Chapter 5.
Groundwater Simulation

Chapter 5. Groundwater Simulation

Daily water demand in Siem Reap has been estimated at a maximum of 86,300 m^3/day in 2030. This amount is far more than the existing water supply capacity of SRWSA. Therefore, the existing water supply system has to be expanded. When the expansion plan is formulated, groundwater is considered as one of the options for water source. Simply considering from the groundwater recharge amount of 516,000 m^3/day, that is about six times the estimated water demand. 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 mentioned in Chapter 4, 4-5-3 Summary of Groundwater Recharge Calculation, because Siem Reap lacks a deep and highly permeable aquifer, if all the recharge amount of 516,000m^3/day were used for water supply, the groundwater level will fall to 5 m below the ground surface in the whole Siem Reap area. The actual water demand is about one sixth of the recharge amount. Therefore, the average groundwater drawdown in the whole water supply service area (refer to Figure4-2) would be smaller than 5 m. However, it is unavoidable to cause groundwater drawdown when there is groundwater withdrawal. And the magnitude of groundwater drawdown might be larger than 5 m in and around the wells.

There are a lot of heritage sites in the Siem Reap area. The land subsidence caused by groundwater level drawdown would negatively affect the heritage sites. Because there are major differences in the shape, size, height, content, structure, history and so on of the heritage sites, no unified threshold value can be decided for these heritage sites. What is expected in viewpoint of protecting the heritage sites from the effect of groundwater development is to make the groundwater level drawdown extent not reach to the sites of heritages or make the magnitude of groundwater drawdown to be as small as possible.

The groundwater level drawdown is unavoidable when groundwater is withdrawn. The extent and magnitude of groundwater level drawdown changes with the production well's location and groundwater withdrawal amount, especially in areas without a deep, highly permeable aquifer, such as is the case in the Siem Reap area. Therefore, the evaluation of the available groundwater development amount has to be based on the groundwater development plan with well location and withdrawal design.

Considering the very important issue of heritage protection, the production wells should be designed as far apart from the heritage sites as possible, because the magnitude of groundwater level drawdown will be highest in the center of the production well field, and the further away, the smaller the magnitude becomes. Therefore, the location of heritage sites is of the highest priority when determining the location of new production wells.

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.

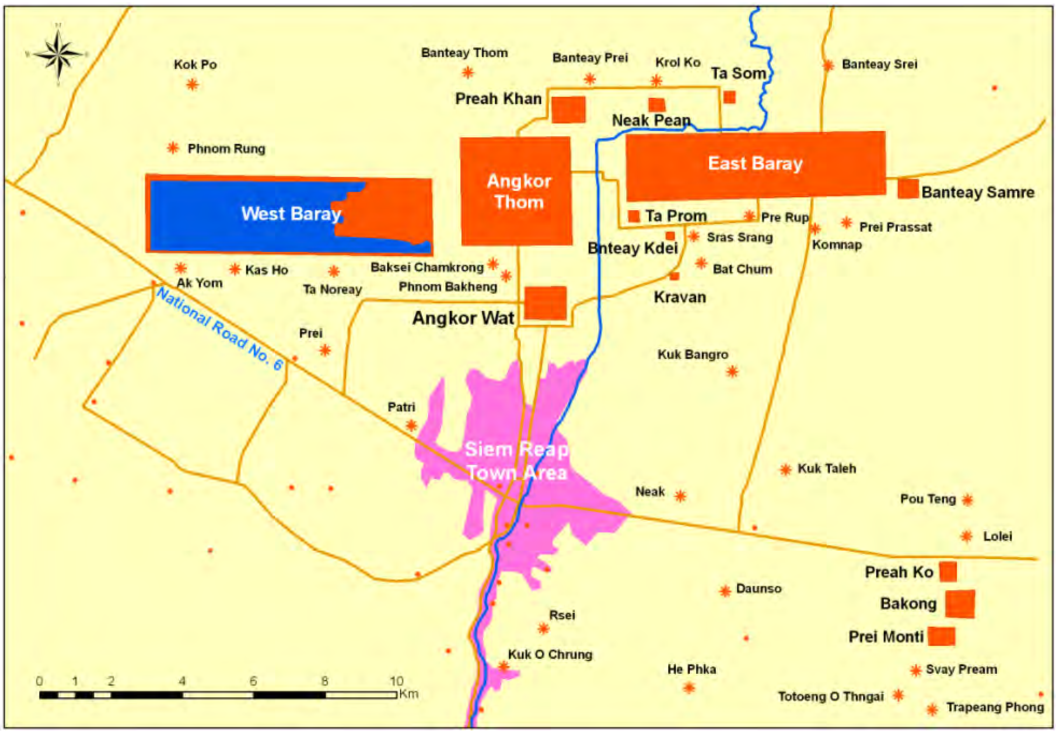

Figure 5.1 Distribution Map of Main Heritage sites in Siem Reap

The main heritage sites shown in the map with a square mark are: Angkor Wat, Angkor Thom (including Bayon, gates, Thommanom, Takeo, Chua Say Tevoda), West Baray, East Baray, Preah Khan, Neak Pean, Ta Som, Banteay Samre, Ta Prohm, and Banteay Kdei.

Other heritages shown in the map with an asterisk are: Kravan, Preah Ko, Bakong, Prei Monti, Kok Po, Banteay Thom, Banteay Prei, Krol Ko, Banteay Srei, Phnom Rung, Ak Yom, Kas Ho, Ta Noreay, Baksei Chamkrong, Phnom Bakheng, Pre Rup, Sras Srang, Bat Chum, Komnap, Prei Prassat, Prei, Kuk Bangro, Patri, Neak, Kuk Taleh, Pou Teng, Rsei, Daunso, Kuk O Chrung, He Phka, Pou Teng, Svay Pream, Totoeng O Thngai, and Trapeang Phong.

Other than the names shown on the heritage distribution map and the above list, a lot of temples are also distributed in Siem Reap and are shown with circle marks on the map.

Millions of tourists from countries all over the world come to Siem Reap every year just to see these heritage sites. And the number of tourists is increasing rapidly, revealing the high level of interest of people from around the world in the heritage sites of Siem Reap. It is no doubt that the protection of heritages has become an issue of world concern.

Surely, the protection of the heritage sites is one of the most important issues when a water supply expansion plan is formulated. When considering groundwater use as a source for water supply, hydrological analysis result has revealed as more as 6 times recharge amount than water demand. Then, the main issue for groundwater utility evaluation can be concentrated on the magnitude of groundwater drawdown to examine if the groundwater drawdown is minor enough as to have no significant effect on the heritage sites. As different groundwater development plans have been taken into consideration, all these plans have to be examined one by one.

For examination of groundwater drawdown when implementing withdrawal, the groundwater simulation can be considered as the most effective method. Therefore, a groundwater simulation model is established.

5-2 Groundwater Simulation Model Structure

The production capacity of a well depends on the aquifer structure, and bears almost no relation to the recharge amount of the aquifer under natural conditions. The structure of an aquifer includes the thickness of aquifer, permeability, extent and relation with other aquifers. In case the aquifer for production well is a confined aquifer with enough thickness, high permeability and vast extent, the withdrawal amount from a production well can be compensated for in a short time. Therefore, the production capacity of the well can be ensured, even though the production amount is far more than the groundwater recharge amount within the area near the well. This kind of situation can be found in many places such as the Kanto plain in Japan.

However, this kind of aquifer does not exist 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-field, 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 hydrogeological survey results and other relative surveys.

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

To create a groundwater simulation model, the target area should definitely be included into the model domain. The model for water supply expansion plan evaluation should cover at least the area of the whole water supply service area and its surrounding area in Siem Reap.

As shown in Figure 4.1 in Chapter 4, a vast area from Mt. Kulen to Tonle Sap Lake can be classified as relevant to the Siem Reap water supply service area from the viewpoint of hydrological analysis. However, all the results of groundwater surveys, including this survey, come up with an obvious awareness that no favorable aquifer exists in Siem Reap. Therefore, the water supply area in the Kulen mountain area can be considered to have little relation to the groundwater in Siem Reap.

On the other hand, increasing of model domain extent without the support of more available relative data would not improve the precision of the simulation. If a groundwater simulation is designed to cover too vast an area, some disadvantages may occur, such as:

1) Increasing the number of model grid to obtain more detailed survey results also makes the model computation speed slower.
2) Making the model grid size too large also reduces the calculation precision.

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. The model domain covers the whole water supply service area, main area of Siem Reap River basin, the northern part of Tonle Sap Lake, the southern part of Mt. Kulen and river basins surrounding the water supply service area.

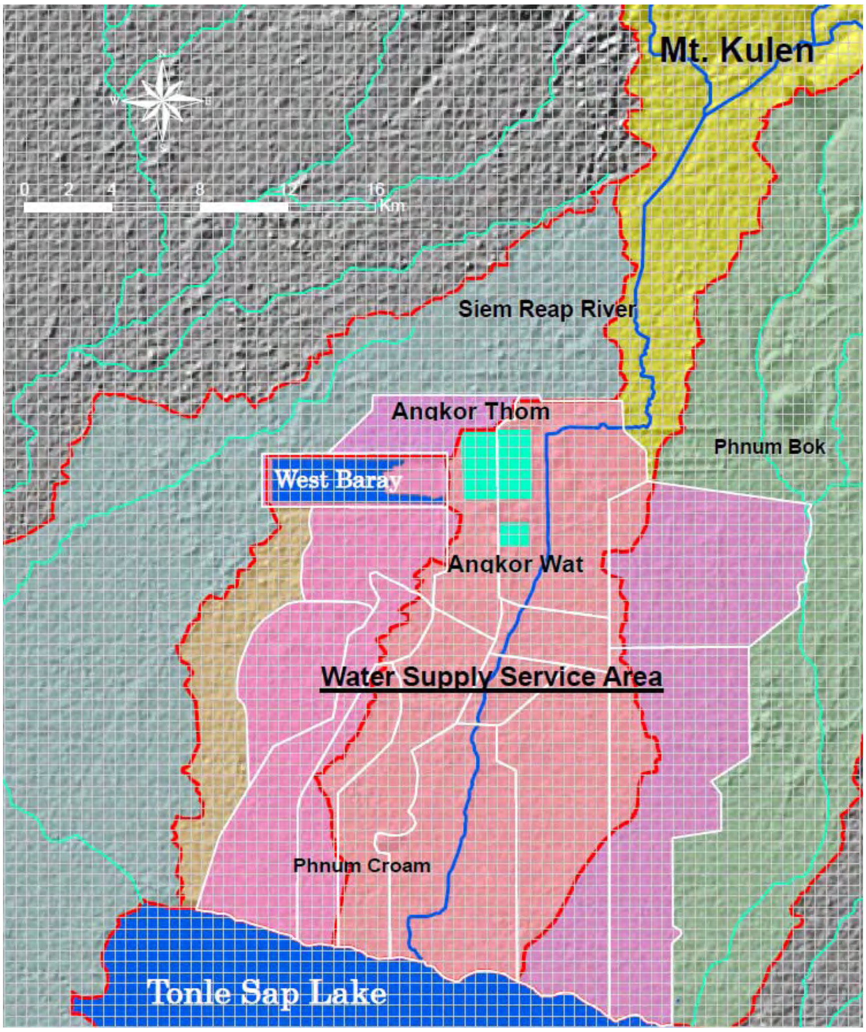

Figure 5.2 Groundwater Simulation Model Domain

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 famous groundwater simulation program, Modflow. Modflow is developed by the 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, 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, it was revealed that aquifers can be separated into two ones: shallow aquifer and deep aquifer in Siem Reap. 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 such as Siem Reap River, Tonle Sap Lake, the moat surrounding Angkor Wat, West Baray and channels in its upper and lower sides. 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.

No constant head water feature is as deep as getting to the bottom of the shallow aquifer. Hence, the model specification would largely differ from the situation in Siem Reap, if the constant head boundary is set to the bottom of the shallow aquifer. In case like this kind of boundary specification, other features would not be able to set into a cell with a constant head boundary. In Siem Reap town area and SRWSA production well sites, there exists the constant head boundary of Siem Reap River and irrigation channel of West Baray. When the Siem Reap River and the irrigation channel are set as constant head boundary, the private wells near the Siem Reap River and production wells of SRWSA near the irrigation channel will not be able to set into the same cell. If a well is set into a constant head boundary cell, the program would be confused for not knowing from which feature the water head should be calculated and then the model would not converge. To avoid this kind of confusion, ensure the model convergence, 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

As mentioned in the model layer specification, if those important surface water features were not specified into the model, a big difference would occur between the model structure and the real situation in Siem Reap. Therefore, all important surface water features are specified into the model as shown in Figure 5.3.

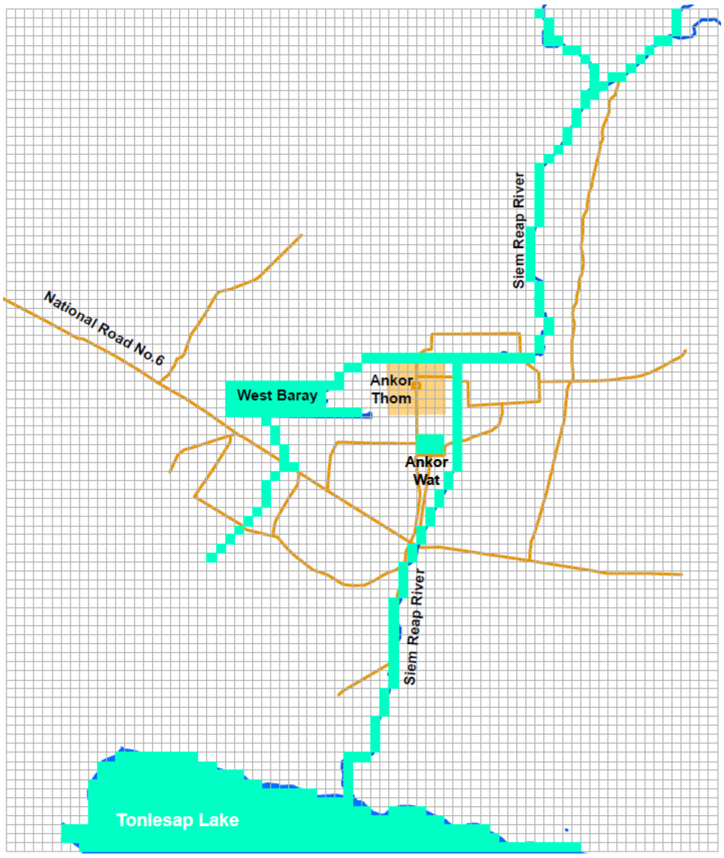

Figure 5.3 Specification of Constant Head Boundary

Constant water head boundary shown in Figure 5.3 includes:

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

5-2-3 Elevation Specification

As shown from the result of the simultaneous groundwater observation, a high coincidence can be confirmed between the water table and the topography in Siem Reap. Therefore, the elevation specification should be conducted carefully to make it fit the topography in Siem Reap.

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. The data set includes more than 140,000 control points. For 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 in the Study on Water Supply System for Siem Reap Region in Cambodia (2000) and geophysical survey results.

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

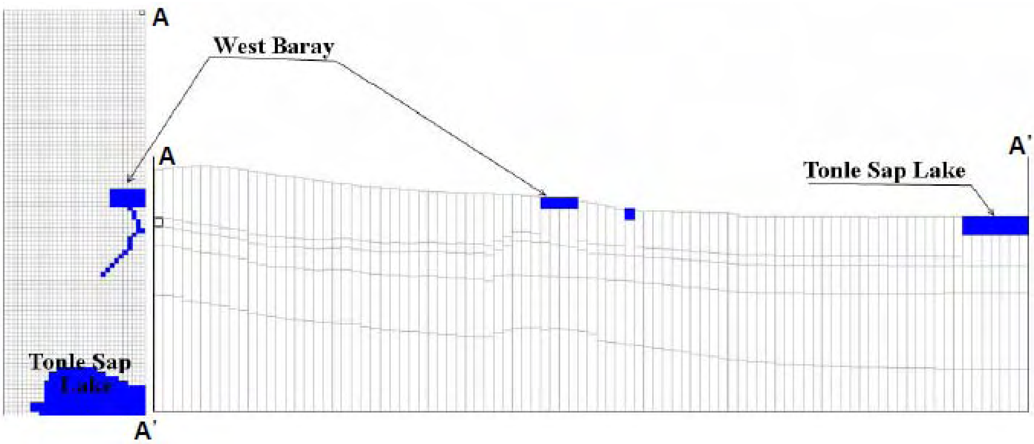

Figure 5-4 Example of Vertical Section in North – South Direction

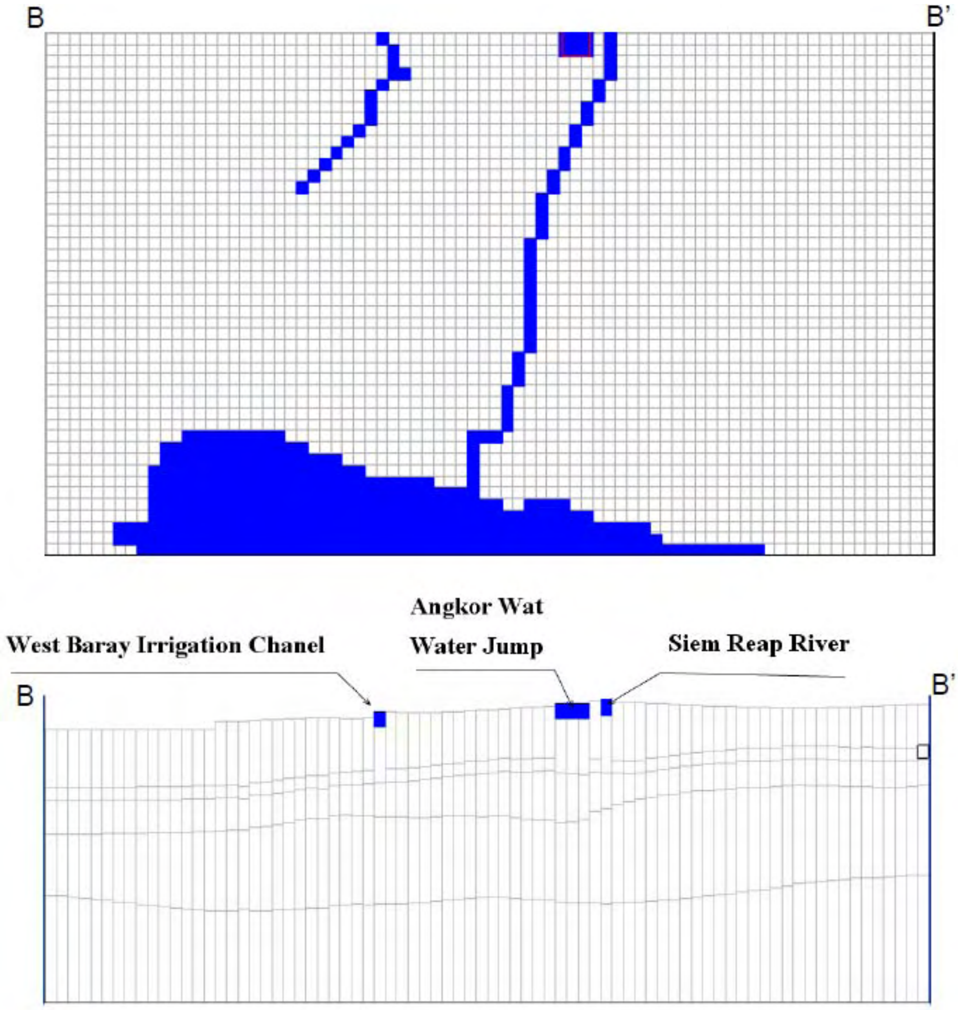

Figure 5-5 Example of Vertical Section in East – West Direction

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, 11.95m/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 0.1 m/day, 0.0077 m/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, 1.21m/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

As mentioned above, a groundwater simulation model includes many parameters specification supported by all available survey results. However, it is impossible to obtain all parameters needed for the model from previous survey results. Therefore, some parameters' specifications have to be estimated by experience, data interpolation and all available methods. If some parameters are not correctly specified into the model, the result of model simulation would be largely different from the real situation in the model area or even the model would not converge. Therefore, it is important to conduct model examination (calibration) before model application.

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.

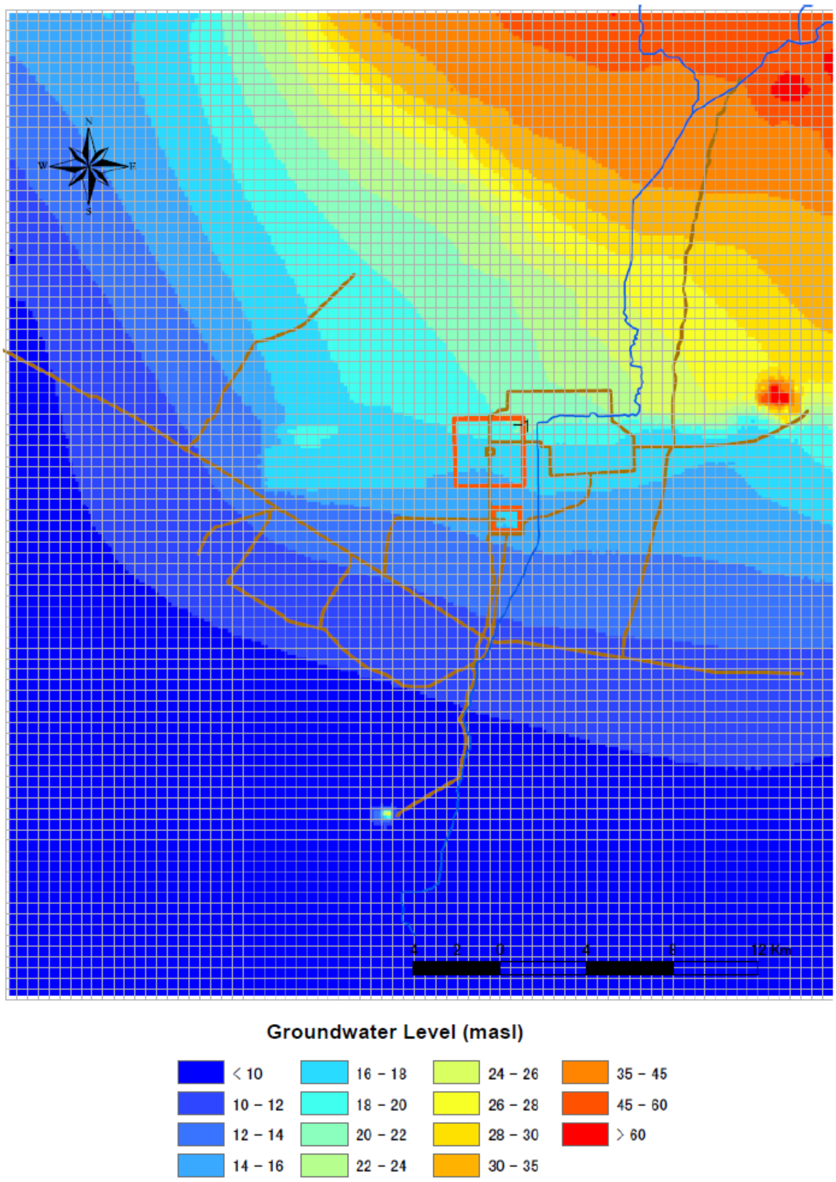

Figure 5.6 Result of Steady Flow Simulation

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

In Siem Reap, 8 production wells of SRWSA have been used for groundwater withdrawal for water supply since 2006. Comparing with other groundwater use in Siem Reap, these wells are used for relatively large groundwater production in a relatively small area. On the other hand, daily production record makes it possible to know the exact water withdrawal amount, and then ensure the precision of groundwater simulation model, because the withdrawal amount is the most important parameter for model calculation when all other parameters have been fixed.

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. And the period of model time division is set as month unit. Hence, the 3 year calculation span is divided into 36 periods, and for each period the corresponding groundwater production amount is set according to the SRWSA production record.

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.

Form the well inventory survey and simultaneous groundwater level survey; it has been made clear that several thousand wells are used in the whole Siem Reap area for domestic water supply. Most deep wells with high daily production are used for hotels or guest houses, and are located in the town area. On the other hand, in the vast countryside, the number of wells is much more than in the town area, but the wells are mainly used for one or several families' water needs, which is a much smaller amount than the town area.

When the amount of withdrawal for the groundwater simulation model was specified, only the SRWSA production wells and wells in the urban area were taken into consideration because of the following reasons:

1) It is difficult to identify the location of all wells in the countryside.
2) If all countryside wells are specified in the model, almost all cells in the model will become well cells, which would be an undesirable condition for the model.
3) For each model cell in the countryside, groundwater withdrawal amount is much smaller than the urban area, so the effect those wells can be neglected.

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.

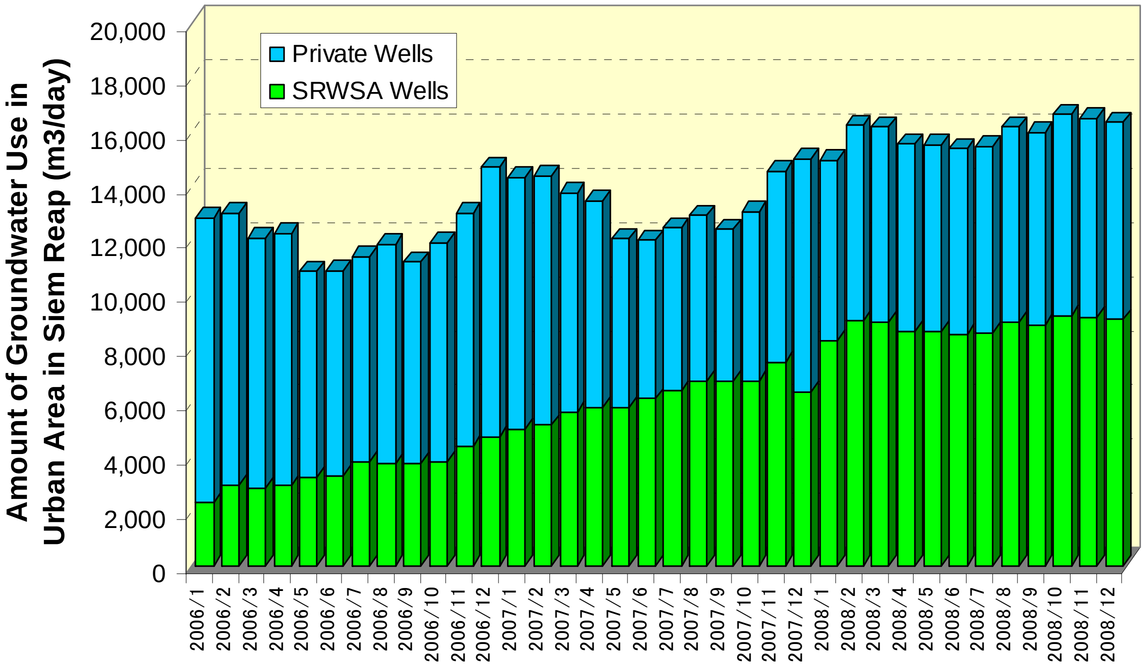

Figure 5.7 Production Amount of SRWSA Existing Wells and Private Wells in Urban Area in Siem Reap from 2006-2008

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

Monthly precipitation for the simulation span was specified following the observation result of Meteorological Station of Siem Reap City. This station is the nearest station to the urban area and SRWSA production wells, and the data of this station is being submitted and saved to the WMO (World Meteorological Organization) database, so the precision and/or reliability of the station can be considered to be the highest of the meteorological stations in Siem Reap. Monthly evaporation was also specified with the observation result in the same station. The monthly recharge and consumption of groundwater were specified on the basis of groundwater recharge analysis using a tank model as illustrated in Chapter 4. The monthly precipitation, evaporation, groundwater recharge and consumption are summarized in Figure 5.8.

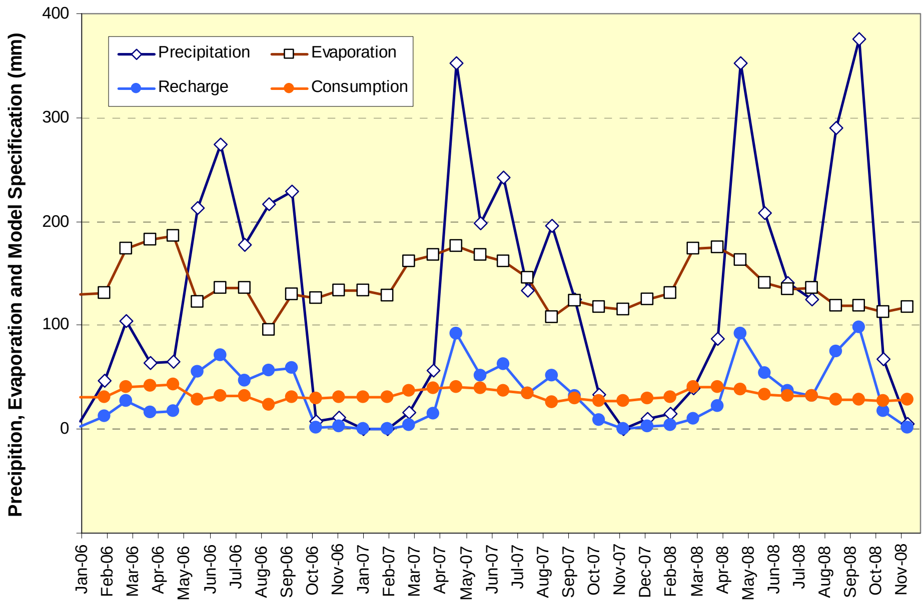

Figure 5.8 Observed Precipitation, Evaporation, Specified Groundwater Recharge and Consumption

5-5-3 Result of Transient Flow Simulation

The simulation result is saved in the model for each cell and each period. The water level, drawdown and other simulation results for any cell in any period of the transient simulation process can be obtained by the procedure as extracting the data for a layer or a section in a period, identifying the location of the cell, picking up the necessary data, and rearranging to save the data to another file. Simulation data check is absolutely necessary, but this procedure takes a long time and is not at all efficient. Therefore, Modflow provides a function of provisional observation well specification. In the Modflow program, a provisional observation well can be set in any cell and any layer to make all the simulation results in that layer and cell to be saved in one file. Then the fluctuation of the water head, drawdown and other items can be easily obtained without the complicated procedure mentioned above.

For transient flow result checking, 5 provisional observation wells (shallow wells: calculation points) 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.

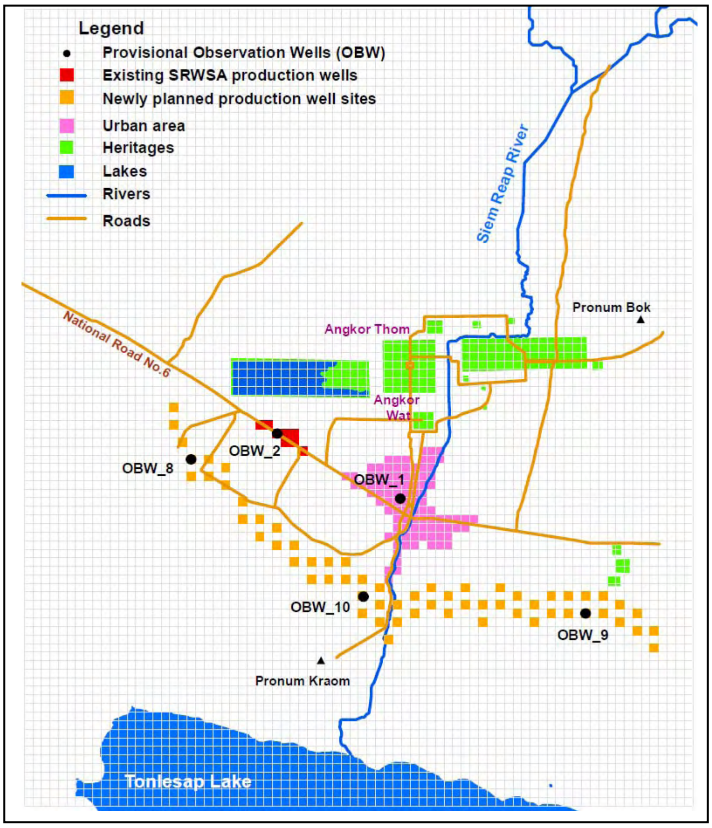

Figure 5.9 Location of Provisional Observation Wells (5 Shallow Wells) and Well Cells

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.

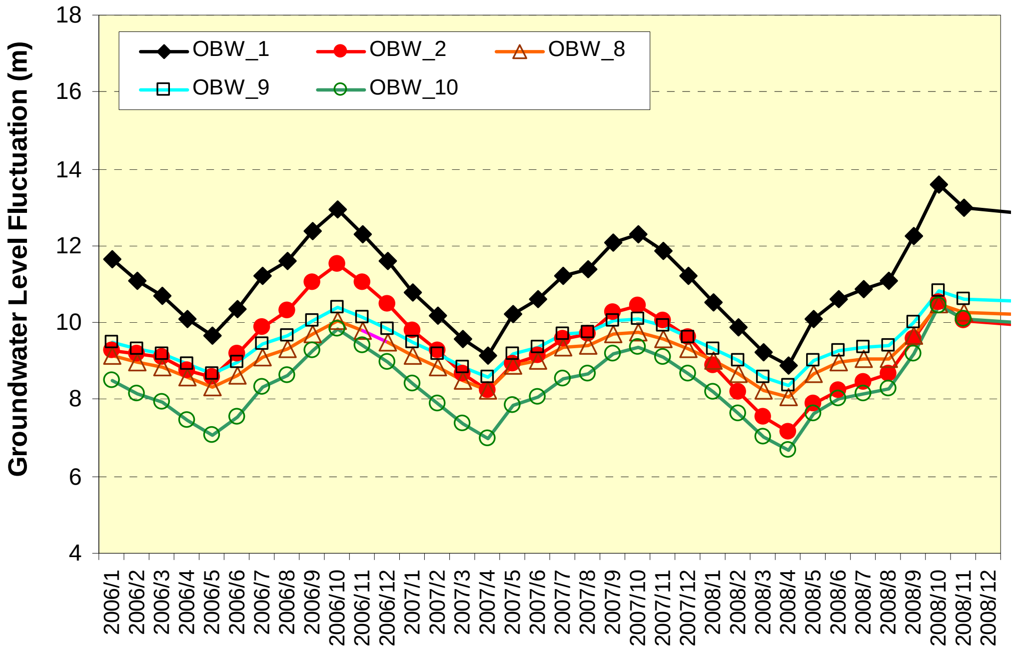

Figure 5.10 Groundwater Level Fluctuation in the Specified Observation Wells (5 Shallow Wells) in the Last 3 Years (2006-2008)

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.

The fluctuation of groundwater level is not only controlled by the change of recharge and consumption of evaporation, but also by the changes of groundwater withdrawal. Therefore, in spite of the increase of groundwater recharge in the whole Siem Reap area, the groundwater level of the provisional observation well OBW_2, which is located in the central part of SRWSA existing production well sites decreased as a result of the increasing of groundwater withdrawal in 2008. In contrast, range of groundwater water level increase in OBW_1 was larger than the other observation wells (OBW8 to 10), because of the decrease of groundwater withdrawal as a result of water supply shifting from private wells to the SRWSA existing wells as shown in Figure 5.7.

5-6 Model Specification for Groundwater Prediction

The groundwater simulation model has been confirmed to be able to reflect the characteristic of groundwater level distribution for Siem Reap because of:

1) The steady flow simulation result certifies the convergence of the model, and shows the coincidence of groundwater level distribution for the whole model domain to the result of simultaneous observation of groundwater level, which was conducted in the rainy and dry seasons, respectively.
2) The transient flow simulation recreated the monthly groundwater level fluctuation in the last 3 years following the change of precipitation, evaporation and groundwater withdrawal.

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 prediction is set as 22 years from 2009 to 2030.

As it is common sense, nobody questions whether or not the groundwater development would cause groundwater level drawdown. The problem is, to what extent the unavoidable groundwater level drawdown would be in the Siem Reap area, especially for a development plan with relatively large amount of groundwater withdrawal. It is unallowable to conduct large groundwater withdrawals just following the water use demand; and then to stop or reduce the amount of production after a significant negative effect has arisen, because it may not be possible to recover from this kind of effect. The effect of groundwater development has to be predicted and evaluated before the implementation of the groundwater development plan. And the groundwater simulation model is one of the most useful tools for the prediction.

Groundwater environment is affected by many factors such as groundwater recharge by precipitation, consumption by evaporation, change of water level in constant head boundary, and location of production wells and amount of withdrawal.

On the other hand, many world famous heritage sites like Angkor Wat, Angkor Thom and West Baray are located in Siem Reap. The most feared effect of groundwater development to the heritage sites can be considered as the groundwater level drawdown causing land subsidence.

The evaluation of the effect of groundwater development on the heritage sites should not be simply conducted by averaging the factors mentioned above. Similar to standards for building construction, even though a big earthquake may or may not occur in the near future, the building should not be constructed without the ability to withstand an earthquake.

Under natural conditions, groundwater level fluctuated following the change of seasons as mentioned in Chapter 2 and shown in the result of simultaneous groundwater observation. However, the highest water level or lowest water level for each year is not just the same. The water level depends on the balance of recharge from precipitation and consumption from evaporation and groundwater development. On the other hand, the precipitation in Siem Reap area changes year by year as shown in Table 5.1. The ratio of precipitation amount of dry year to the rainy year changes in Siem Reap from 40 % to 80 %, based on the 5 meteorological stations, within different observation durations.

Table 5.1 Yearly Precipitation at Meteorological Stations in Siem Reap

(Unit: mm)

Year	City Station	Prasat Bakong	Ankor Thom	Puok	Phnon Kraom
1988	1328.2	-	-	-	-
1989	1562.7	-	-	-	-
1990	1264.4	-	-	-	-
1991	1643.4	-	-	-	-
1992	1157.8	-	-	-	-
1993	1524.4	-	-	-	-
1994	1179.8	-	-	-	-
1995	1766.4	-	-	-	-
1996	1488.3	-	-	-	-
1997	1551.3	-	-	-	-
1998	1327.8	-	-	-	-
1999	1469.3	-	-	-	-
2000	1637.2	-	-	-	-
2001	1752.5	1245.8	1267.9	-	-
2002	1141.4	1039.8	993.8	-	-
2003	1271.2	1496.8	1059.7	1276.1	-
2004	1610.4	1496.8	1291.6	1444.4	1427.1
2005	1495.5	1685.5	1233.4	1550.1	1534.4
2006	1414.8	1615.0	964.9	1433.2	1119.6
2007	1355.8	1678.0	562.1	1511.0	1130.7
2008	1715.8	1507.2	1334.1	1298.0	-
Average	1459.9	1470.6	1088.4	1418.8	1303.0
Maximum	1766.4	1685.5	1334.1	1550.1	1534.4
Minimum	1141.4	1039.8	562.1	1276.1	1119.6

It is supposed no one would doubt that in a dry year, the groundwater level would become lower than in a year of normal precipitation, because the groundwater water will receive a smaller amount of recharge from precipitation than in a normal year. And then the extremely low groundwater level will appear in an extreme dry year with the extremely low precipitation amount. If this condition is not taken into consideration and examined earnestly, the situation would be similar to building a house without considering the occurrence of a big earthquake.

The extreme groundwater level drawdown happens in an extreme dry year. After that, the groundwater level will recover because a normal or rainy year will surely appear after the dry year based on the hydrological cycle. The temporary and significant groundwater level drawdown in an extreme dry year may not be a major problem for the purposes of water supply, and then if the evaluation is limited to the water balance over a long period, such as the hydrological cycle, the effect of the extreme dry year's appearance can almost be neglected.

However, to evaluate the effect on heritage sites in Siem Reap, the most critical situation should be examined most earnestly because this situation would cause a most serious problem for heritage protection, much as a major earthquake would to a house. That is, the appearance of an extreme dry year should certainly be taken into the simulation model to calculate the magnitude of groundwater level drawdown, especially in areas near and under the heritage sites.

On the other hand, groundwater is the main source of water supply in Siem Reap at present. And the water demand will increase following the increase of population and tourists. The highest water demand, during this water supply expansion plan, will be reached at or near 2030, the target year of the plan. In case an extreme dry year appears in the year with the highest water demand, nobody would disagree that the highest groundwater level drawdown will happen, and then the biggest effect to the heritage sites would be caused. Only on condition that the safety of the heritage sites can be assured under such circumstances, can the groundwater development plan be accepted. Therefore, the most important task for groundwater prediction by using the simulation model should be set for making clear the magnitude and extent of groundwater level drawdown under these considerably critical circumstances.

5-6-2 Station Selection for Precipitation Probability Calculation

Extreme groundwater level drawdown happens in an extremely dry year. Therefore, the amount of precipitation in an extreme dry year has to be made clear for groundwater simulation model specification. The standard procedure for dry year identification in hydrological analysis is probability calculation. And many methods have been developed for this kind of calculation.

When implementing the probability calculation for precipitation or any other hydrological factors, a long series of data generally results in the improvements of analysis precision.

Of 5 meteorological observation stations (City Station, Prasat Bakong, Ankor Thom, Puok, Phnon Kraom) 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. Therefore, it can be taken as the most appropriate station for precipitation analysis. The data were collected from the City Station and the database of WMO (World Meteorological Organization, 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. The monthly precipitation data obtained from different sources are shown in Figure 5.11.

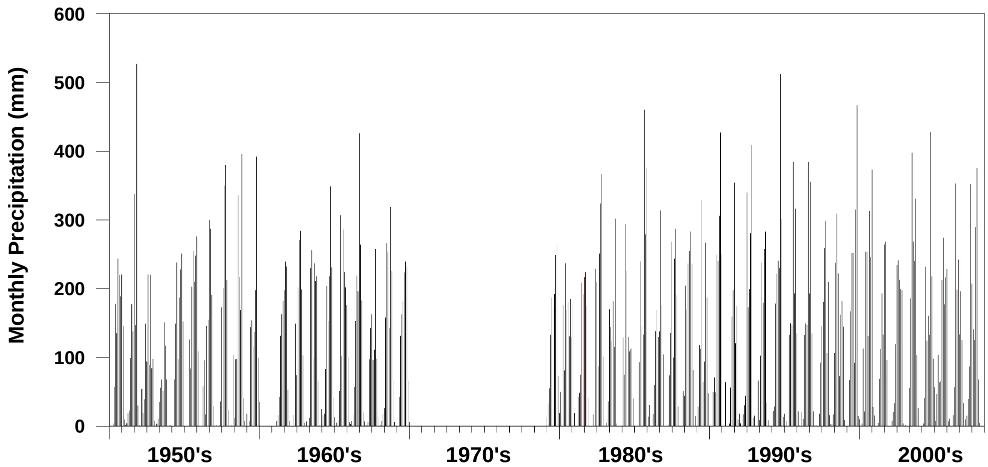

Figure 5.11 Monthly Precipitation Fluctuation in Siem Reap City Meteorological Station

5-6-3 Methods and Results of Probability Analysis

Four of the most often used and evaluated methods were selected from the many available methods for precipitation probability analysis. The four selected methods are:

- 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

Table 5.2 shows the result of probability analysis by using the data from Siem Reap meteorological station by the 4 selected methods.

Table 5.2 Result of Precipitation Probability Analysis

R_Year		Normal D.	Log-normal D.	Log-pearson Type III D.	Plotting Position	Average
Wet	100	1787	1805	1855	1783	1808
	50	1773	1789	1802	1769	1783
	25	1745	1758	1452	1741	1674
Dry	25	1374	1352	1084	1360	1293
	50	1055	1059	1032	1054	1050
	100	1041	1045	987	1040	1028

(Note) R_Year: Return year
Normal D: Normal distribution analytical method
Log-normal D.: log normal distribution analytical method
Log-Pearson Type III D. Log-Pearson Type III analytical method
Plotting Position: Plotting Position analytical method (Hazen method)

Figure 5.12 shows the probability curve obtained by Log-Pearson Type III analytical method combined with plots obtained from Plotting Position method (Hazen).

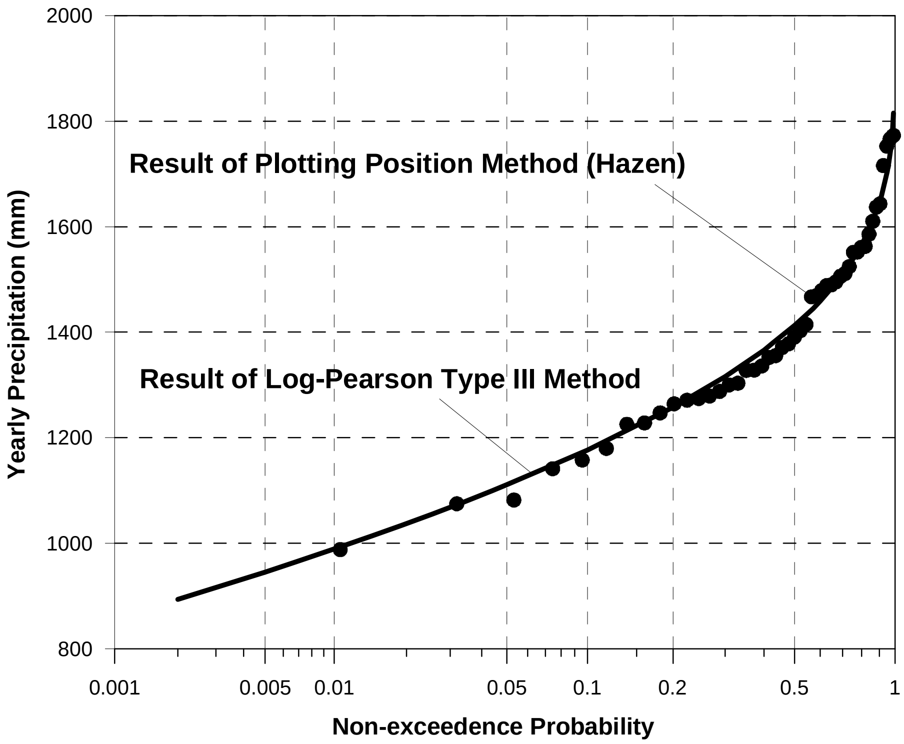

Figure 5.12 Probability Curve of Precipitation in Siem Reap City Meteorological Station

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

Both well sites of SRWSA existing production wells and new planned production wells (expressed as SRWSA well sites hereinafter) are within the coverage of the meteorological station Siem Reap. And as mentioned above, the station can be considered to have the highest precision and reliability in Siem Reap. Furthermore, the station has the longest series of data, more than 48 years, to be used for precipitation probability calculation. Therefore, the observation result of the station was taken as the basic data for groundwater prediction.

Precipitation changes year by year, therefore, it is impossible to know the amount of precipitation exactly in the next year or any year in the future. However, precipitation is known to change periodically, known as the hydrologic cycle. Therefore, the last 20 years observation results from 1989 to 2008 were taken for precipitation specification in the former 20 years of the simulation span from year 2009 to 2028. The influence of precipitation for a certain year will appear the highest recharge amount in the end of the rainy season in the same year and the lowest recharge in the end of dry season in the next year. Therefore, the most risky precipitation condition should not be set in the last year of the simulation span, 2030, but in 2029. The risky precipitation condition was specified using the probability of dry year of 50 return years based on the probability analysis result. After the risky precipitation condition year, a normal year was specified for the last simulation year, 2030.

The specifications of precipitation, evaporation, and groundwater recharge and consumption by evaporation was summarized in Figure 5.13.

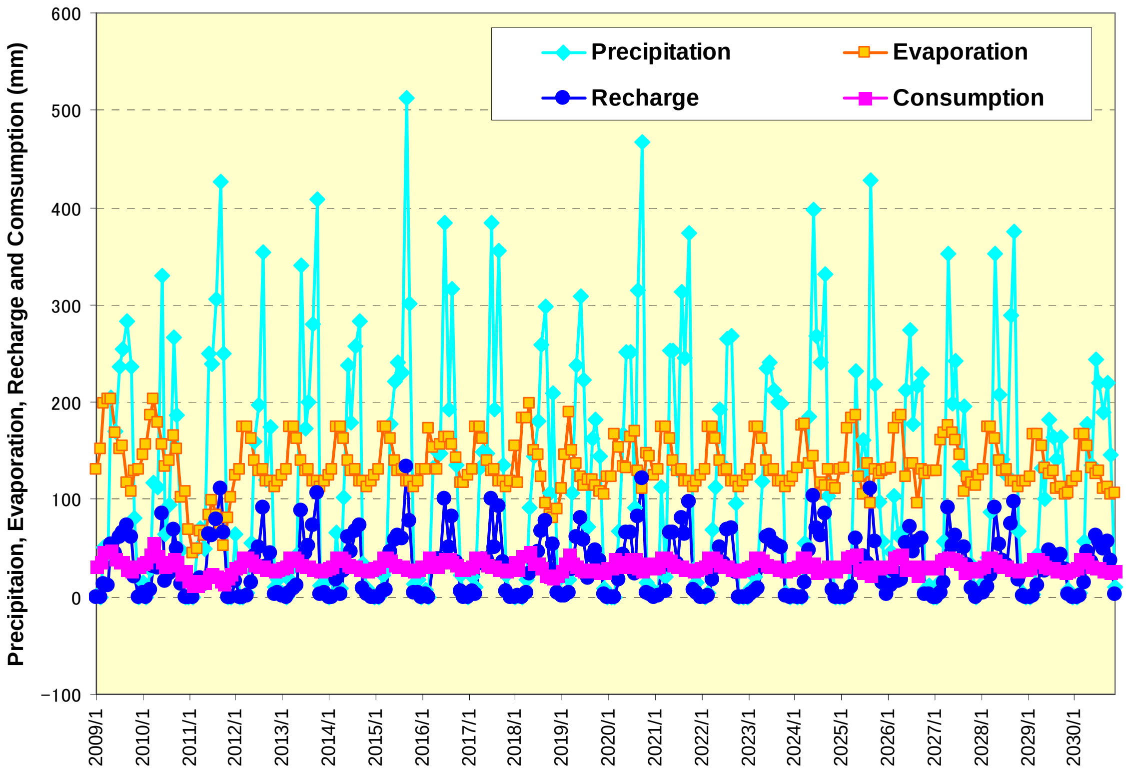

Figure 5.13 Specification of Recharge and Consumption for the Simulation Span 2009 -2030 Based on the Observation Data from 1989 to 2008 and Probability Analysis Result with a Return Year of 50

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

Collected river observation data indicates a range of about 4 m for yearly change of river level in the study area. The base of river level change, that is, the average river level for river cells (constant head boundary cells) were obtained from the result of steady flow simulation. Similar to the groundwater level, river level also changes with the fluctuation of precipitation year by year. Therefore, the river level specification was set as a variable of precipitation in the range of 5 m. That is, in the rainy year or dry year the river level will be higher or lower than other years, but not more than or less than 2.5 m of the average river level. The specification of monthly river level fluctuation for the 22 simulation years is shown in Figure 5.14.

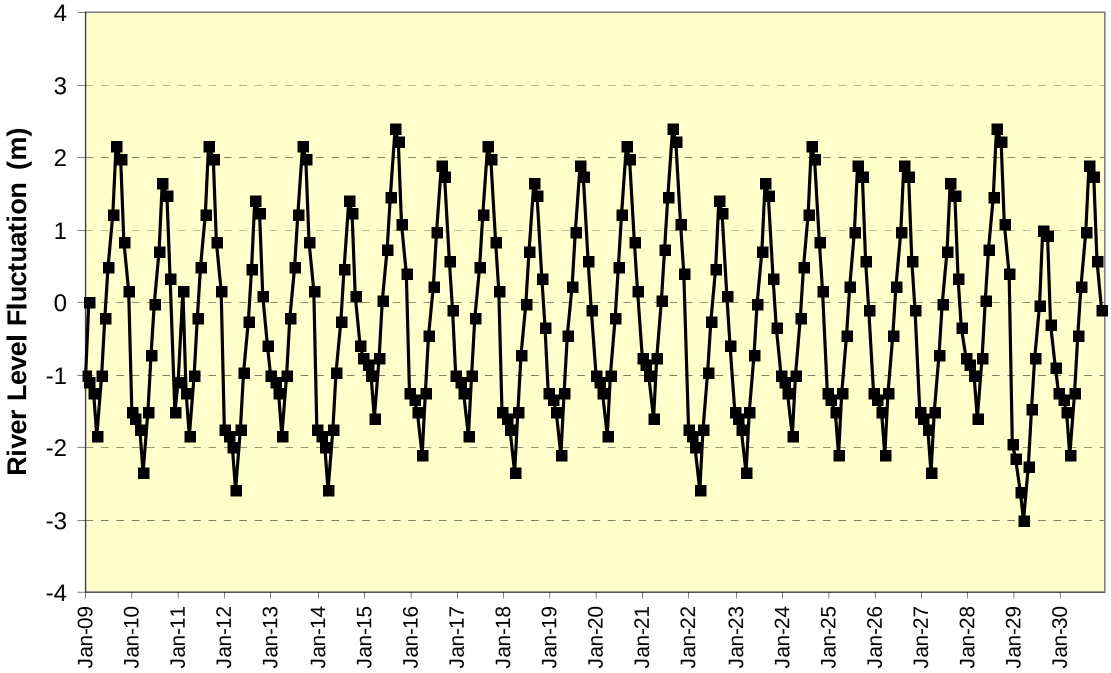

Figure 5.14 Specification of River Level Fluctuation

River level in the study area changes with precipitation fluctuation. However, the water level in Tonle Sap Lake is not controlled by the amount of precipitation in Siem Reap. Water level of Tonle Sap Lake is following the water level of Mekong River, which is in the lower reaches of Tonle Sap Lake. On the other hand, the Tonle Sap Lake is important for the groundwater simulation model, because the lake is set as constant head boundary and will influence the recharge or discharge of groundwater, especially for those newly planned production wells.

There is only 10 years of water level data for Tonle Sap Lake from September 2000 to July 2009. Therefore, this data was repeated twice to specify the Tonle Sap Lake water level fluctuation. The fluctuation of Tonle Sap Lake is from nearly 0 m to over 9 m, about double of the river level change within the study area. The specification of Tonle Sap Lake water level is shown in Figure 5.15.

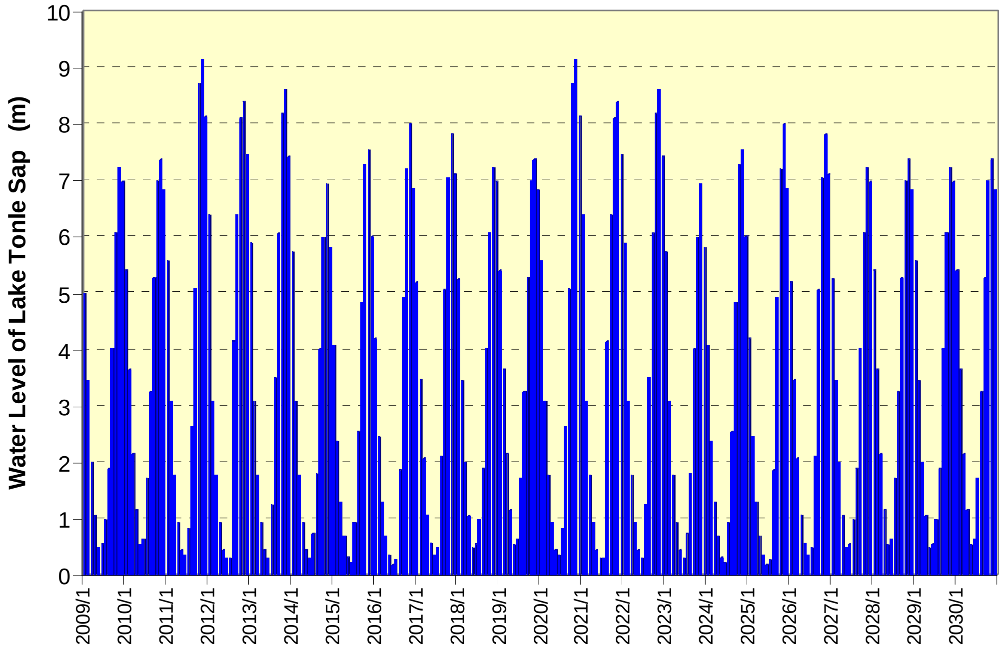

Figure 5.15 Specification of Tonle Sap Lake Water Level Fluctuation

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

Several kinds of water supply expansion plans have been taken into consideration, and then seven scenarios were specified as internal factors for the Siem Reap groundwater simulation model to conduct groundwater predictions under different conditions.

Scenario 1: Comparison Object Case

No matter whether the groundwater is developed or not, groundwater level changes following the alternation of seasons and hydrological years. There is no doubt that groundwater level will be lower in a dry year than a normal year. Considering the history of the heritage sites in Siem Reap, they have existed for 900 years from the 12th century. During the last 900 years, dry year with probability of 50 return years have surely happened several times. However, no major damage caused by groundwater level drawdown on the heritage sites can be confirmed. From this fact, it can be deduced that the effect on heritage sites from groundwater level drawdown by a dry year with probability of 50 return years is limited. Or, the 50 return year's dry year under natural conditions can be considered as within safe limits of the heritage sites.

The problem is what would happen when groundwater development is conducted in the same dry year. In this situation, both the reduced precipitation and the high groundwater withdrawal will result in groundwater level drawdown and in a larger drawdown than would naturally occur. This drawdown has to be examined earnestly to confirm whether it would affect the heritage sites or not.

Two kinds of groundwater level drawdown data are needed for examination, the drawdown under natural conditions and the drawdown whereby groundwater has been developed. To get the magnitude of groundwater level drawdown under natural conditions, a scenario is needed to make clear groundwater level fluctuation in all kinds of hydrological years specified in the model. 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

At present, water demand in Siem Reap has been far more than the water supply capacity of SRWSA. And the 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 on the basis of this option, using only groundwater to meet the water demand by 2030 and the new water supply facilities is supposed to be complete in 2016.

A facility construction plan has been set according to the water supply expansion plan. Considering the essential issue of limiting the effect on heritage sites to a minimum degree, the new facilities were designed in the downstream area of Siem Reap. As shown in Figure 5.15, peak water level in Tonle Sap Lake can get to an elevation of near 10 m above sea level. Therefore, 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).

{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)}

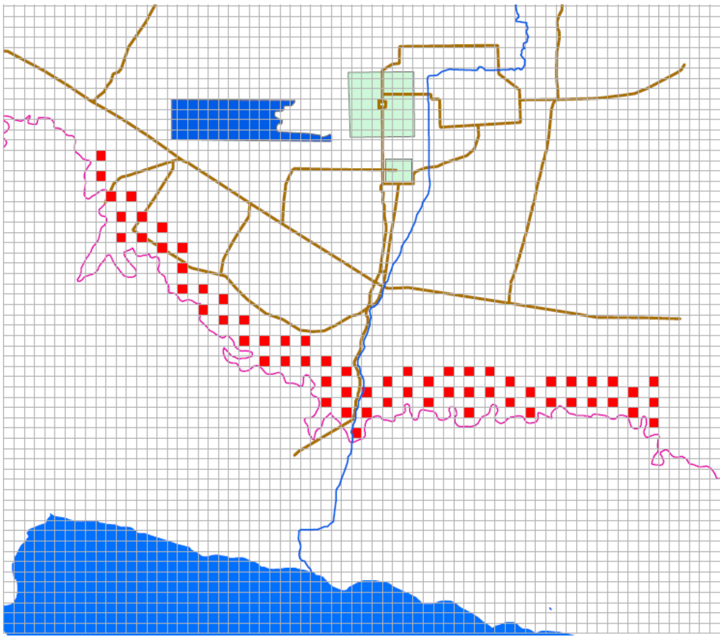

Figure 5.16 Location of New Production Wells for Scenario 3

In scenario 3, production of groundwater can be divided into 3 sectors; existing SRWSA production wells, private wells in urban area and new production wells shown in Figure 5.17. According to the new water supply facility's construction plan, water supply amount in monthly units has been calculated up to 2030.

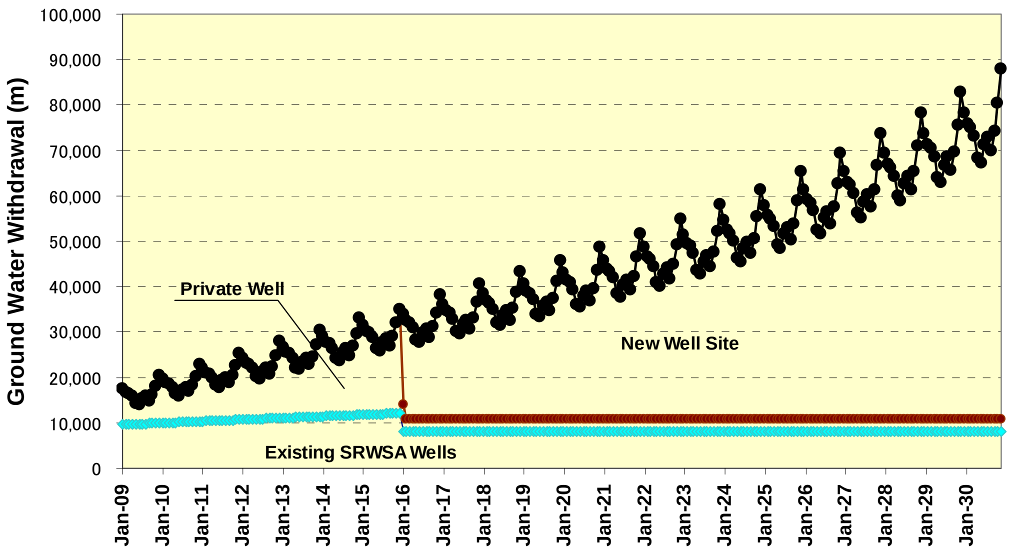

Figure 5.17 Specification of Groundwater Withdrawal for Scenario 3

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 5.18.

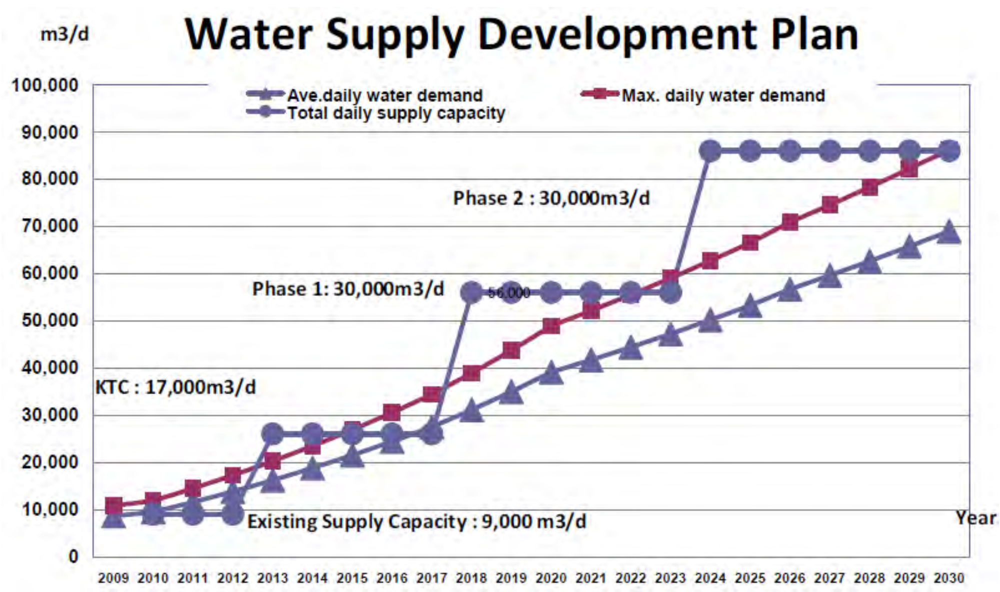

Figure 5.18 Water Supply Development Plan

Three curves are shown in the figure. The blue line with blue color triangle markers shows the change of average daily water demand; purple color line with purple color square markers shows change of maximum daily water demand; and the blue line with blue color circles shows the schedule of new water supply facilities construction and water supply capacity expansion plan. The water supply expansion plan is divided into 2 phases to make 30,000 m^3/day water supply capacity increased in each phase. Phase I is designed to be completed in 2016 and phase II in 2023.

In the water supply development plan shown in Figure 5.16, 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 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)}

Figure 5.19 shows the changes and components of water supply capacity in scenario4 based on the average daily demand.

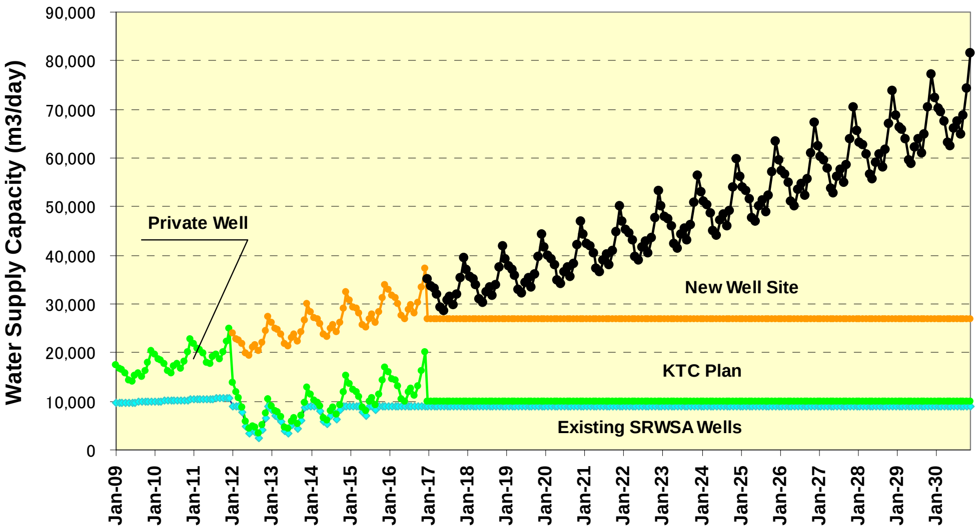

Figure 5.19 Specification of Water Supply Apportionment for Scenario 4

Figure 5.20 shows the changes and components of water supply capacity in scenario 5 based on the average daily demand.

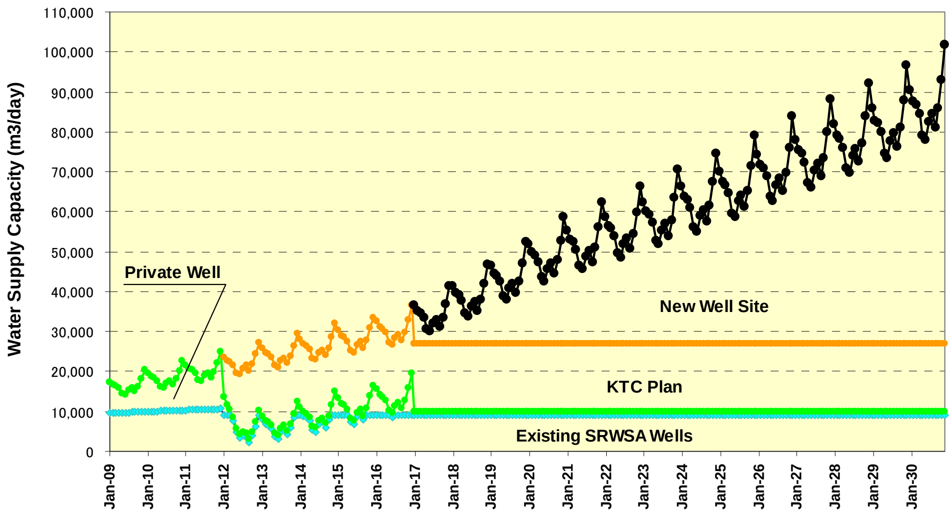

Figure 5.20 Specification of Water Supply Apportionment for Scenario 5

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 5.21.

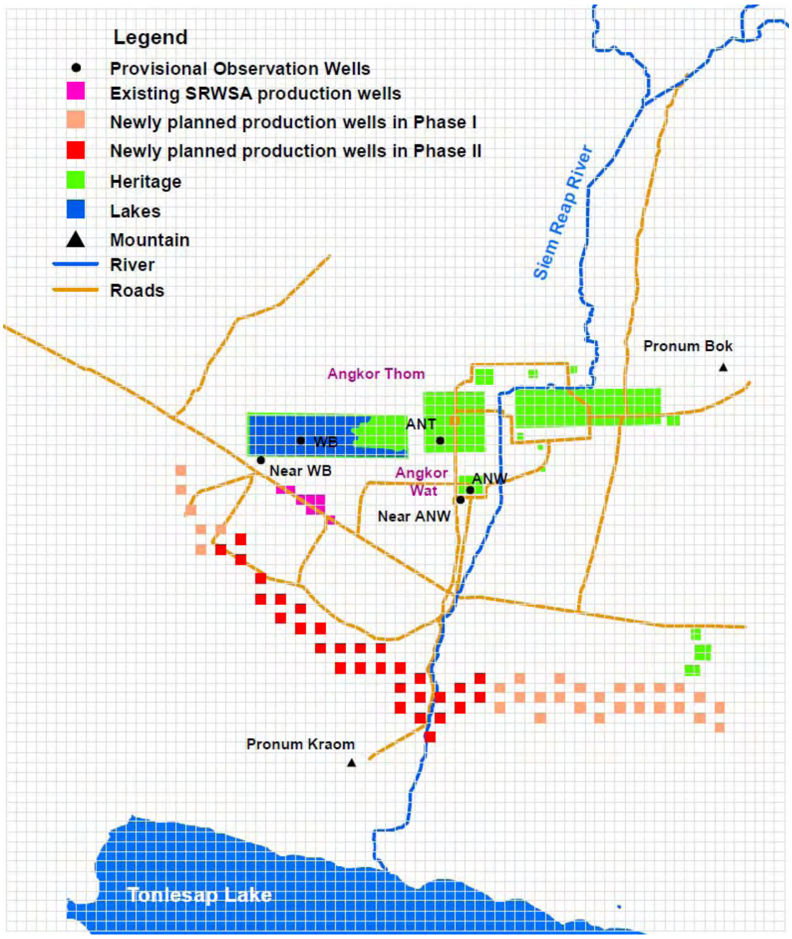

Figure 5.21 Specified New Production Wells and Provisional Observation Wells (5 Deep Wells) for Examination of Effect to the Heritage sites in Each Simulation Scenario

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

As shown in Figure 5.18, new wells in the expansion plans are designed for 2 phases. In phase I most wells are designed on the west side of Siem Reap River. The basic consideration for this design is for making wells as near as possible to the water treatment facilities, so that the construction cost would be low and the well management would be easy. On the other hand, an important heritage group of Bakong is located on the east side of Siem Reap River. The risk of negative effect to the heritage group of Bakong would be increased if the new wells are near them. So scenario 6 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)}

Figure 5.22 shows the components and changes of water supply in Scenario 6.

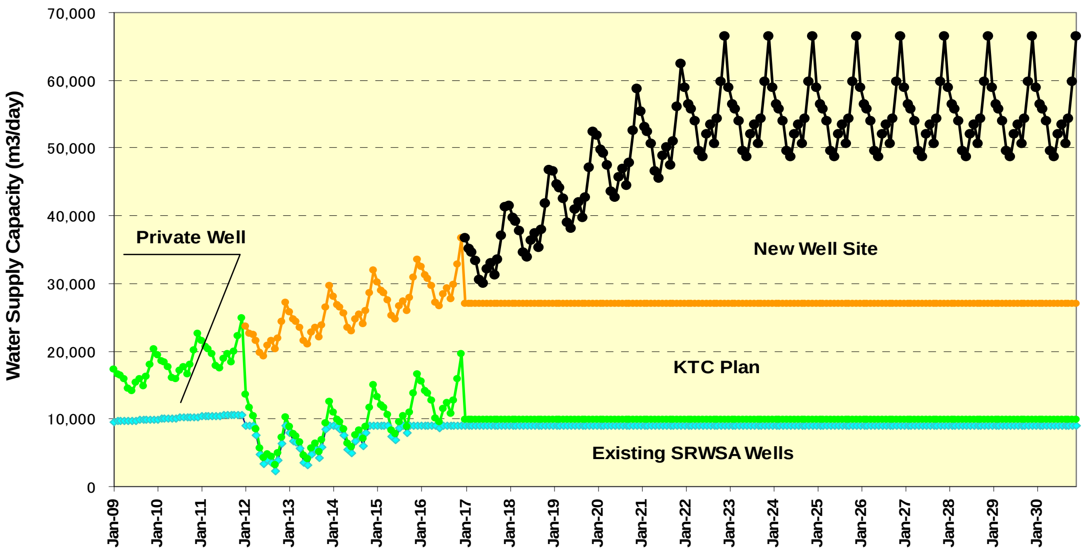

Figure 5.22 Specification of Water Supply Apportionment for Scenario 6

Scenario 7: Using Surface Water as Water Supply Source to Reduce Groundwater Withdrawal

Groundwater level drawdown is unavoidable in groundwater development. The only surefire way to prevent or limit the groundwater level drawdown is to stop or reduce groundwater development. Therefore, a new water supply expansion plan has been formulated to change the source of water supply from groundwater to surface water, and use surface water to meet the increasing water demand. 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. This is the plan to be implemented under scenario 7. (Total withdrawal volume = SRWSA wells' extraction volume = 9,000 m^3/day)

Figure 5.23 shows the components and changes of water supply in Scenario 7.

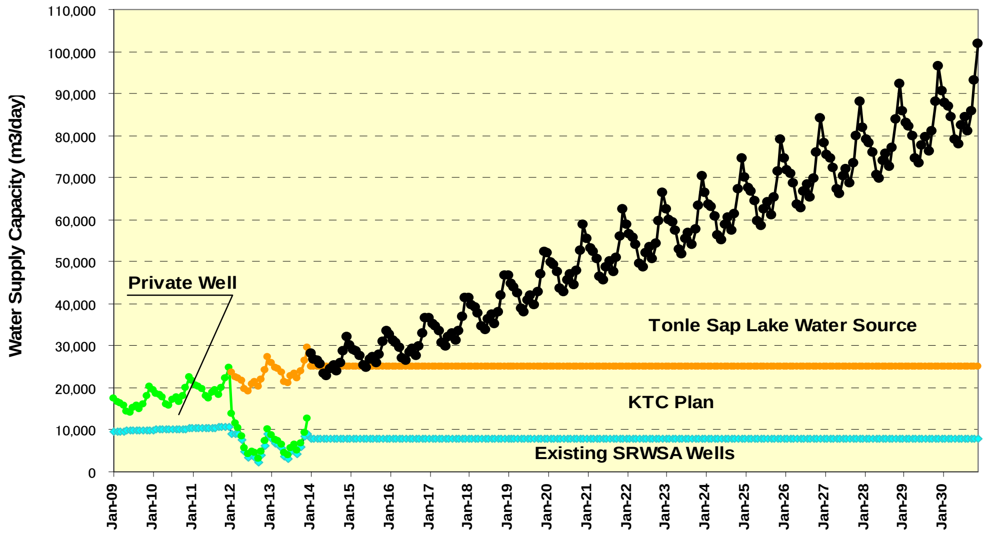

Figure 5.23 Specification of Water Supply Apportionment for Scenario 7

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. These 5 provisional observation wells (deep wells: calculation points) are mainly specified near the existing production wells. (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 ANW: near Angkor Wat, ANT: under Angkor Thom, WB: under West Baray, Near WB: near West Baray)

However, one of the most important issues for groundwater simulation is to examine the effects on the heritage sites in Siem Reap caused by different water supply expansion plans. On the other hand, many constant head features in and surrounding the heritage sites have been specified into the simulation model so that no or very little groundwater level drawdown can occur in shallow aquifers under and near the main heritage sites.

As mentioned in Chapter 4, it has been made clear that two aquifer exist in Siem Reap, a shallow aquifer and a deep aquifer. The constant head features can effectively prevent groundwater level drawdown in the shallow aquifer, but give little effect in the deep aquifer, because of an aquiclude between the two aquifers. When the groundwater development plan is implemented, groundwater level drawdown would occur in both shallow and deep aquifers. Even though it is clear that the groundwater level drawdown in the shallow aquifer will have a very minimal or no effect on the heritage sites, they cannot be considered as safe without examining the effect of water level drawdown in the deep aquifer. For summarizing and extracting simulation results in deep aquifer in and near the heritage sites, 5 provisional observation wells (deep wells) are specified under and near the heritage sites of Angkor Wat, Angkor Thom and West Baray as shown in Figure 5.21.

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)

Compared with the natural condition (scenario 1), the largest groundwater level drawdown is about 2 m in scenario 3, which has the biggest groundwater withdrawal amount. However, groundwater level drawdown does not appear in 2030, when a dry year with a probability of 50 return years occurs, but in 2015, which is the year before the new water supply facilities construction.

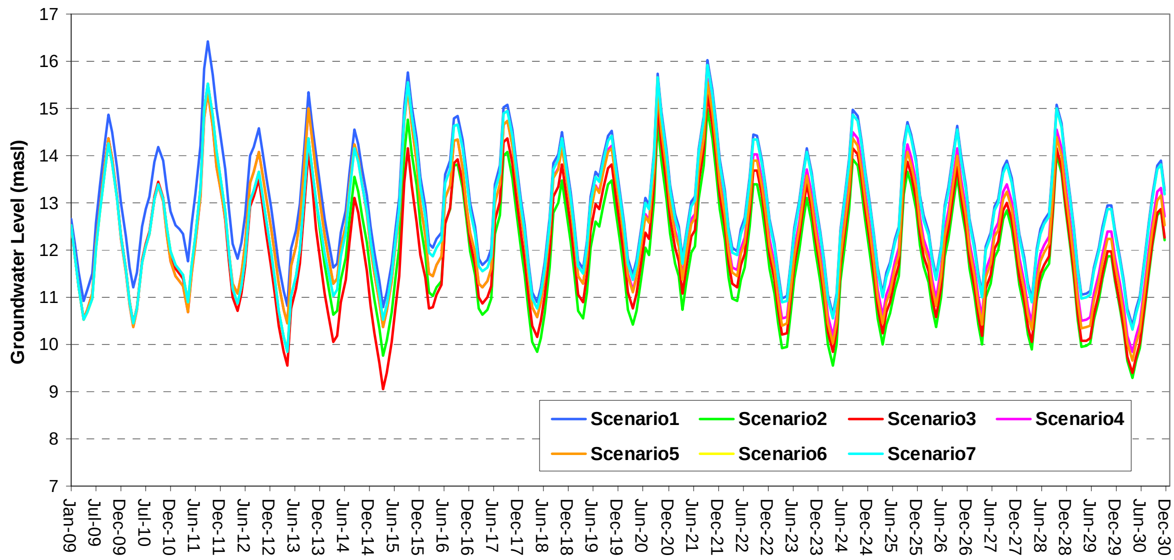

Figure 5.24 Water Level Fluctuation of Provisional Observation Well No.1 (Central Part of Siem Reap City, Shallow Aquifer)

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

Compared with the natural condition (scenario 1), the largest groundwater level drawdown is about 4 m from scenario 3. The same as in provisional observation well No.1, the largest groundwater level drawdown does not appear in 2030, but in 2015, because the production amount specification in scenario 3 for SRWSA production wells reaches its maximum in this year, as shown in Figure 5.17.

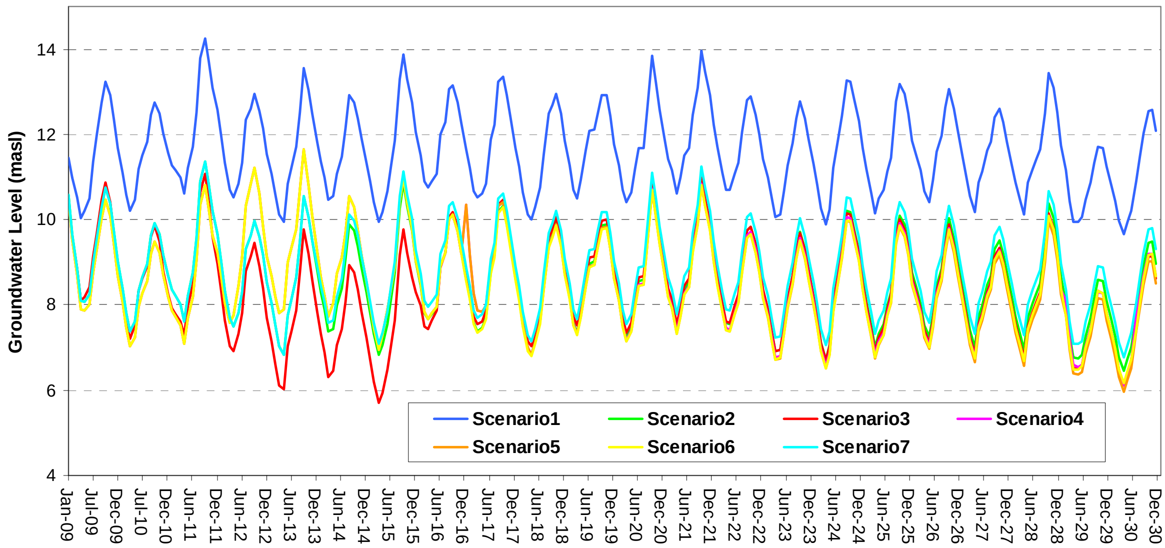

Figure 5.25 Water Level Fluctuation of Provisional Observation Well No.2 (Central Part of Existing SRWSA Wells, Shallow Aquifer)

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

The range of groundwater level annual fluctuation in this deep aquifer specified provisional observation well is within 1 m, much smaller than wells specified in shallow aquifer (refer to provisional observation wells No.1 and No.2). This difference coincides with the groundwater observation result from sites LTa and LTb to show how well the groundwater simulation model fits the situation in Siem Reap.

Groundwater level fluctuation is affected by both climate change and groundwater development. 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 (refer to Figure 5.17), 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 5.26. 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.

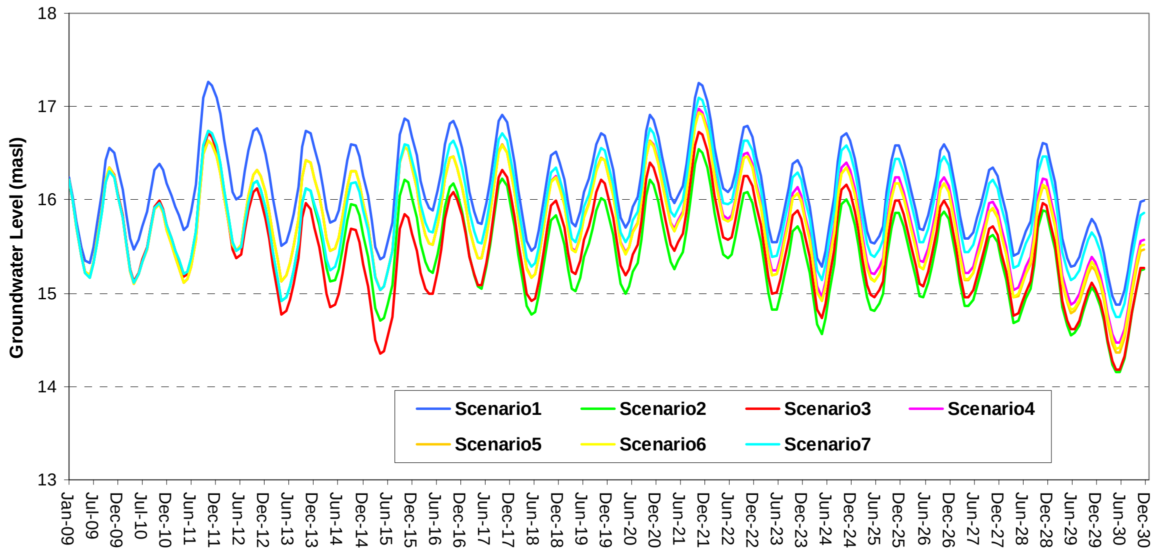

Figure 5.26 Water Level Fluctuation of Provisional Observation Well No.3 (Near Angkor Wat, Deep Aquifer)

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

The provisional observation well is specified near West Baray, and near existing SRWSA production well and new production well also. The effect of existing SRWSA production wells can be examined from scenario 2, which is specified as keeping the present production amount until 2030. The result from scenario 2 shows the water level in the provisional observation well would keep the same fluctuation as natural conditions, at a level about 1 m below it. The effects of groundwater production increasing in the existing SRWSA production wells and new wells can be found from the water level change in scenario 3. Groundwater production amount from existing SRWSA wells is specified to increase until 2015 when the new water supply facilities are constructed. And then the water level in the provisional well will decrease until the same year, 2015. From 2016, the extra production from existing SRWSA production wells is set to be shifted to new production wells; and then the water level in the observation well shows a tendency of recovery. However, according to the increasing of production amount in new wells, its effect is getting bigger, and the recovery of water level in the provisional observation well stops in the year near 2018. From 2019, a new groundwater level drawdown tendency can be found as the effect of groundwater production amount increasing in new wells.

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 scenario 3, 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. In scenario 6, groundwater production amount is specified as stopping all other production, only keeping water supply capacity from existing SRWSA production wells. The result shows that the existing SRWSA production wells alone may cause about 1m groundwater level drawdown when compared with natural conditions.

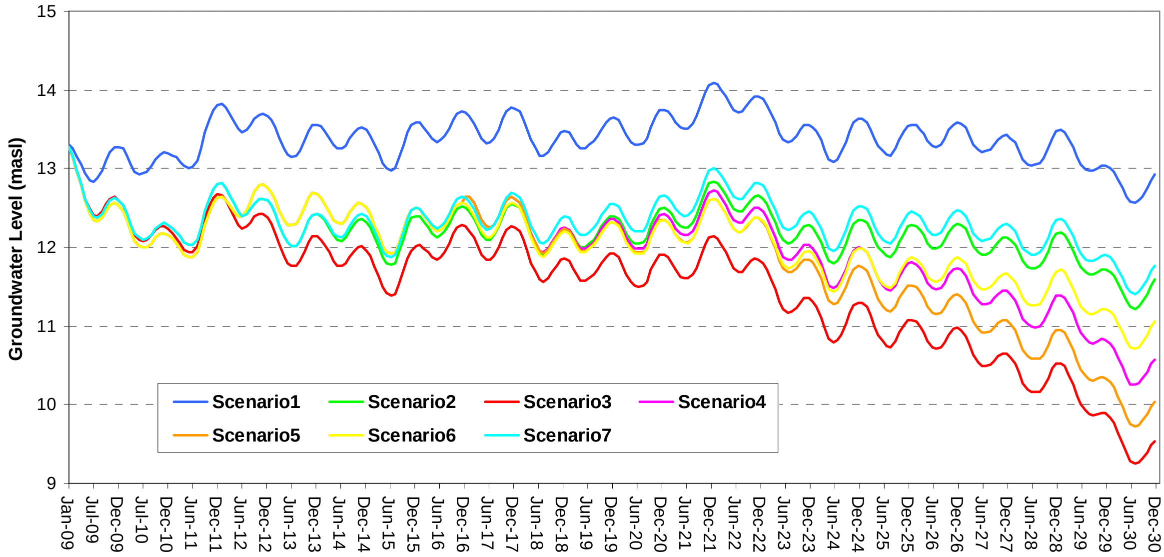

Figure 5.27 Water Level Fluctuation of Provisional Observation Well No.4 (Near West Baray, Deep Aquifer)

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

The curves of groundwater level fluctuation are similar with the provisional observation well no.4. However, 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, because well no.5 is further than no.4 from the existing SRWSA production wells and new production wells; also because the constant head boundary of West Baray has been set in shallow aquifer above the provisional observation well.

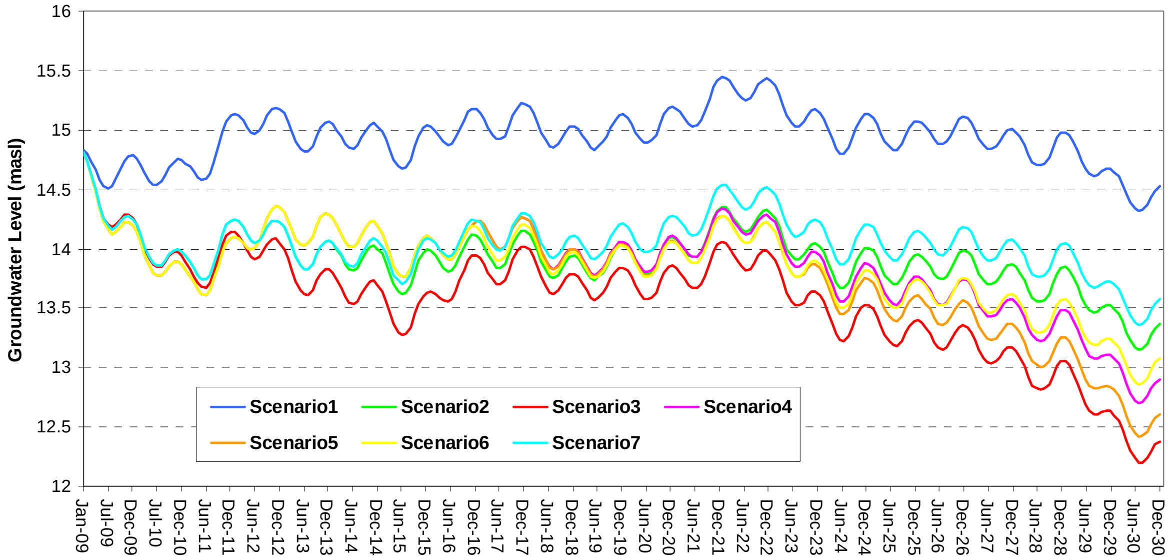

Figure 5.28 Water Level Fluctuation of Provisional Observation Well No.5 (Under West Baray, Deep Aquifer)

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

For all scenarios, the maximum groundwater level drawdown appears in May 2030. 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.

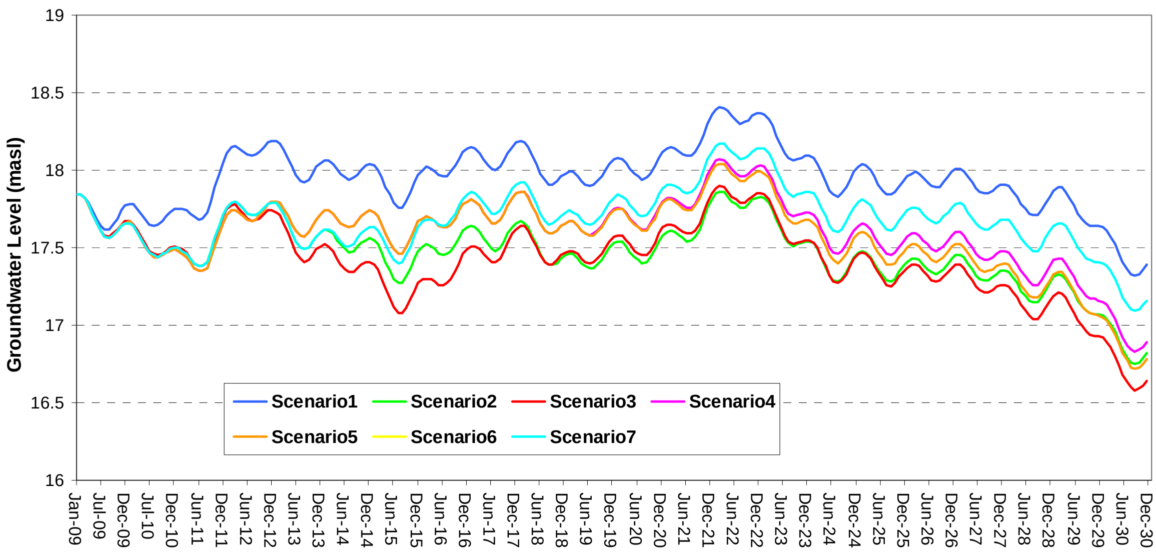

Figure 5.29 Water Level Fluctuation of Provisional Observation Well No.6 (Under Angkor Thom, Deep Aquifer)

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

Similar to provisional observation well no.6, the maximum groundwater level drawdown appears in May 2030 for all scenarios. Compared with the natural condition, the water level drawdown for different scenarios changes from 0.1 m to 0.7 m.

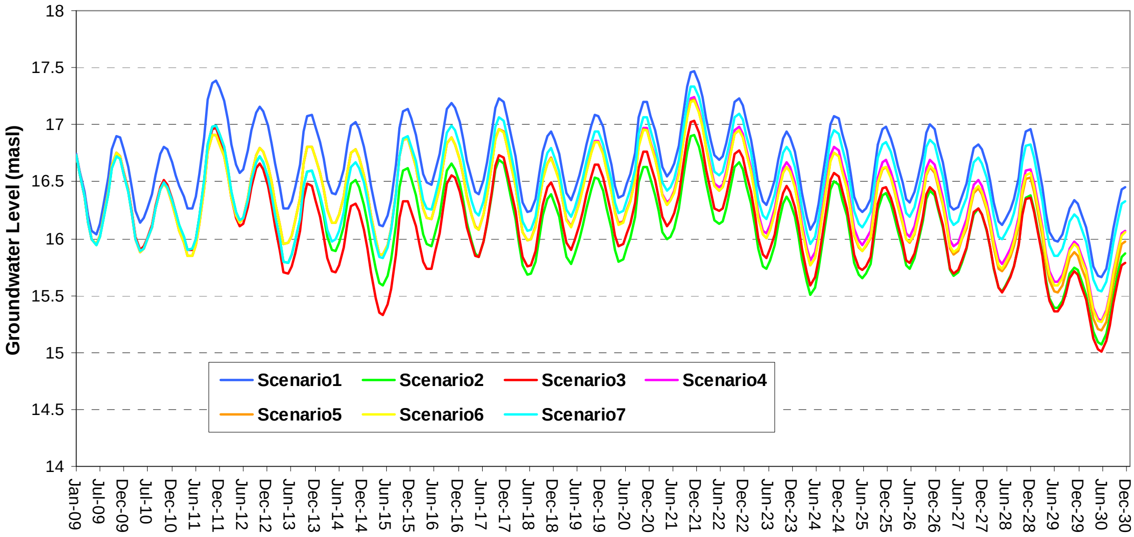

Figure 5.30 Water Level Fluctuation of Provisional Observation Well No.7 (Under Angkor Wat, Deep Aquifer)

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

By the year of 2015, which is the year of new production well construction, water level from all scenarios keep the same fluctuation as the natural condition to indicate no effect from SRWSA existing production wells and private wells in the urban area of Siem Reap on this provisional observation well site. In specification for scenario 3, new wells will be constructed in 2015. Therefore, a groundwater level drawdown occurs from 2016 and decreases year by year with a seasonal fluctuation. In scenario 4 and 5, the effect of new wells in phase I is small and the rapid groundwater level drawdown happens from the new wells constructed in Phase II in 2023.

The maximum groundwater level drawdown occurs for scenario 3 to 5 in May 2030. 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.

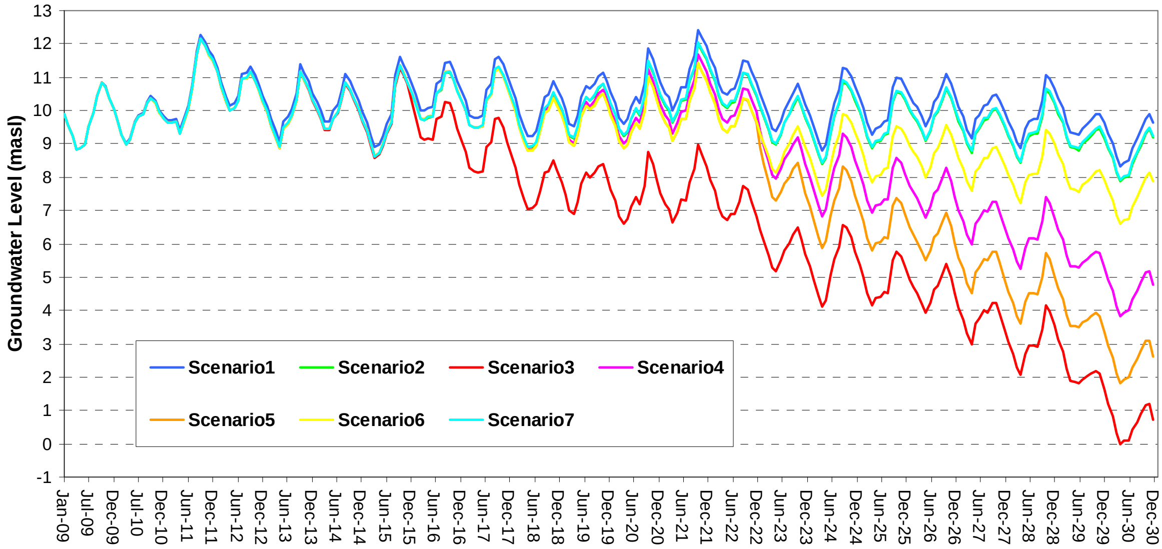

Figure 5.31 Water Level Fluctuation of Provisional Observation Well No.8 (Southwest of West Baray, Shallow Aquifer)

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

Similar to the provisional observation well no.8, the curves in Figure 5.32 show 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. The Maximum groundwater level drawdown occurs in May 2030. Comparing with the natural condition the maximum groundwater level drawdown changes from about 4 m to 6.8 m according to specifications of groundwater production amount in each scenario.

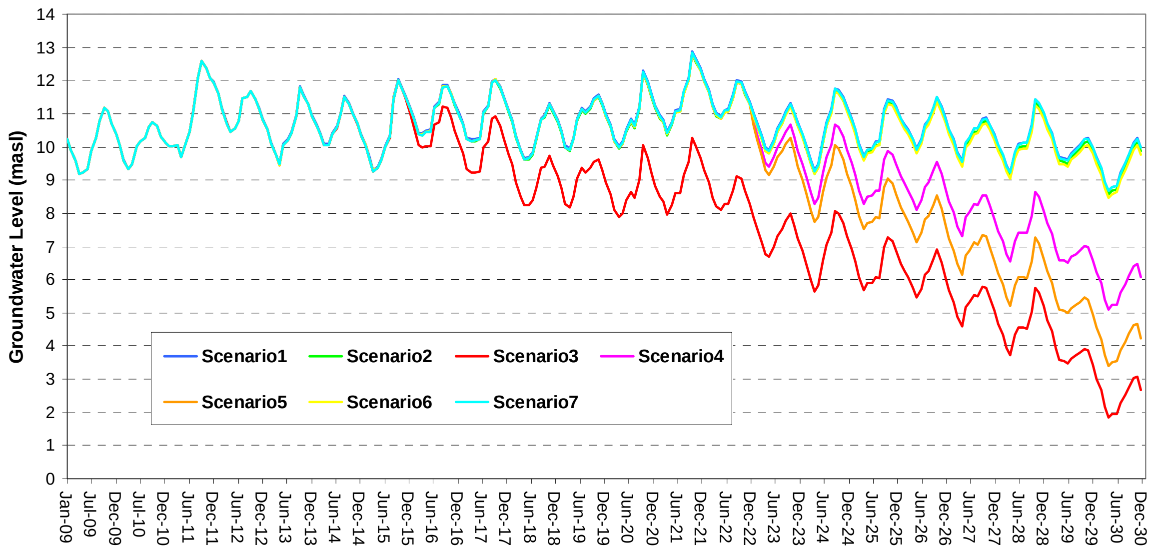

Figure 5.32 Water Level Fluctuation of Provisional Observation Well No.9 (Southeast of Siem Reap City, Shallow Aquifer)

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

The same as provisional observation well no.8 and no.9, no effect from SRWSA existing production wells and private wells in urban area of Siem Reap can be identified on this well. The groundwater level drawdown is only caused by new production wells, in the 3 scenarios: scenario 3, 4 and 5. According to the increasing of groundwater production from new wells the groundwater level drawdown is getting bigger year by year. The maximum groundwater level drawdown occurs in May 2030. Compared with the natural condition, 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. Within the three provisional observation wells specified in central part of new wells, this well, no.10, shows the smallest groundwater level drawdown because this well is specified near a constant head boundary of Siem Reap River.

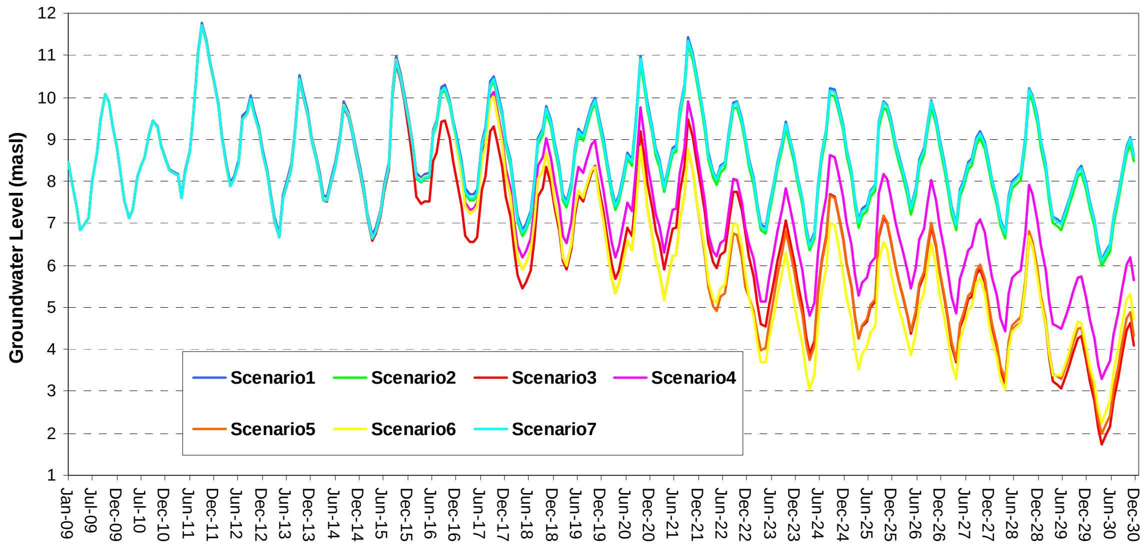

Figure 5.33 Water Level Fluctuation of Provisional Observation Well No.10 (Southern Part of Siem Reap City, Shallow Aquifer)

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 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 5.3.

As shown in Figure 5.26 to Figure 5.30, the maximum groundwater level drawdown in the 5 provisional observation 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 can be considered as within safety limitation for heritage protection. Hence, what should be examined is the difference of water level between each scenario and scenario 1, the natural condition scenario. Therefore, these differences have been calculated and summarized into the same table.

Table 5.3 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 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 5.21.
Each location which is indicated by each well number is as follows:

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

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

There are a lot of heritage sites in and around Siem Reap, as shown in the heritage distribution map in section 1 of this chapter. It is unnecessary and nearly impossible to set a provisional observation well under or near each and every heritage site in the groundwater simulation model. However, in the eastern part of Siem Reap, to the south of National Road Number 6 is the heritage group of Bakong. This heritage group is different from Angkor Wat and West Baray, because there is no permanent water moat surrounding the heritage group to protect it from the effects of groundwater level drawdown.

Therefore, unlike the sites where provisional observation wells have been specified in the deep aquifer to ascertain the continuous groundwater level fluctuation, no provisional wells are specified for the heritage group of Bakong. On the other hand, almost all of the 10 provisional observation well simulation results clearly show that the largest groundwater level drawdown appears in May 2030, the end of the dry season with a return-year of relatively high probability. Hence, the water level data in the simulation period number 256, which corresponds to the month of May 2030, have been collected for all scenarios. Then, 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 scenario 1, and the calculation result is summarized in Table 5.4.

Table 5.4 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.

Even though there is no doubt that groundwater level drawdown may cause land subsidence, the degree of land subsidence will not be all the same for a fixed value of groundwater level drawdown. The degree of land subsidence will change with the degree of groundwater level drawdown and soil type, land also whether it has experienced land subsidence in the past.

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.

After confirming the location of the monitoring wells in relation to the heritage sites, and confirming the depth of soil samples for compression tests and aquifers, the potential land subsidence calculation can be conducted using the equation below:

$$\text{Potential land subsidence} = Mv * H * \Delta P$$

Here,
Mv: Volume Compressibility (m^2/kg).
H: thickness of the corresponding aquifer (m)
ΔP: Pressure change caused by groundwater level drawdown (kg/m^2)

According to the pumping test results, the thickness of the deep aquifer changes from 8.3m to 12 m. The screen length can be used to calculate the thickness of the deep aquifer. In this case the nearest test well to the Angkor Wat heritage site is LTb, with a screen from 72.8 to 64.12 m under the ground surface. Therefore, the thickness of deep aquifer near Angkor Wat can be calculated as 8.29 m. Because no pumping test has been conducted near the West Baray heritage site, the thickness of the deep aquifer near West Baray can be calculated by averaging the deep aquifer test results of the three nearest wells (WT-5, WT-7 and LTb) to obtain a thickness of 10.64 m. Based on all the necessary parameter examinations mentioned above, potential land subsidence for each site of provisional observation well and each scenario were calculated and summarized in Table 5.5.

Table 5.5 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 5.21.
Each location which is indicated by each well number is as follows:

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

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 5.6.

Table 5.6 Potential Land Subsidence Amount Prediction for Heritage Site of Bakong

(Unit: mm)

Scenario	S 2	S 3	S 4	S 5	S 6	S 7
Shallow A	1.59	48.73	20.45	29.93	1.9	0.34
Deep A	0.71	24.23	11.19	16.51	0.92	0.11
Total	2.3	72.96	31.64	46.44	2.82	0.45

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

5-7-3 Result of Groundwater Level Drawdown Prediction

As shown in Figure 5.24 to Figure 5.33, the maximum groundwater level drawdown for most scenarios occurs in May 2030, the last month of a dry year with a probability of 50 return-years. Therefore, the water head calculation results by the simulation model were extracted in May 2030 (period no.256) and compared with the water head in scenario1, which is the scenario specified in natural condition without groundwater withdrawal. The results are shown in Figure 5.34 to Figure 5.45.

Scenario 2

Scenario 2 is specified as keeping the present groundwater production amount until 2030. The present groundwater production includes SRWSA production wells and private wells in the urban area of Siem Reap; and then the groundwater level drawdown is centered on the SRWSA production well sites and urban areas as shown in Figure 5.34 and Figure 5.35. The maximum groundwater level drawdown appears in the area of SRWSA production wells, because the relatively higher amount of groundwater production compared with private wells in the urban area. 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

Scenario 3 is specified as using only groundwater for water supply by new groundwater production facilities construction before 2016. Scenario 3 is the case of the most groundwater use in all scenarios with maximum daily water supply amount of 86,300 m^3/day.

The construction of new production wells makes it possible to reduce production amount from private wells in the urban area of Siem Reap. And the production amount from new wells is as much as about 6 times that of existing SRWSA production wells. As shown in Figure 5.36 and Figure 5.37, the groundwater level drawdown is centered on the new production wells. Compared with scenario 2, the extent of groundwater level drawdown in scenario3 is much vaster, and the maximum drawdown is predicted as high as 8.3 m in shallow aquifer and 7.4 m in deep aquifer. On the other hand, similar to scenario 2, affected by specification of constant head boundary in shallow aquifer, the extent of groundwater level drawdown in shallow aquifer is smaller than deep aquifer. This kind of result can be found from all scenarios as the same specifications of constant head boundaries.

Scenario 4

In scenario4 new production wells are specified in phase I and Phase II, respectively. The daily water demand is estimated as 69,000 m^3/day. Not only groundwater, but also 17,000 m^3/day of surface water is designed as part of the water supply. Therefore, the maximum amount of groundwater production is 52,000 m^3/day; nearly 74 % of that in scenario 3.

Similar to scenario 3, most groundwater production is set using new wells, so that the groundwater level drawdown is centered on the new well site as shown in Figure 5.38 and Figure 5.39. Both maximum groundwater level drawdown and extent of the drawdown are smaller than scenario 3 because the small amount of groundwater production. The maximum groundwater level drawdown is 4.5 m in shallow aquifer and 4.0 m in deep aquifer, respectively.

Scenario 5

Specification of groundwater use in scenario 5 is almost the same as scenario 4, except the groundwater production amount. The specification of production amount is based on the maximum daily demand in the water development plan. The groundwater production amount is specified as 69,250 m^3/day by taking 17,000 m^3/day of surface water use amount from total water supply demand of 86,300 m^3/day.

The same as scenario 3 and scenario 4, majority of groundwater production is taken from new wells, so that groundwater level drawdown is centered on the new well sites as shown in Figure 5.40 and Figure 5.41. As the groundwater production amount is specified between scenario 3 and scenario 4, the extent of groundwater level drawdown and maximum groundwater level drawdown are also between scenario 3 and scenario 4. The maximum groundwater level drawdown is 6.5 m in shallow aquifer and 5.96 m in deep aquifer, respectively

Scenario 6

Scenario 6 is specified as stopping further groundwater development after implementation of 30,000 m^3/day water supply capability in Phase I of the water expansion plan. Most new wells are concentrated in the west side of Siem Reap River in this scenario, so the effect to the heritage group of Bakong can be expected smaller than that in the scenario 3, 4 and 5.

The maximum groundwater level drawdown is centered on the new well sites as shown in Figure 5.42 and Figure 5.43 to be 5.84 m in shallow aquifer and 5.77 m in deep aquifer, respectively. Comparing the extents of groundwater level drawdown with scenario 3, 4 and 5, it is clear that this scenario gives much smaller effect to the heritage group of Bakong, as expected.

Scenario 7

Scenario 7 is specified as stopping all groundwater production in 2016, except the existing SRWSA production wells. This is the scenario most similar to scenario1 of natural condition. Therefore, the groundwater level drawdown is centered on the existing SRWSA production well sites as shown in Figure 5.44 and Figure 5.45; with groundwater level drawdown extent and maximum drawdown degree to be the smallest in all scenarios. 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

In Siem Reap, groundwater recharge amount has been calculated to be nearly 6 times of water demand. Form the view point of the balance between the development amount and recharge amount, there would not be any problem in using groundwater as the source for water supply in Siem Reap.

However, the water balance is not the only applicable standard when evaluating the groundwater development plans. After the standard of water balance has been cleared, the next indispensable task is to examine the effect groundwater development has on the environment. As the effect depends on the content of the groundwater development plan, firstly plans must be formulated in order to evaluate their effect. Several considerable plans have been formulated by taking all the relative factors into consideration, such as: minimizing the effect on the heritage sites, setting wells in an appropriate elevation, balancing the production amount and aquifer capability, making the facilities' management easy, reducing project costs, and so on. The evaluation of all the considered plans were conducted using a groundwater simulation model with parameters specified on the basis of all available data and analysis results.

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 5.7.

Table 5.7 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 evaluation degree 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 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, which is within the land displacement range in each year as shown in the observation well of LTa and LTb (refer to Table 4.4 and Table 4.6). 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 5.24 to Figure 5.33). For a clay created work on a scale of several km^2 like West Baray, the plasticity is more than enough to compensate for land subsidence on a magnitude not more than 4.19 mm in a period of several months. Therefore, not only the deformation would not be detected, because 4.19 mm is too small to be perceived by humans in a work 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.

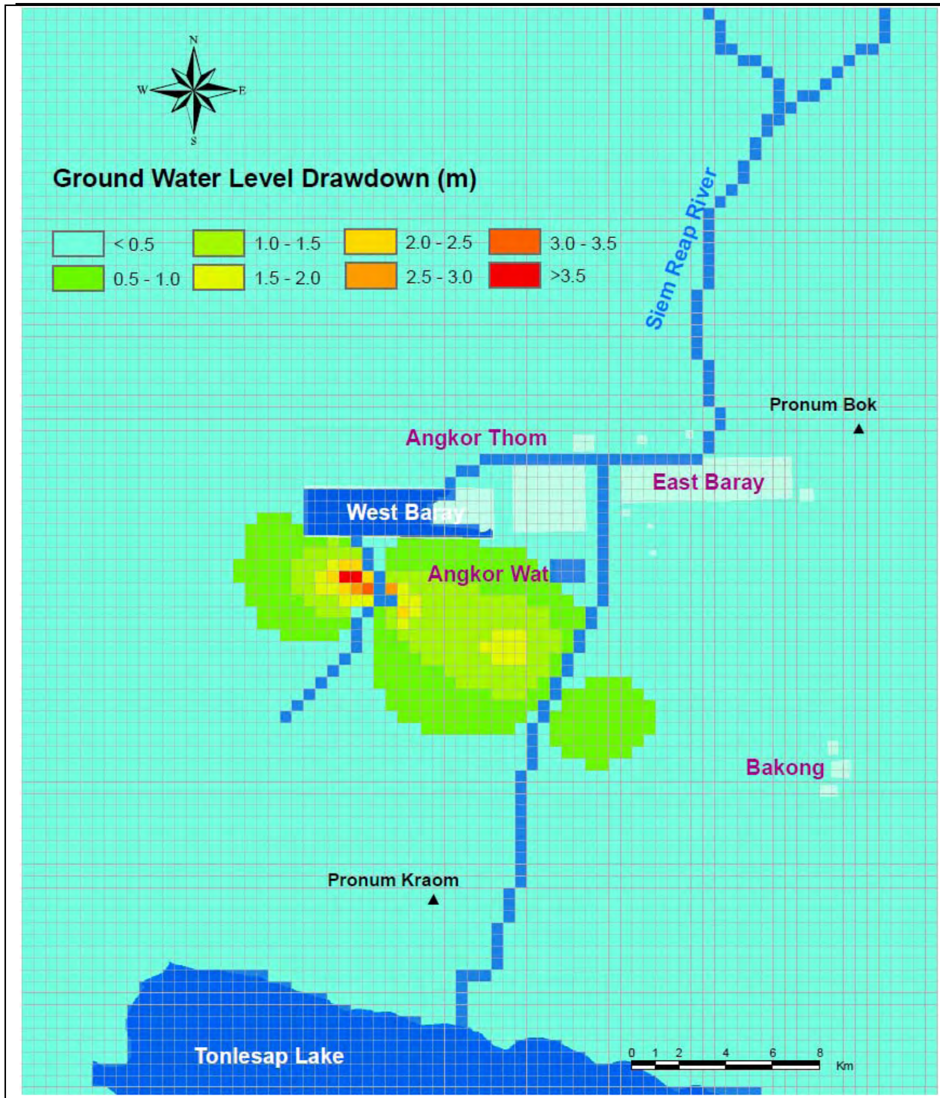

Figure 5.34 Groundwater Level Drawdown in Shallow Aquifer (Scenario 1-Scenario 2)

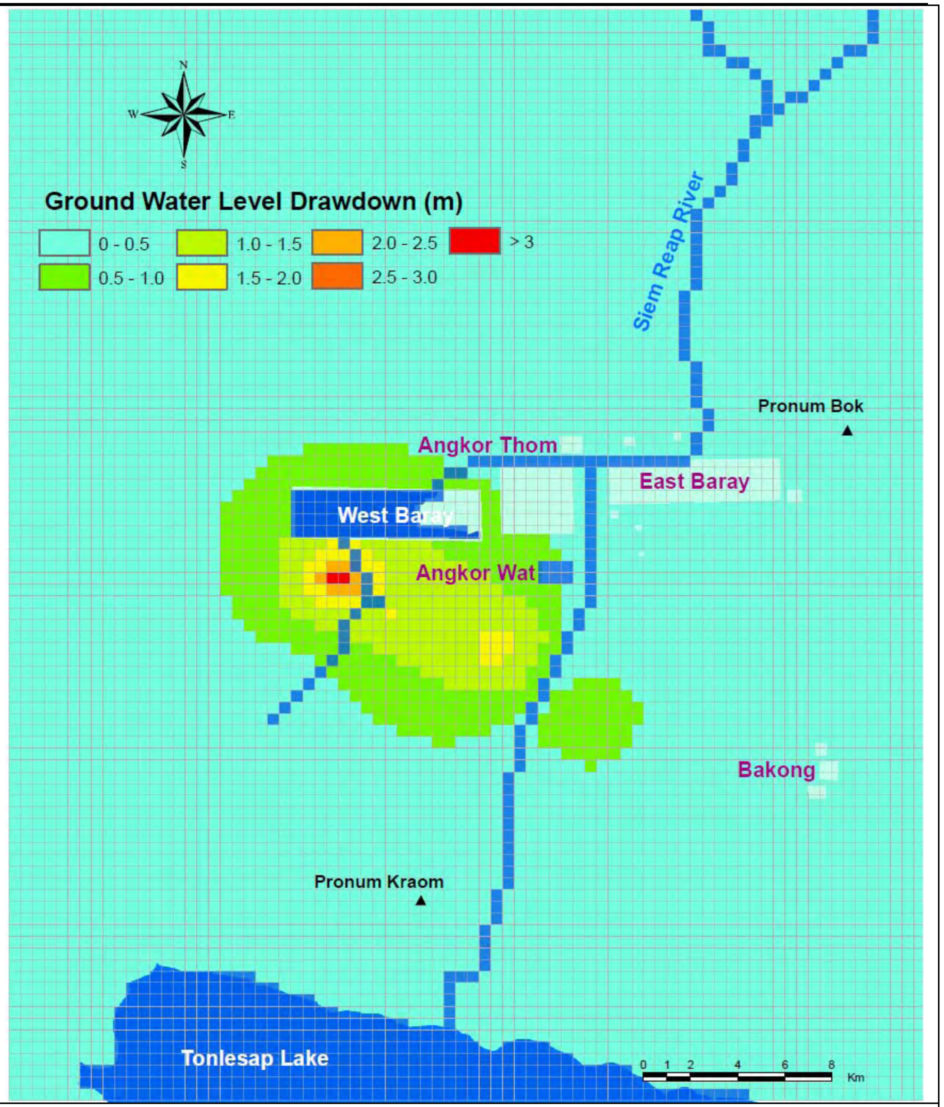

Figure 5.35 Groundwater Level Drawdown in Deep Aquifer (Scenario 1-Scenario 2)

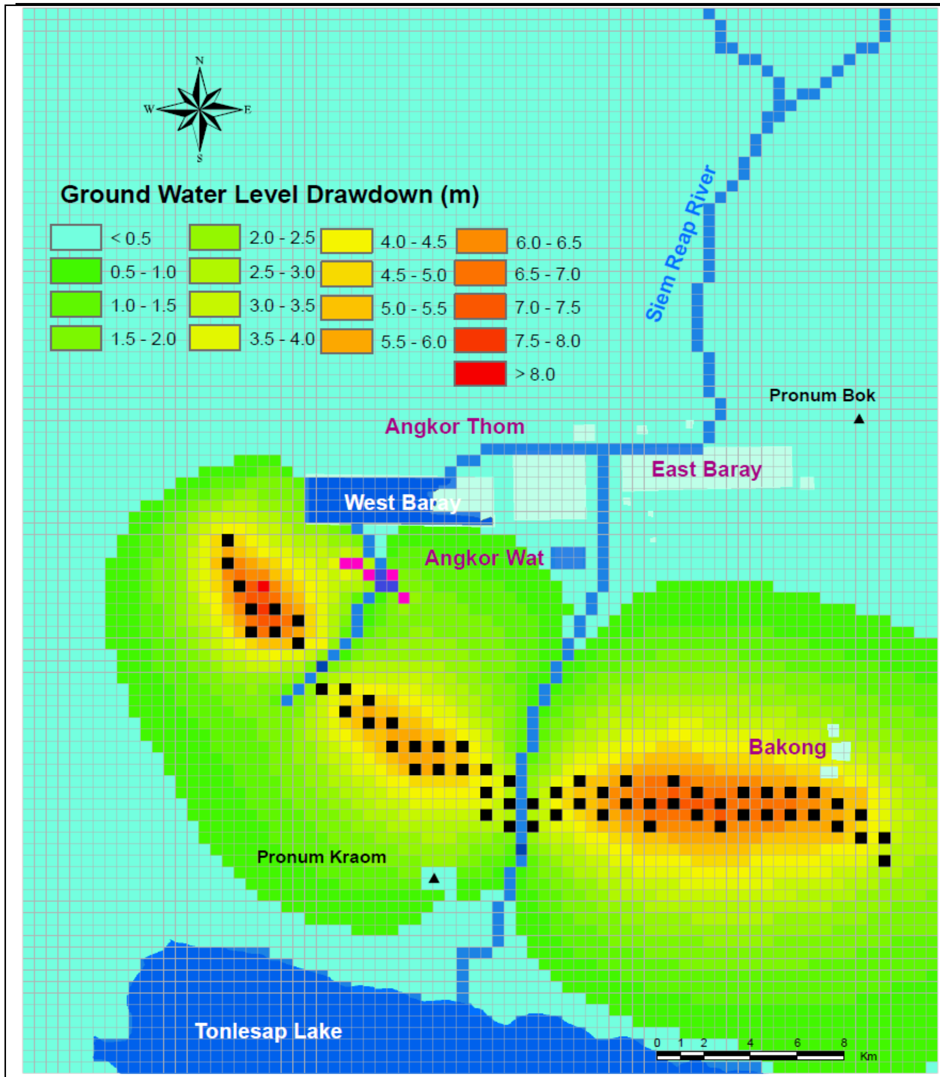

Figure 5.36 Groundwater Level Drawdown in Shallow Aquifer (Scenario 1-Scenario 3)

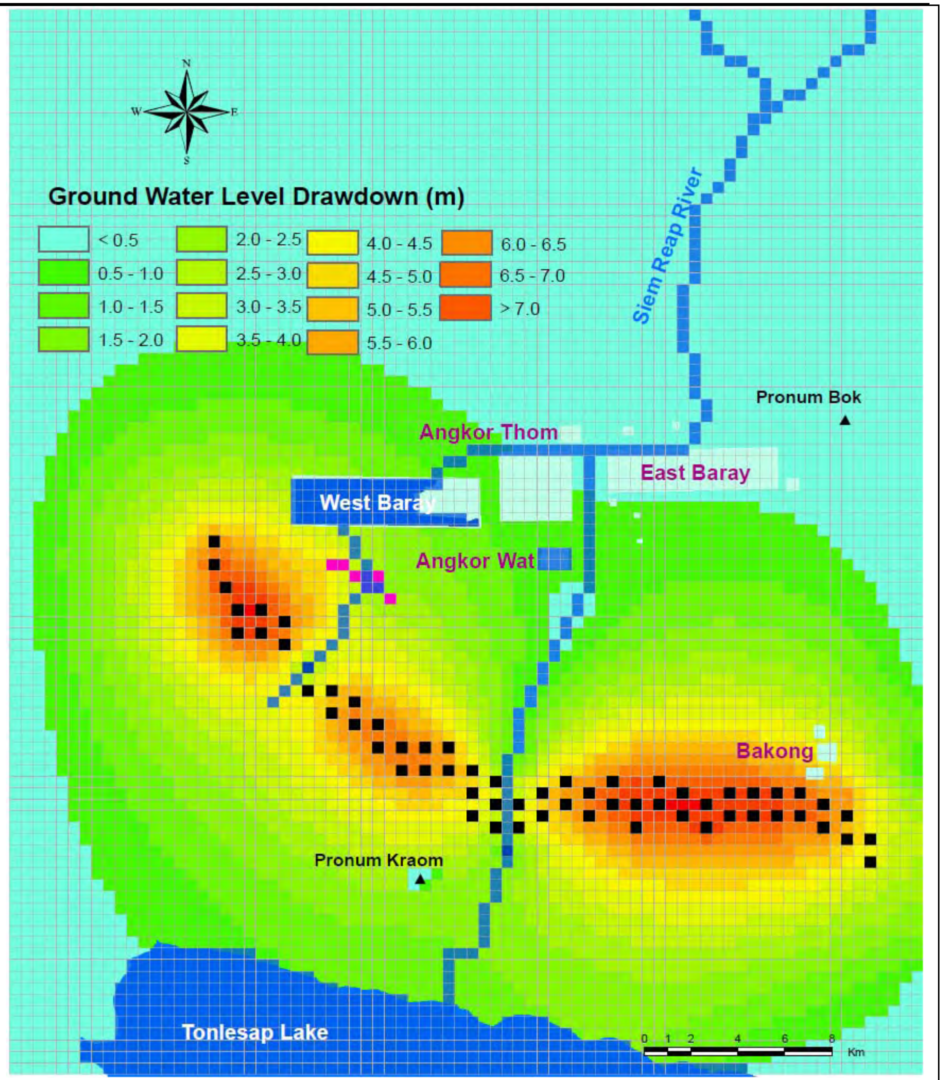

Figure 5.37 Groundwater Level Drawdown in Deep Aquifer (Scenario 1-Scenario 3)

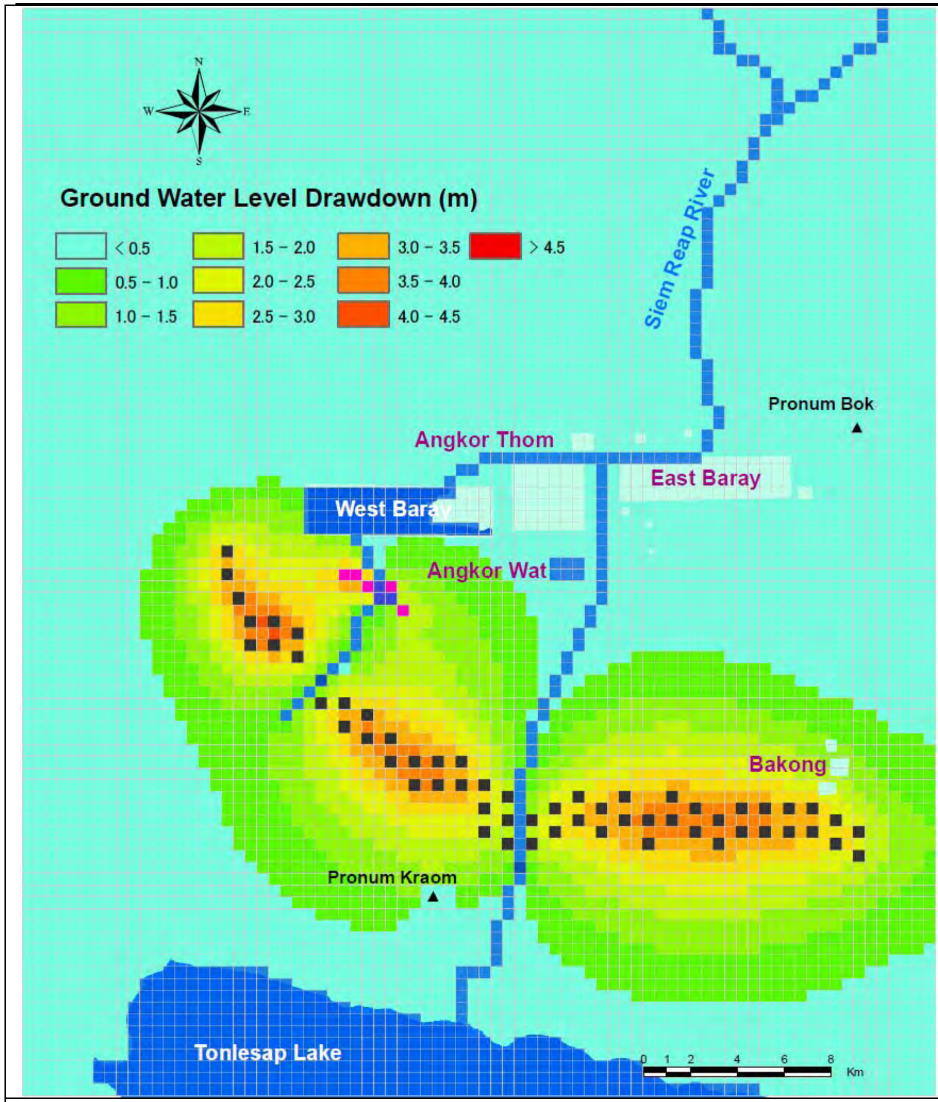

Figure 5.38 Groundwater Level Drawdown in Shallow Aquifer (Scenario 1-Scenario 4)

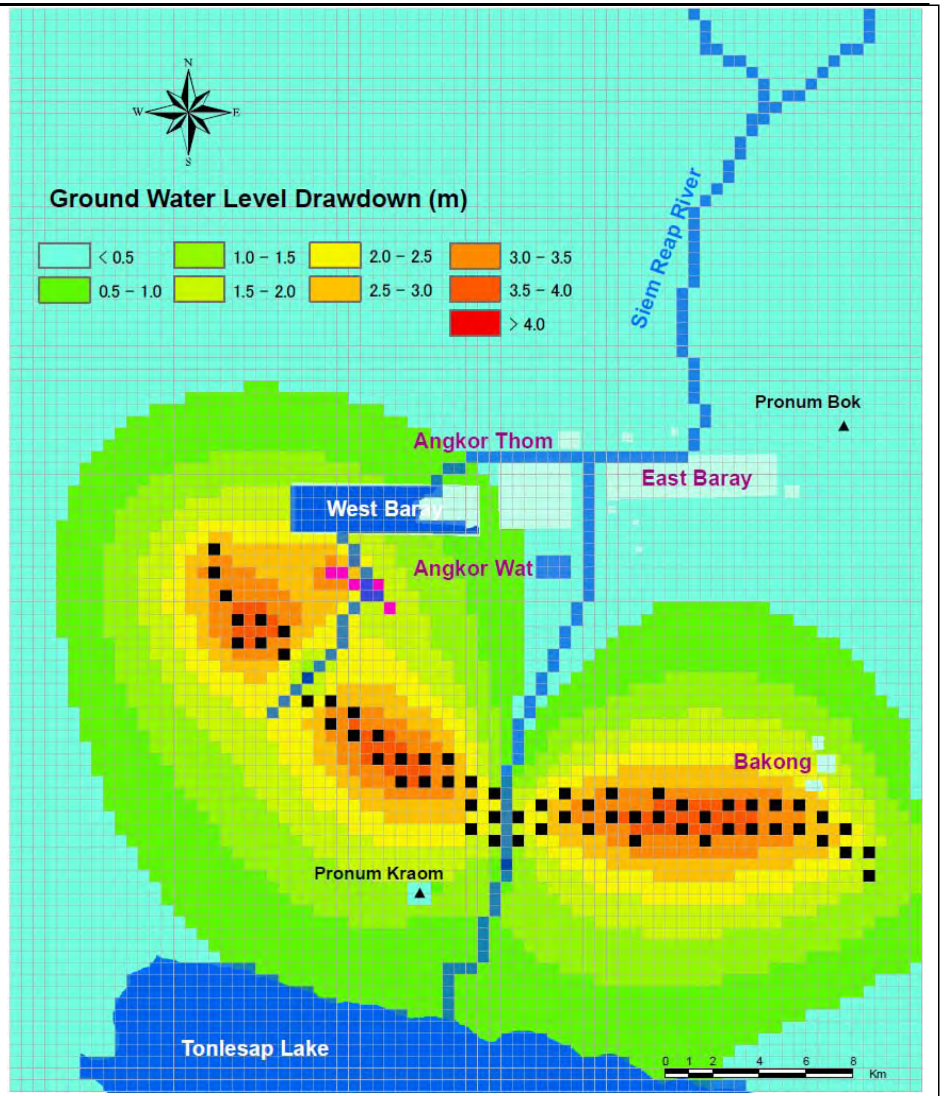

Figure 5.39 Groundwater Level Drawdown in Deep Aquifer (Scenario 1-Scenario 4)

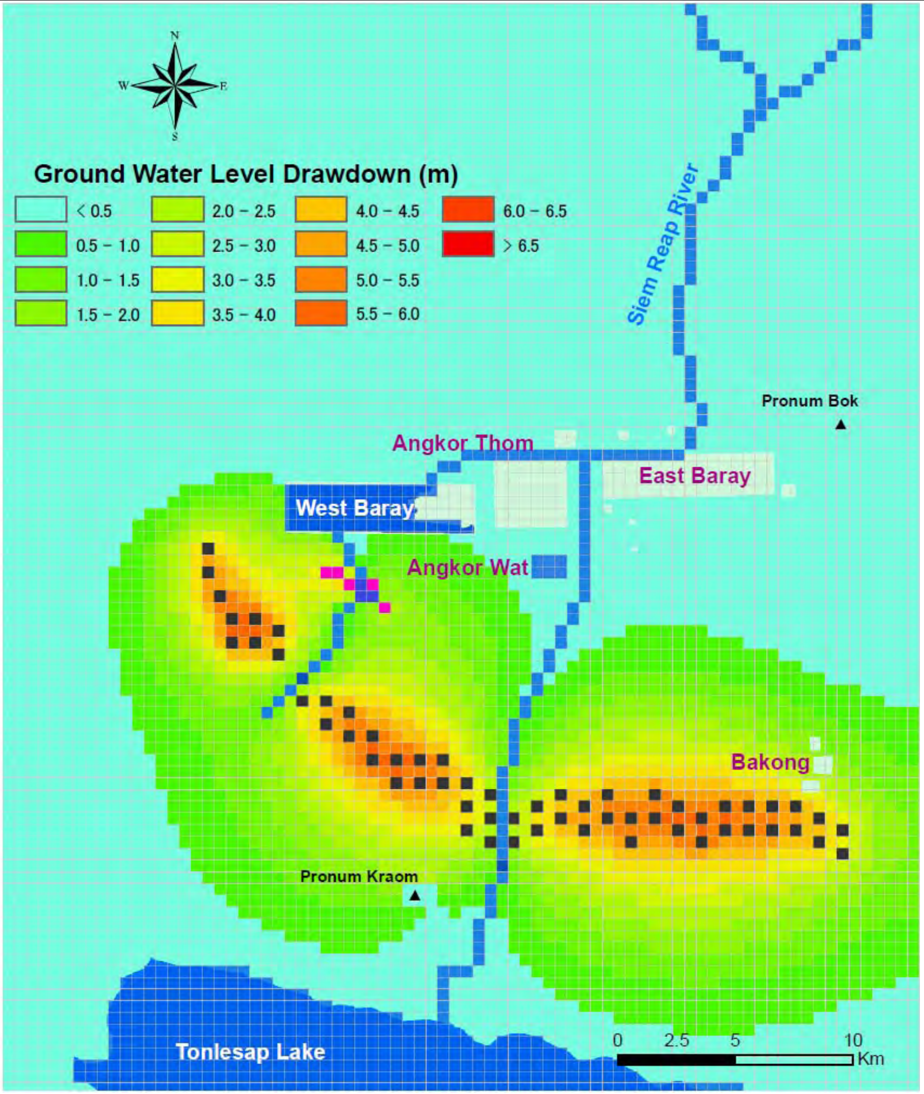

Figure 5.40 Groundwater Level Drawdown in Shallow Aquifer (Scenario 1-Scenario 5)

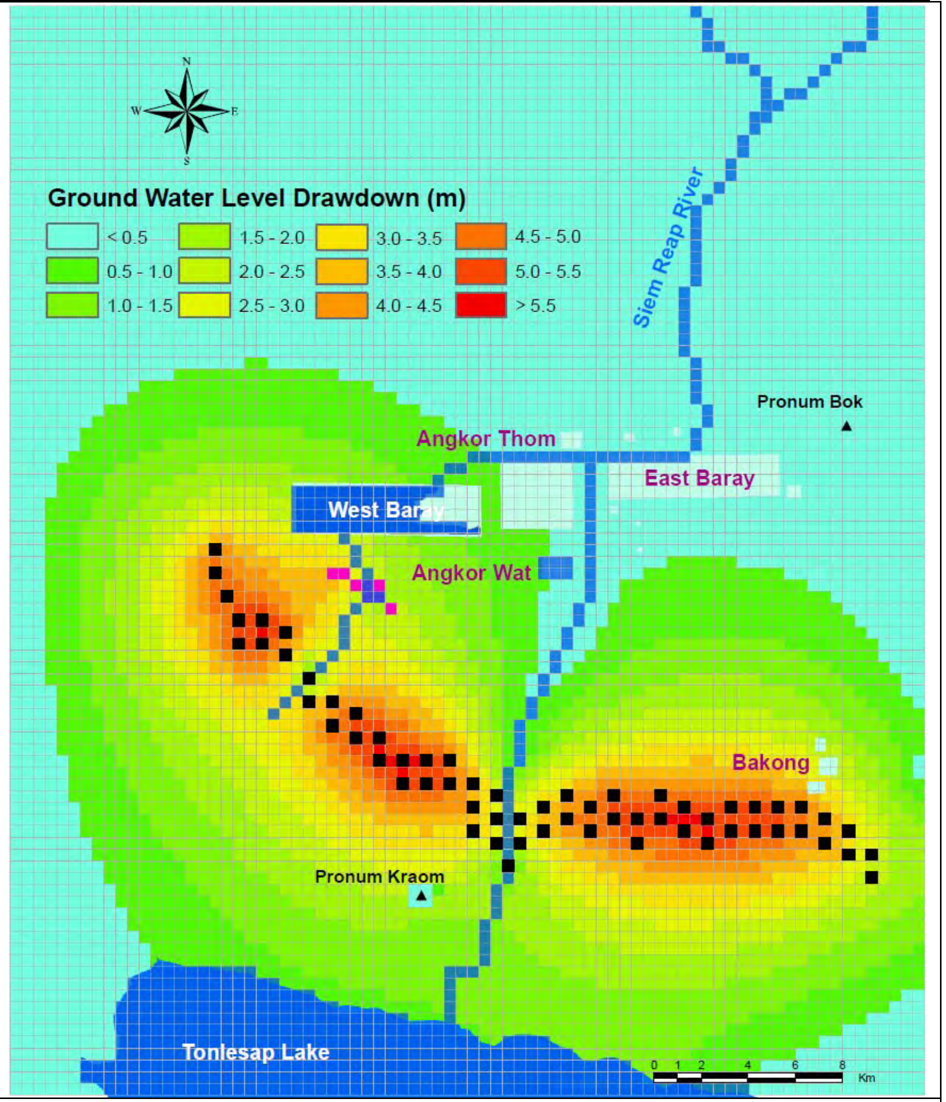

Figure 5.41 Groundwater Level Drawdown in Deep Aquifer (Scenario 1-Scenario 5)

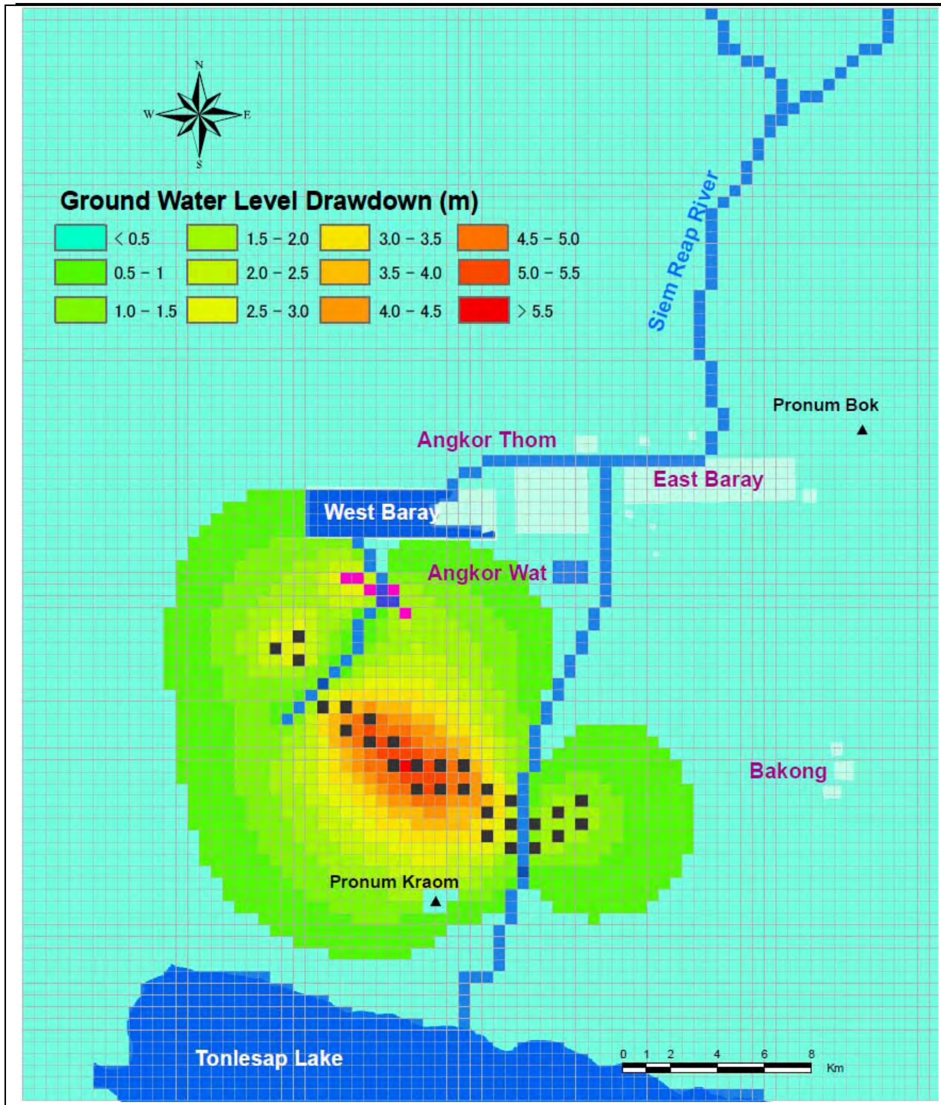

Figure 5.42 Groundwater Level Drawdown in Shallow Aquifer (Scenario 1-Scenario 6)

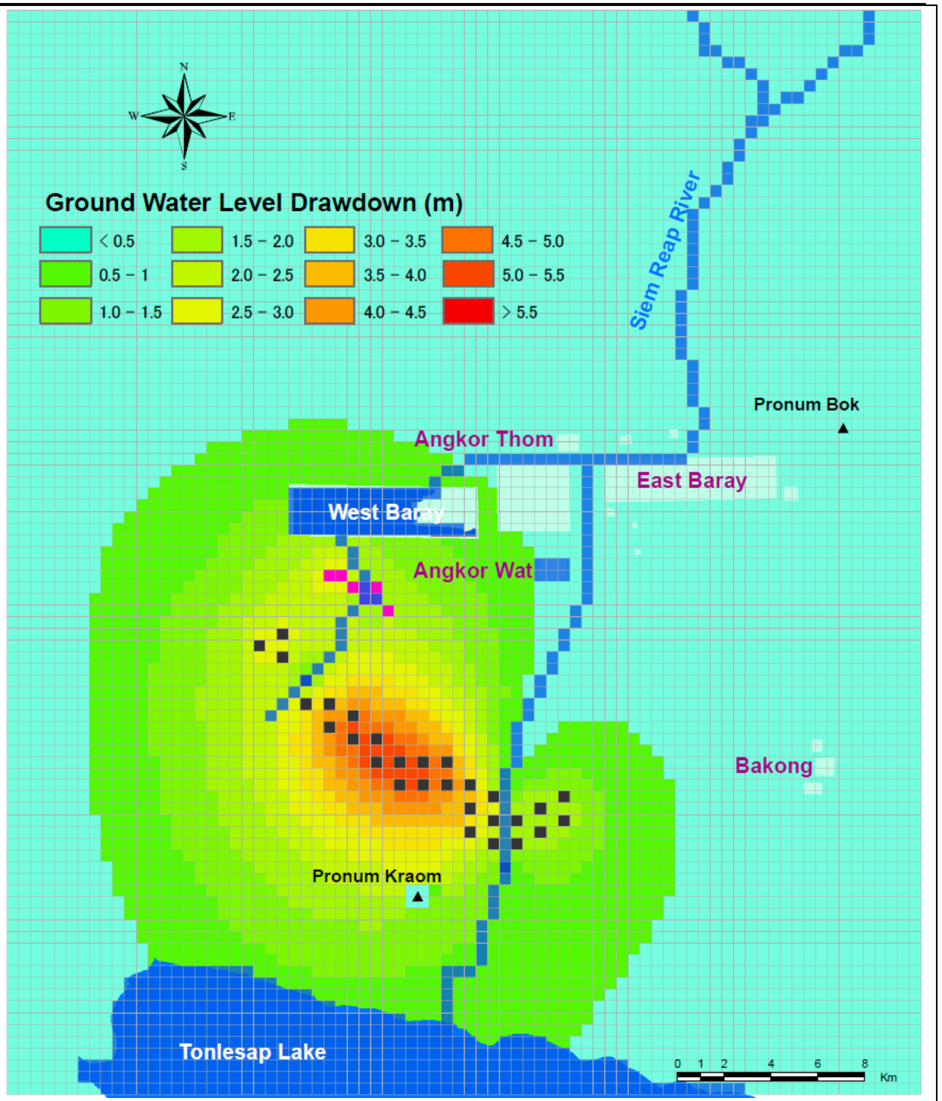

Figure 5.43 Groundwater Level Drawdown in Deep Aquifer (Scenario 1-Scenario 6)

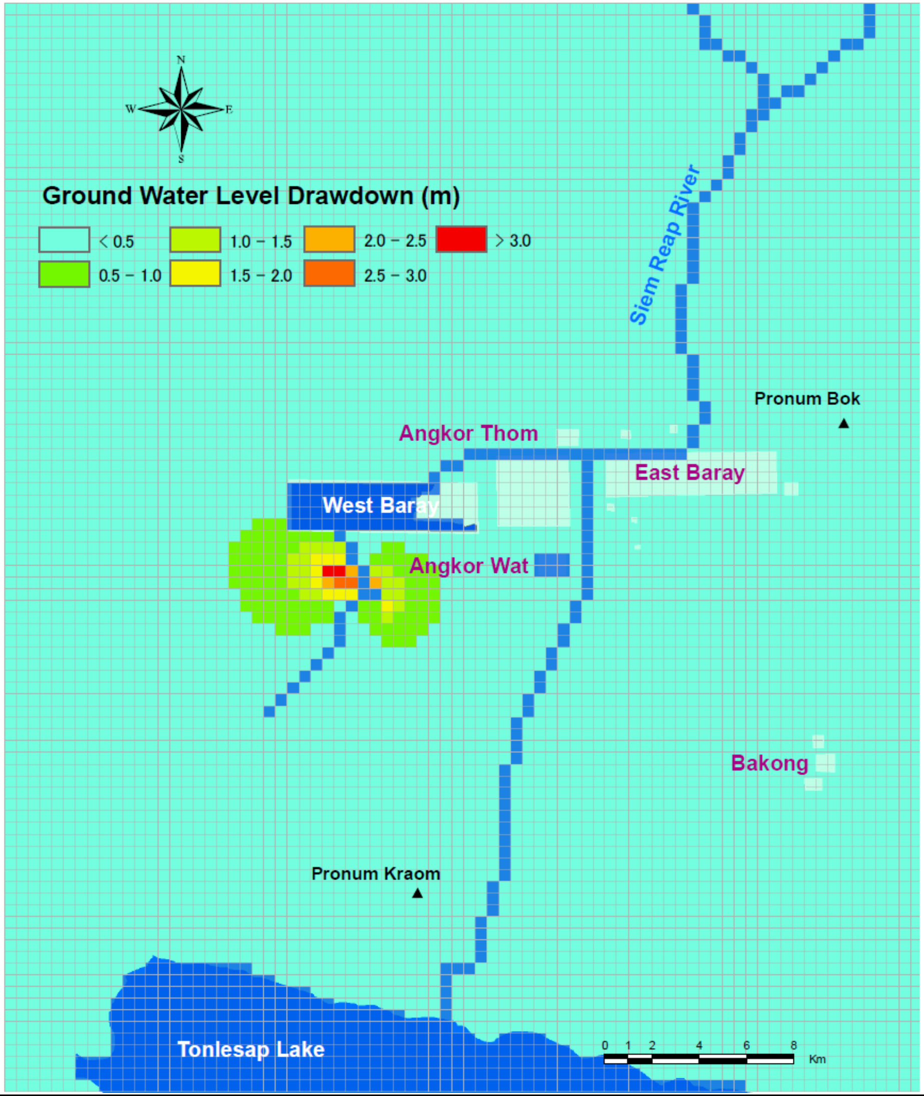

Figure 5.44 Groundwater Level Drawdown in Shallow Aquifer (Scenario 1-Scenario 7)

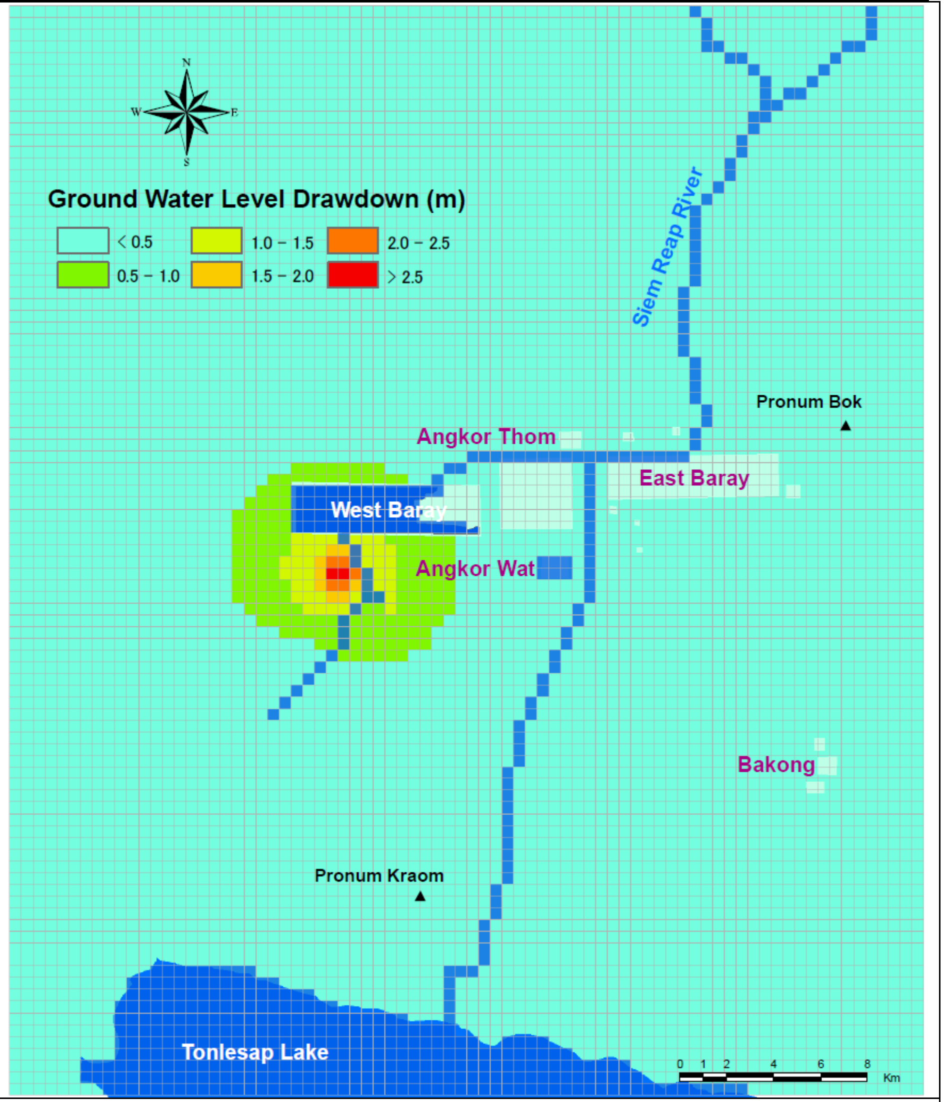

Figure 5.45 Groundwater Level Drawdown in Deep Aquifer (Scenario 1-Scenario 7)

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 m^3/day is presently at least extracted in the city area.

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

To identify this phenomenon, monitoring data of groundwater level of existing observation wells were analyzed. As a result, in monitoring data, small fluctuation of groundwater level influenced by pumping wells near monitoring wells was identified but constant and large drawdown of groundwater level was not observed. In addition, lowering of groundwater level by pumping of SRWSA production wells in WT-4 monitoring well was not observed. WT-4 well is located along National Road No.6 and apart about 2.6 km from SRWSA wells. As a result, the influence of groundwater withdrawal was not identified under existing conditions.

To review the influence to world heritage in future water demand, groundwater simulation was conducted. In this simulation, the following 6 scenarios to deal with future water demand (86,000 m^3/day) for water supply planning year 2030 were prepared and reviewed.

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

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

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

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

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

(2) Enforcement of Monitoring System

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

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

6-2 Recommendation

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

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

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

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

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

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