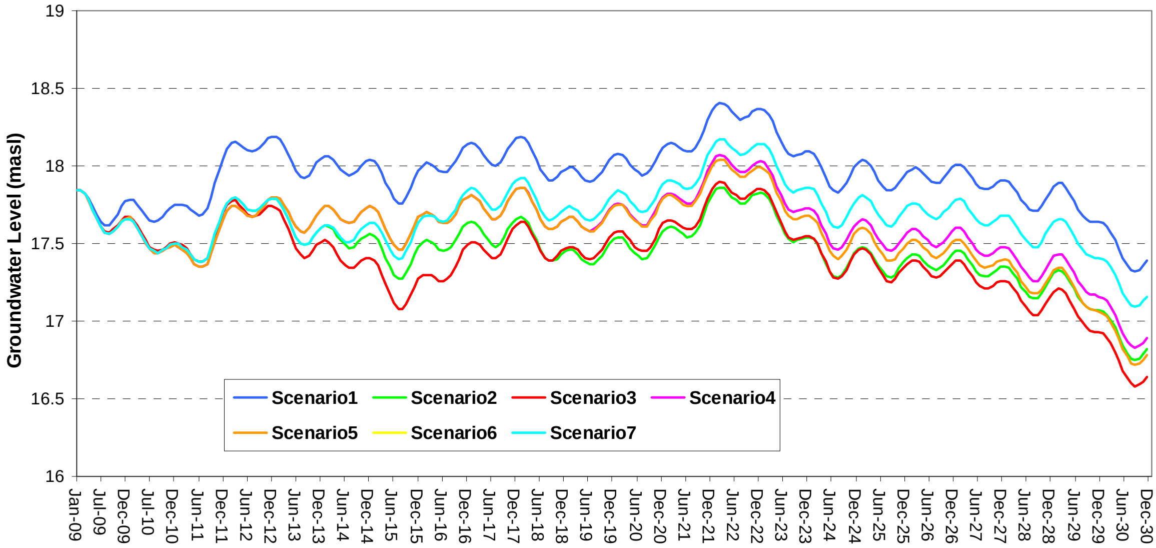


Figure 5.24 Water Level Fluctuation of Provisional Observation Well No.6 (Under Angkor Thom; Deep Aquifer)

Provisional Observation Well No.7 (Under Angkor Wat heritage site; deep aquifer)

Compared with the natural condition, the water level drawdown for different scenarios changes from 0.1 m to 0.7 m.

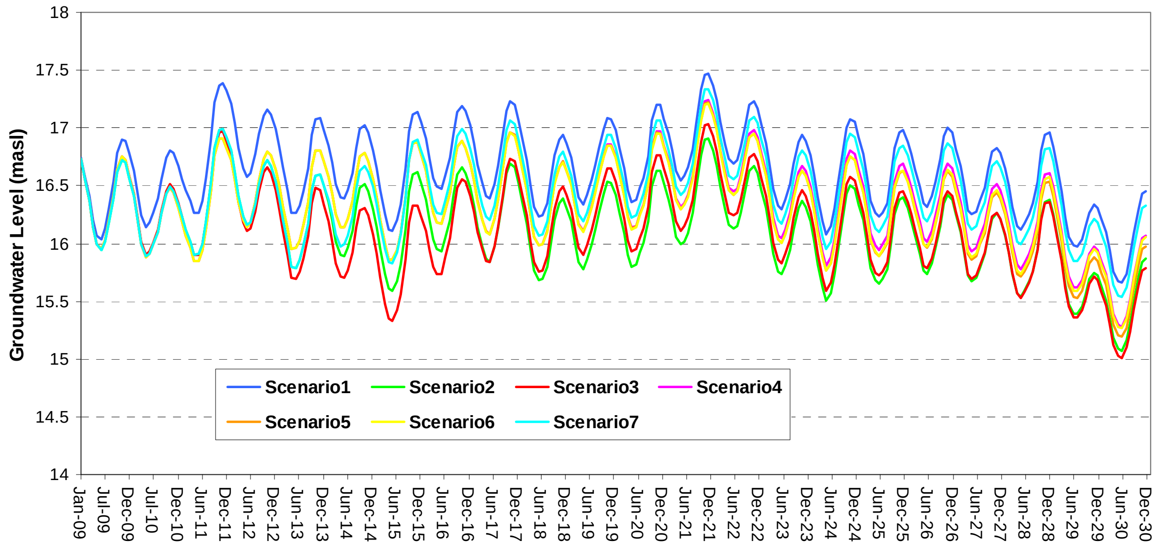


Figure 5.25 Water Level Fluctuation of Provisional Observation Well No.7 (Under Angkor Wat, Deep Aquifer)

Provisional Observation Well No.8 (Southwest of West Baray; central part of new well site; shallow aquifer)

Compared with the natural condition the maximum groundwater level drawdown changes from 4.5 m to 6.5 m according to specification of groundwater production amounts in each scenario.

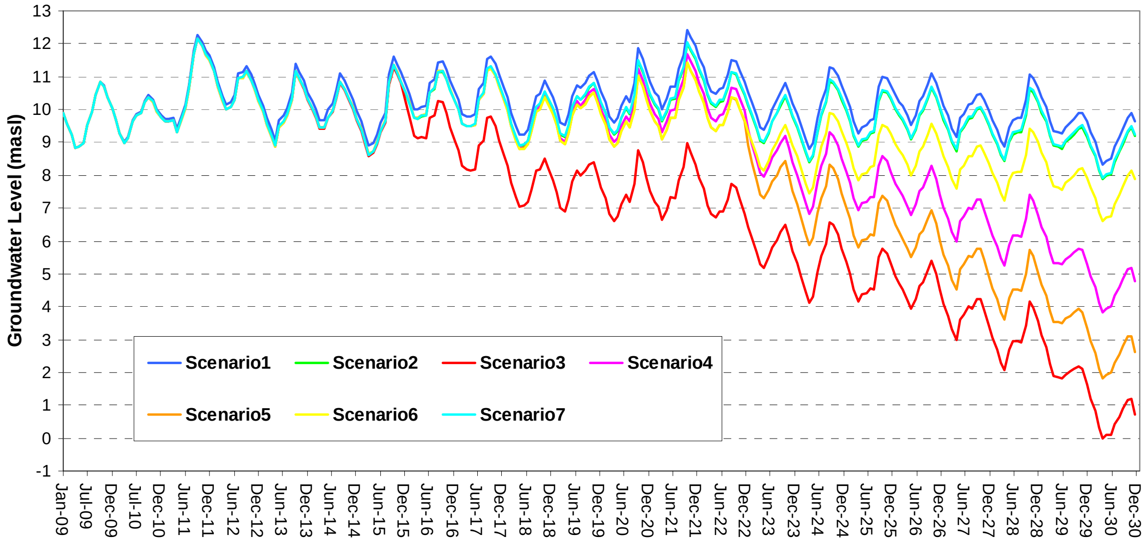


Figure 5.26 Water Level Fluctuation of Provisional Observation Well No.8 (Southwest of West Baray, Shallow Aquifer)

Provisional Observation Well No.9 (Southeast of Siem Reap; new well site; shallow aquifer)

Figure 5.27 shows no effect from SRWSA existing production wells and private wells in urban area of Siem Reap on this well. Groundwater level drawdown is caused mainly by withdrawal from new wells that are specified in scenario 3 to 5.

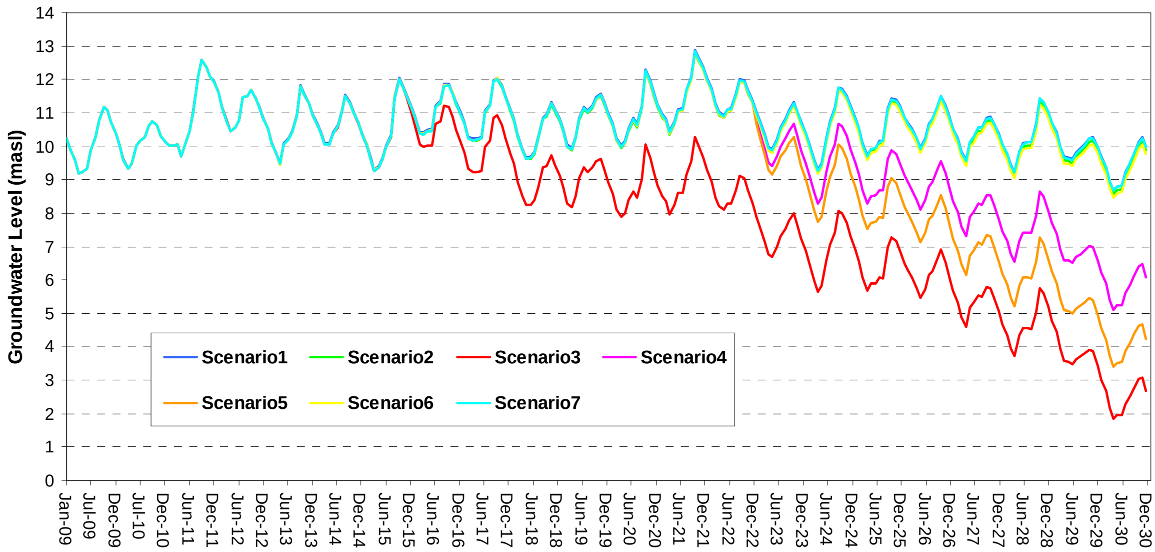


Figure 5.27 Water Level Fluctuation of Provisional Observation Well No.9 (Southeast of Siem Reap City; Shallow Aquifer)

Provisional Observation Well No.10 (South of Siem Reap; central part in new well site; shallow aquifer)

The maximum groundwater level drawdown changes from about 2.6 m to 4.4 m according to specifications of groundwater production amount in each scenario.

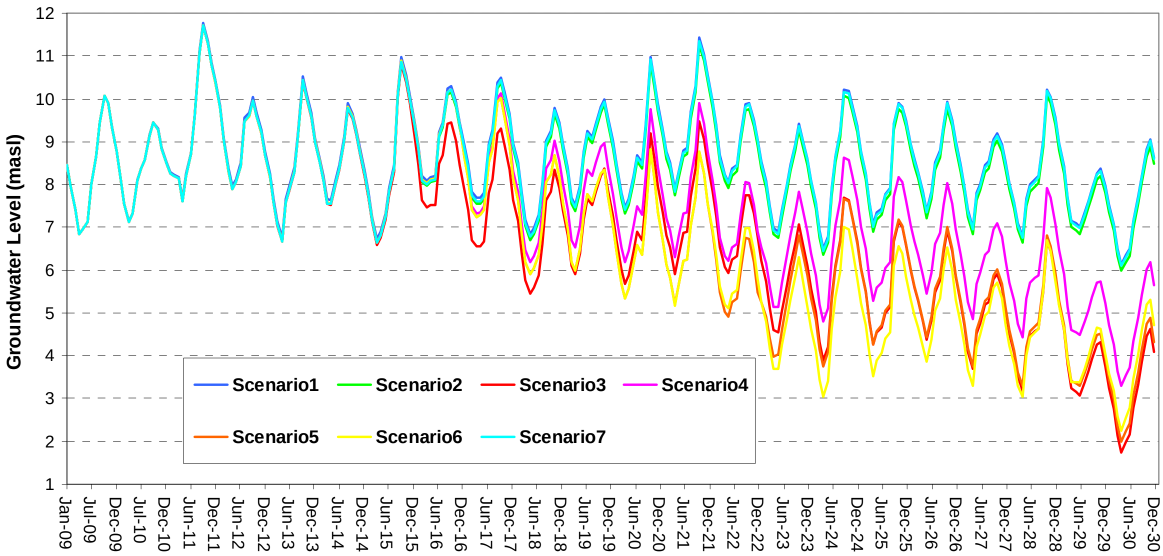


Figure 5.28 Water Level Fluctuation of Provisional Observation Well No.10 (Southern Part of Siem Reap City, Shallow Aquifer)

For evaluation of groundwater development plan in Siem Reap, the effect on heritage sites by groundwater level drawdown should be taken as the most important issue. Therefore, 5 provisional observation wells (deep wells) have been specified under and near the most famous heritage sites of Angkor Wat, Angkor Thom and West Baray. The maximum and minimum water levels in each observation well site in the 22 year simulation span from 2009 to 2030 (264 periods) is summarized and shown in Table 5.1.

As shown in Figure 5.21 to Figure 5.255.25, the maximum groundwater level drawdown in the 5 provisional observation wells (deep wells) occurs in May 2030, the last month of dry year with a probability of 50 return years. The maximum groundwater level drawdown in natural condition also occurs in this month and this degree of groundwater level drawdown in natural condition can be considered as within safety limitation for heritage protection. Hence, what should be examined is the difference of water level between scenario 1 (under natural condition) and each scenario, the natural condition scenario. Therefore, these differences have been calculated and summarized into the same table.

Table 5.1 Summary of Water Level Fluctuation for the 5 Provisional Observation Wells Specified Under or Near Heritage Sites

(Unit: m)

	Scenario	Near_ANW*	ANW*	ANT*	Near WB*	WB*
Maximum Water Level	Scenario 1	17.26	17.47	18.41	14.09	15.45
	Scenario 2	16.74	16.99	17.86	13.27	14.81
	Scenario 3	16.73	17.03	17.9	13.27	14.81
	Scenario 4	16.97	17.24	18.07	13.27	14.81

	Scenario	Near_ANW*	ANW*	ANT*	Near WB*	WB*
	Scenario 5	16.94	17.22	18.04	13.27	14.81
	Scenario 6	16.94	17.22	18.04	13.27	14.81
	Scenario 7	17.1	17.34	18.17	13.27	14.81
Minimum Water Level	Scenario 1	14.88	15.66	17.32	12.56	14.32
	Scenario 2	14.15	15.07	16.75	11.22	13.15
	Scenario 3	14.18	15.01	16.58	9.25	12.2
	Scenario 4	14.47	15.28	16.83	10.25	12.7
	Scenario 5	14.37	15.19	16.72	9.73	12.42
	Scenario 6	14.43	15.28	16.83	10.85	12.98
	Scenario 7	14.75	15.54	17.09	11.4	13.36
Difference	Min1-Min2	0.73	0.59	0.57	1.34	1.17
	Min1-Min3	0.7	0.65	0.74	3.31	2.12
	Min1-Min4	0.41	0.38	0.49	2.31	1.62
	Min1-Min5	0.51	0.47	0.6	2.83	1.9
	Min1-Min6	0.45	0.38	0.49	1.71	1.34
	Min1-Min7	0.13	0.12	0.23	1.16	0.96

(Note): (Column heading*) is the code of each provisional observation well and the locations of each provisional observation well are shown in Figure 5.18.

Each location which is indicated by each well number is as follows:

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

Difference = (Minimum Water Level of Scenario 1) – (Minimum Water Level of Scenario X),
Scenario 1: calculated water level under natural condition

There is the heritage group of Bakong in the eastern part of Siem Reap, to south of National Road Number 6. The data in the cell corresponding to the location of Prasat Bakong were extracted for groundwater drawdown calculation. The groundwater level drawdown of each scenario is calculated by comparing with the groundwater level in scenario1, and the calculation result is summarized in Table 5.2.

Table 5.2 Amount of Groundwater Drawdown for Each Scenario in the Groundwater Simulation Model Cell of Heritage Bakong

(Unit: m)

Scenario		S 2 *	S 3 *	S 4 *	S 5 *	S 6 *	S 7 *
Drawdown	Shallow A	0.102	3.134	1.315	1.925	0.122	0.022
	Deep A	0.106	3.597	1.661	2.452	0.136	0.016

(Note) (Column heading*) is the initial letter and the number of each scenario.
Shallow A: shallow aquifer
Deep A: deep aquifer

5-7-2 Examination of the Land Subsidence

Groundwater level drawdown can cause land subsidence. However, within and around the heritage sites artificial surface water features have been created like moats, lake and channels. These surface water features control the groundwater level in and around the heritage sites, meaning the groundwater level drawdown is kept within a safe range in dry years, and, in case of groundwater development in the shallow aquifer.

In a previous JICA study (The Study on Water Supply System for Siem Reap Region in Cambodia, 2000), soil samples were taken from different sites to conduct compression tests. The values of Volume Compressibility (Mv) from 7 groundwater monitoring well sites change not only with well's location, but also with the sample's depth (refer to the data sheet in data book. The data sheet shows the Mv in different observation wells and different depths from the same previous JICA study mentioned in the beginning of this paragraph).

The nearest monitoring well to Angkor Wat, the most important heritage site, with compression test results is WT-8. The Mv in WT-8 at a depth corresponding to the deep aquifer is 1.16E-6 m^2/kg on average.

The monitoring well WT-4 is located only several hundred meters from another important heritage of West Baray. The Mv in WT-4 at a depth corresponding to the deep aquifer is 4.1E-7 m^2/kg on average.

There is no monitoring well near the heritage group of Prasat Bakong; the nearest monitoring well is WT-5, about 7 km from the group. WT-8 is the second nearest monitoring well with almost the same distance to the group as WT-5. Another monitoring well, WT-7, is also about 7 km from the group. Therefore, the Mv in these three wells are used for analysis of potential land subsidence in the Bakong heritage site. The average value of Mv in the 3 wells corresponding to the shallow aquifer and deep aquifer are 6.22E-7 and 6.33E-7, respectively.

According to the pumping test results, the thickness of the deep aquifer changes from 8.3 m to 12 m. Based on all the necessary parameter mentioned above, potential land subsidence for each site of provisional observation well and each scenario were calculated and summarized in Table 5.3.

Table 5.3 Potential Land Subsidence Amount Prediction

(Unit: mm)

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

Location	Near_ANW*	ANW*	ANT*	Near WB*	WB*
Scenario 7	1.25	1.15	2.21	5.06	4.19

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

In the site of heritage group Prasat Bakong, the potential land subsidence has to be calculated for not only the deep aquifer, but also the shallow aquifer, because it has no water moat surrounding it. And then the potential land subsidence in this site should be the sum of the potential land subsidence in both shallow and deep aquifers. The calculation result is summarized in Table 5.4.

Table 5.4 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 Aquifer	1.59	48.73	20.45	29.93	1.9	0.34
Deep Aquifer	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) S: Scenario

5-7-3 Result of Groundwater Level Drawdown Prediction

The results of groundwater level drawdown prediction on each scenario by groundwater computer simulation are shown below.

Scenario 2

Scenario 2 is specified as keeping the present groundwater production amount until 2030. The value of maximum groundwater level drawdown is predicted as 3.69 m in shallow aquifer and 3.26 m in deep aquifer, respectively. Though the maximum groundwater level drawdown in deep aquifer is smaller than shallow aquifer, the affected extent of groundwater level drawdown in deep aquifer is vaster than shallow aquifer, because of the constant head boundary specification in shallow aquifer.

Scenario 3

The maximum drawdown is predicted as high as 8.3 m in shallow aquifer and 7.4 m in deep aquifer.

Scenario 4

The maximum groundwater level drawdown is 4.5 m in shallow aquifer and 4.0 m in deep aquifer, respectively.

Scenario 5

The maximum groundwater level drawdown is 6.5 m in shallow aquifer and 5.96 m in deep aquifer, respectively

Scenario 6

The maximum groundwater level drawdown is centered on the new well sites to be 5.84 m in shallow aquifer and 5.77 m in deep aquifer, respectively.

Scenario 7

The maximum groundwater level drawdown is 3.3 m in shallow aquifer and 2.9 m in deep aquifer, respectively.

5-7-4 Evaluation of All Considerable Plans

The simulation results reveal that groundwater level drawdown and then potential land subsidence would occur in all water supply expansion plans, even though the magnitude of land subsidence or effect on heritage sites changes according to the difference of the plans. The following table summarizes the amount groundwater production is expanded by in each plan, and the potential land subsidence amount in the main heritage sites of Angkor Wat, West Baray and Bakong. If no water supply expansion plan can be confirmed to not cause groundwater level drawdown and then the potential land subsidence, the evaluation of different plans can only be conducted by comparing the risk levels; which are summarized in Table 5.5.

Table 5.5 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.

Remark: in scenario 2 no new wells would be constructed, but the effect to the Angkor Wat heritage site is ranked as second degree. That is because in this scenario, which maintains the present situation, more than 7,000 m^3/day of groundwater is used by private wells in the town area, and the town area is much closer to the Angkor Wat heritage site than the new wells.

It is common knowledge regarding the effect of land subsidence that the most risky situation is not from the magnitude or absolute amount of land sinking, but from uneven settlement. However, it is much more difficult to predict uneven settlement than potential land subsidence, because this prediction needs a very detailed soil investigation. Not only would the cost for this kind of investigation in the area of all heritage sites be very huge, but it is also impossible to conduct the survey under the most important place directly under the base of the heritage sites. Therefore, the best way is to select the scenario with the lowest degree of effect, scenario 7, as shown in the table above.

For water supply plan scenario 7, even though the majority of water resources will be obtained from Tonle Sap Lake instead of groundwater use, the existing SRWSA production wells are planned to continue for water supply in Siem Reap. When an extremely risk situation (drought phenomenon) happens, pumping up by these wells would cause the effect on all the three heritages of Angkor Wat, West Baray and Bakong as shown in the table above, even though the effects are the smallest in all considerable plans. 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; this value exceeds the land displacement range, so needs to be evaluated earnestly. Considering the structure of the heritage West Baray, it is different from most other heritage sites in its scale and the amount of materials used to make it. Angkor Wat and most of other heritages were created mainly using stone with very small plasticity. However, the West Baray 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, as shown in groundwater level fluctuation curves (refer to Figures 5.18 to Figure 5.27). For a clay created work on a scale of several km2 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 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 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.

Chapter 6.
Conclusion and Recommendation

Chapter 6. Conclusion & 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 m3/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	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 5	
Scenario 6	To lessen the impact to Bakong ruins, new production wells are not planned in eastern bank area of the Siem Reap River.
Scenario 7	As water sources for water supply, pumping by existing wells excluding SRWSA production wells are halted. Only lake water of Tonle Sap is used.

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

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 Tone 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 builds up mechanism and structure for sharing and putting each monitoring data to practical use with APSARA and DOWRAM.