5. Influence of a New Groundwater Development Plan

If steady pumping is implemented and maintained, the groundwater level of the aquifer will reach a certain level and, once achieved, will be maintained forever (discounting seasonal and daily changes, and assuming other recharge and boundary conditions remain constant). To evaluate influence on the surrounding area by pumping from a new well, steady-state simulations were made for 1) without the new well (present condition) and 2) with the new well, assuming the last 10 years climatic condition will continue for the time being. Both results were then compared.

Location of production wells

Place: South of West Baray and near Siem Reap airport

Plan of groundwater withdrawal:

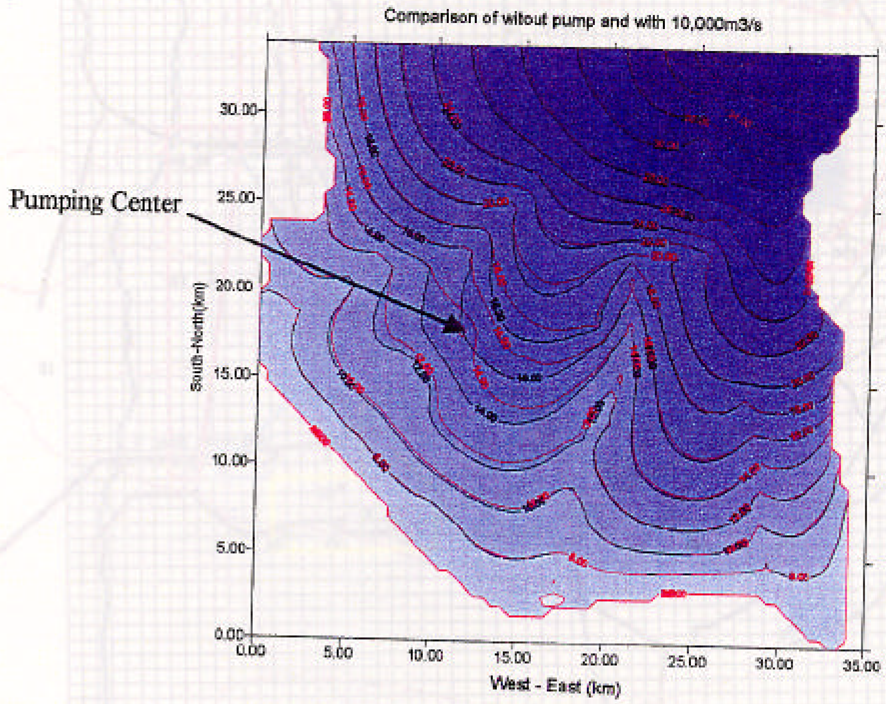
Case-1: 5,000 cubic meter per day, which is equivalent to 50,000 persons' water requirement.

Case-2: 10,000 cubic meter per day

Case-3: 15,000 cubic meter per day

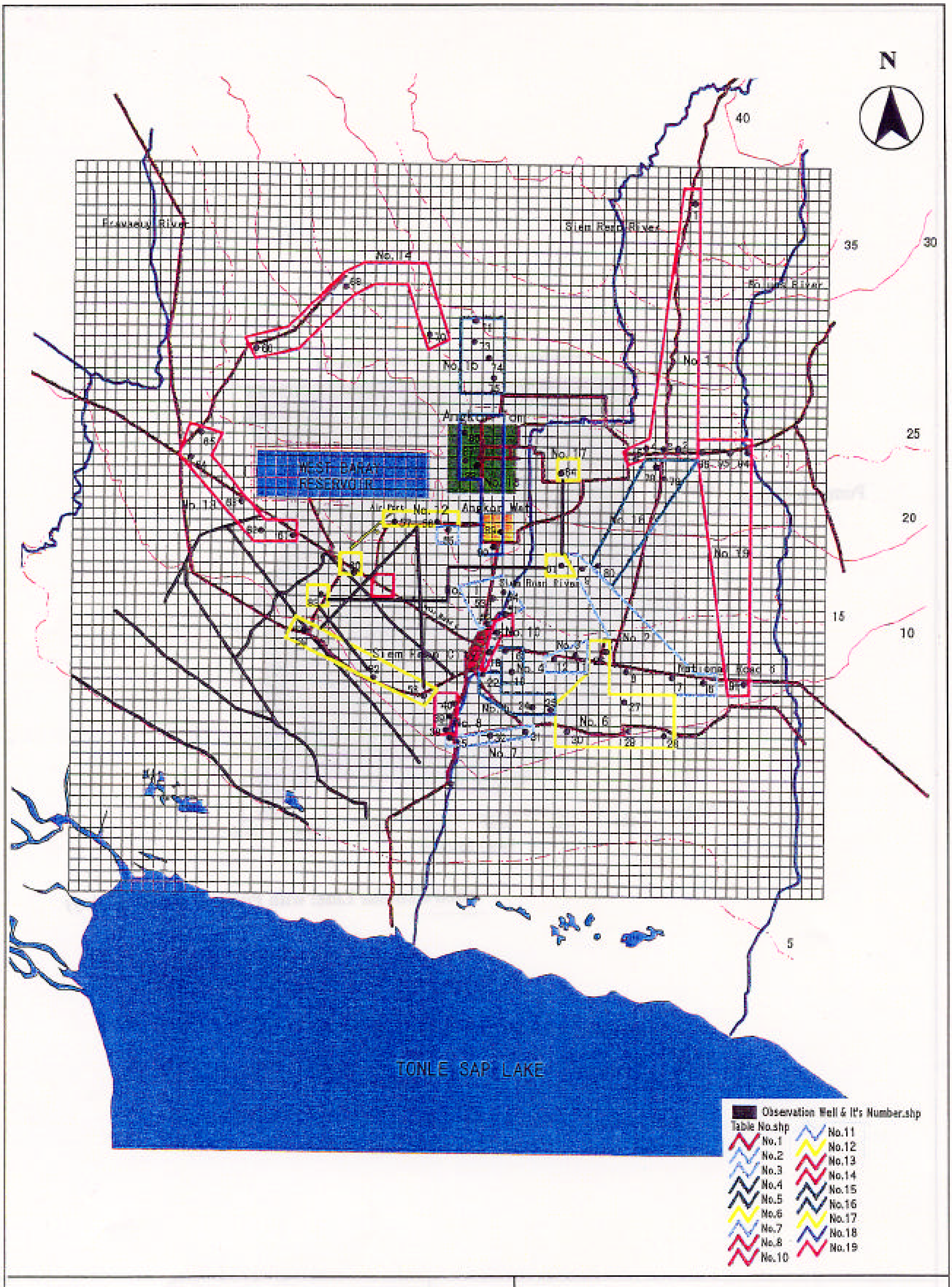
1) Simulation Results

Figure 5.1 shows the simulated groundwater levels for the Case-2, a) with pumping, represented by red contour lines, and b) without pumping, represented by black contour lines, respectively. Table 5.1 shows the details for every observation well whose location is shown in Figure 5.2.



(Red Contour Line: with Pump of 10,000 m^3/day)

The Study on Water Supply System for Siem Reap Region in Cambodia	Figure 5.1 Comparison with Case-2 and the Present Condition
Japan International Cooperation Agency	



The Study on Water Supply System for Siem Reap Region in Cambodia	Figure 5.2 Location of Observation Wells
Japan International Cooperation Agency	

Table 5.1(1/2) Influence by Groundwater Withdrawal

	coordinates		Present condition	with pump ($5000m^3$/day)	Drawdown	with pump ($10000m^3$/day)	Drawdown	with pump ($15000m^3$/day)	Drawdown
no.	I	J	GWL(m)	GWL(m)	GWL(m)	GWL(m)	GWL(m)	GWL(m)	GWL(m)
0	33	24	16.04	13.28	2.76	10.61	5.43	7.68	8.36
1	5	58	36.85	36.85	0	36.85	0	36.85	0
2	27	57	25.4	25.35	0.05	25.35	0.05	25.35	0.05
3	27	55	24.46	24.41	0.05	24.41	0.05	24.41	0.05
4	27	54	23.87	23.82	0.05	23.82	0.05	23.82	0.05
5	28	53	23.08	23.03	0.05	23.03	0.05	23.03	0.05
6	49	59	13.14	13.12	0.02	13.12	0.02	13.12	0.02
7	48	56	14.57	14.52	0.05	14.52	0.05	14.52	0.05
8	48	52	15.57	15.46	0.11	15.46	0.11	15.46	0.11
9	38	48	17.71	17.62	0.09	17.62	0.09	17.62	0.09
10	40	45	15.19	15.11	0.08	15.11	0.08	15.11	0.08
11	46	47	15.52	15.39	0.13	15.39	0.13	15.39	0.13
12	47	45	14.56	14.44	0.12	14.44	0.12	14.44	0.12
13	46	44	14.27	14.16	0.11	14.16	0.11	14.16	0.11
14	46	43	13.77	13.66	0.11	13.66	0.11	13.66	0.11
15	45	41	12.73	12.65	0.08	12.65	0.08	12.65	0.08
16	46	41	12.81	12.72	0.09	12.72	0.09	12.72	0.09
17	49	42	12.96	12.86	0.1	12.86	0.1	12.86	0.1
18	48	42	13.14	13.04	0.1	13.04	0.1	13.04	0.1
19	46	39	11.94	11.91	0.03	11.91	0.03	11.91	0.03
20	47	40	12.33	12.27	0.06	12.27	0.06	12.27	0.06
21	47	39	11.89	11.86	0.03	11.86	0.03	11.86	0.03
22	48	39	11.84	11.79	0.05	11.79	0.05	11.79	0.05
23	50	42	12.72	12.63	0.09	12.63	0.09	12.63	0.09
24	51	43	12.8	12.71	0.09	12.71	0.09	12.71	0.09
25	51	45	13.42	13.31	0.11	13.31	0.11	13.31	0.11
26	46	50	16.28	16.15	0.13	16.15	0.13	16.15	0.13
27	50	52	14.62	14.51	0.11	14.51	0.11	14.51	0.11
28	54	56	11.43	11.4	0.03	11.4	0.03	11.4	0.03
29	53	52	13.07	12.98	0.09	12.98	0.09	12.98	0.09
30	53	46	12.78	12.7	0.08	12.7	0.08	12.7	0.08
31	53	43	12.06	11.99	0.07	11.99	0.07	11.99	0.07
32	54	40	10.62	10.58	0.04	10.58	0.04	10.58	0.04
33	54	37	9.26	9.25	0.01	9.25	0.01	9.25	0.01
34	57	37	8.54	8.53	0.01	8.53	0.01	8.53	0.01
35	54	36	9.04	9.04	0	9.04	0	9.04	0
36	57	35	8.42	8.41	0.01	8.4	0.02	8.4	0.02
37	59	36	7.17	7.17	0	7.17	0	7.17	0
38	53	35	9.25	9.21	0.04	9.21	0.04	9.2	0.05
39	52	36	8.71	8.7	0.01	8.7	0.01	8.7	0.01
40	50	36	10.27	10.24	0.03	10.23	0.04	10.23	0.04
41	49	37	11.08	11.08	0	11.08	0	11.08	0
42	47	37	11.17	11.16	0.01	11.16	0.01	11.16	0.01
43	44	35	13.04	12.76	0.28	12.69	0.35	12.63	0.41
44	43	34	13.66	13.32	0.34	13.23	0.43	13.13	0.53
45	42	32	14.36	13.95	0.41	13.8	0.56	13.66	0.7
46	47	38	11.51	11.51	0	11.51	0	11.51	0
47	46	39	11.94	11.91	0.03	11.91	0.03	11.91	0.03
48	39	29	15.54	14.93	0.61	14.64	0.9	14.35	1.19
49	45	36	12.34	12.11	0.23	12.07	0.27	12.03	0.31
50	44	40	11.97	11.93	0.04	11.93	0.04	11.93	0.04

Table 5.1(2/2) Influence by Groundwater Withdrawal

	coordinates		Present condition	with pump (5000m³/day)	Drawdown	with pump (10000m³/day)	Drawdown	with pump (15000m³/day)	Drawdown
no.	I	J	GWL(m)	GWL(m)	GWL(m)	GWL(m)	GWL(m)	GWL(m)	GWL(m)
51	42	41	12.01	11.95	0.06	11.95	0.06	11.95	0.06
52	43	39	11.85	11.83	0.02	11.83	0.02	11.83	0.02
53	41	40	11.46	11.45	0.01	11.45	0.01	11.45	0.01
54	40	40	12.17	12.1	0.07	12.08	0.09	12.06	0.11
55	35	35	17.31	16.87	0.44	16.69	0.62	16.51	0.8
56	34	35	17.87	17.44	0.43	17.25	0.62	17.07	0.8
57	34	30	17.78	17.02	0.76	16.59	1.19	16.15	1.63
58	50	33	11.02	10.83	0.19	10.8	0.22	10.77	0.25
59	44	22	12.25	11.96	0.29	11.83	0.42	11.69	0.56
60	38	27	15.49	14.75	0.74	14.35	1.14	13.94	1.55
61	35	21	14.04	13.25	0.79	12.67	1.37	12.07	1.97
62	35	18	12.65	12.25	0.4	11.98	0.67	11.71	0.94
63	32	16	12.76	12.41	0.35	12.22	0.54	12.03	0.73
64	28	12	10.32	10.27	0.05	10.25	0.07	10.24	0.08
65	25	12	11.44	11.38	0.06	11.38	0.06	11.38	0.06
66	18	18	18.71	18.55	0.16	18.54	0.17	18.54	0.17
67	16	21	20.92	20.76	0.16	20.76	0.16	20.76	0.16
68	12	26	24.44	24.3	0.14	24.3	0.14	24.29	0.15
69	11	29	25.72	25.59	0.13	25.59	0.13	25.58	0.14
70	16	33	24.3	24.24	0.06	24.23	0.07	24.22	0.08
71	15	38	27.03	26.89	0.14	26.88	0.15	26.87	0.16
72	16	39	26.75	26.59	0.16	26.58	0.17	26.57	0.18
73	17	38	25.95	25.8	0.15	25.78	0.17	25.76	0.19
74	18	39	25.56	25.39	0.17	25.37	0.19	25.35	0.21
75	20	40	24.32	24.16	0.16	24.14	0.18	24.12	0.2
76	21	45	23.62	23.55	0.07	23.54	0.08	23.53	0.09
77	21	50	24.59	24.58	0.01	24.58	0.01	24.58	0.01
78	28	55	24.18	24.12	0.06	24.12	0.06	24.12	0.06
79	29	55	23.9	23.83	0.07	23.83	0.07	23.83	0.07
80	38	49	18.31	18.2	0.11	18.2	0.11	18.2	0.11
81	37	46	16.35	16.29	0.06	16.29	0.06	16.29	0.06
82	48	29	12.22	11.94	0.28	11.86	0.36	11.78	0.44
83	40	24	13.92	13.38	0.54	13.09	0.83	12.8	1.12
84	29	46	18.3	18.25	0.05	18.25	0.05	18.25	0.05
85	29	44	16.44	16.4	0.04	16.4	0.04	16.4	0.04
86	25	37	20.98	20.79	0.19	20.71	0.27	20.64	0.34
87	28	37	19.79	19.56	0.23	19.47	0.32	19.37	0.42
88	28	38	19.47	19.27	0.2	19.19	0.28	19.11	0.36
89	34	40	15.84	15.69	0.15	15.64	0.2	15.59	0.25
90	36	40	14.22	14.07	0.15	14.03	0.19	13.98	0.24
91	49	63	12.67	12.61	0.06	12.61	0.06	12.61	0.06
92	39	65	18.31	18.29	0.02	18.29	0.02	18.29	0.02
93	32	64	22.08	22.04	0.04	22.04	0.04	22.04	0.04
94	27	63	23.67	23.67	0	23.67	0	23.67	0
95	27	61	25.49	25.46	0.03	25.46	0.03	25.46	0.03
96	27	59	25.91	25.86	0.05	25.86	0.05	25.86	0.05

Note: Well no. 0 means a new production well.

The groundwater drawdown caused by new wells means the average values in the 500 m cell. The results are summarized below:

Drawdown in The production well(no.0)		Drawdown caused by pumping at Angkor Wat and Angkor Thom area
Case 1	2.3m	15-20cm
Case 2	5.5m	20-30cm
Case 3	8.5m	30-40cm

6. Perennial-yield Pumping Plan

1) Combined Simulation and Optimization Model

The combined simulation and optimization (S/O) model was used to optimize the perennial-yield pumping for the Siem Reap region. The combined model can predict the behavior of a complex aquifer (a multi-layer, unconfined/confined) and optimizes the perennial–yield pumping plan for the specified objectives and constraints. The model was written in the GAMS (General Algebraic Modeling System (GAMS) language. Optimization was performed with the MINOS LP solver using an advanced simplex method.

2) Model Components

The spatial distribution of the model used in the steady-state simulation is directly involved in the S/O model. The following object function and constraints were used for the model.

Objective function. The objective function of the model is to maximize total groundwater extraction

$$CR_{l,i,j+1/2}(h_{l,i,j+1}-h_{l,i,j})+CR_{l,i,j-1/2}(h_{l.i,j-1}-h_{l,i,j})$$
$$+CC_{l,i+1/2,j}(h_{l,i+1,j}-h_{l,i,j})+CC_{l,i-1/2},j(h_{l,i-1,j}-h_{l.i,j})$$
$$+CV_{l+1/2,i,j}(h_{l+1,i,j}-h_{l,i,j})+CV_{l-1/2,i,j}(h_{l-1,i,j}-h_{l,i,j})$$
$$=\sum^{N}_{n-1}q^{*}_{l,j,j}$$

where,

$$CR_{l,i,j+1/2}=2dx_j(T^j_{l,i,j}\ T^j_{l,i,j+1})/(T^j_{l,i,j}dy_{i+1}+T^j_{l,i,j+1}dy_i)$$
$$CC_{l,i+1/2,j}=2dy_i(T^i_{l,i,j}\ T^i_{l,i+1,j})/(T^i_{l,i,j}dx_{j+1}+T^j_{l,i+1,j}dx_j)$$
$$CV_{l+1/2,i,j}=dx_jdy_i/\{(dz_1/2Kz_{l,i,j})+(dz_{l+1}/2Kz_{l+1,i,j})\}$$

$h_{l,i,j}$ potentiometric head, (L);

l,i,j layer, row, column indices of a finite different cell;

CR, CC hydraulic conductance (harmonic averages of transmissivities) along x, y axes, (L^2/T);

CV vertical conductance between the nodes, (L^2/T);

$T_{l,i,j}$ transmissivity of a cell, (L^2/T);
Transmissivity of an unconfined layer is a function of head (T=kh). Transmissivity of a confined layer is constant.

dx,dy,dz cell sizes in layer l, row i, and column j, (L);

$Kz_{l,i,j}$ vertical hydraulic conductivity, (L^2/T);

$q^*_{l,i,j,n}$ (n th) external flow term in a cell, (L^3/T);

As in MODFLOW-96, several external flows are involved in the model as constraints.

Known constant recharge (q^r). The 1976-1998 average recharge was applied in the area. This is a deep percolation estimated from the water balance around the root zone including precipitation, irrigation seepage, surface runoff, and evapotranspiration.

Drain discharge (q^d). This discharge is simulated as saturated flow using a function of the water table elevation.

$$q^d_{l,i,j} = \Gamma^d_{l,i,j}(h_{l,i,j} - B^d_{l,i,j}) \quad \text{for } h_{l,i,j} \geq B^d_{l,i,j}$$
$$= 0 \quad \text{for } h_{l,i,j} < B^d_{l,i,j}$$

where

Γ^d hydraulic conductance between the aquifer and drains, (L^2/T);

B^d bottom elevation of the drains, (L).

Stream-aquifer interflow (q^s). Flow between the aquifer and Siem Reap River is formulated as a function of the water table elevation.

$$q^s_{l,i,j} = \Gamma^s_{l,i,j}(h_{l,i,j} - \sigma_{l,i,j}) \quad \text{for } h_{l,i,j} \geq B^s_{l,i,j}$$
$$= \Gamma^s_{l,i,j}(B^s_{l,i,j} - \sigma_{l,i,j}) \quad \text{for } h_{l,i,j} < B^s_{l,i,j}$$

where

Γ^s hydraulic conductance between the aquifer and river, (L^2/T);

σ elevation of the free water surface in the river, (L):

B^s bottom elevation of the river, (L).

3) Bounds on Pumping and Head

3-a: Maximum allowable drawdown in the well field

The maximum allowable well drawdown in a cell of the candidate well field (total 69 cells) is varied from 1.00m, 2.00m, and 3.00m

3-b: Maximum allowable drawdown and pumping at the pumping location

The maximum allowable drawdown at the exact pumping center is assumed to be 10m (around 40% of the thickness of Layer 1). On the other hand, maximum pumping rates are varied from $0.02m^3$ /s and $0.01m^3$/s.

The drawdown, calculated from the finite difference model, is the average over a 500m x 500m size cell. Thus, in a cell with pumping, the drawdown at the pumping center is larger than the average. In order to estimate a groundwater drawdown by pumping at the exact point of planned production wells, Thiem's equation was applied:

$$H_w = H_{ij} - Q/2\pi T \times \ln(r_2/r_1)$$

Where,

H_w:	head of groundwater in well, (L)
H_{ij} :	head of groundwater, calculated using a finite difference model, (L)
Q :	discharge, (L^3/T)
r_2 :	equivalent well radius where actual groundwater head equals to $H_{i,j}$ (=0.208a, a=Δx), (L)
r_1 :	radius of well
T:	transmissivity

In case of H_w = 5m, H_{ij} = 15m, T = 25m x 1 x 10^{-4} m/sec and r_1 = 0.05m, Q = 0.0205 m^3/sec is estimated. Thus, the maximum of pumping is assumed to be $0.02m^3$/s for each pumping cell. This can be pumped up using two wells installed in one cell (500m x 500m) if one well can produce 600 liters/minute.

The above maximum pumping of $0.02m^3$/s is obtained, assuming one production well can produce the almost same rate of 500 liters per minute at the test well WT4 Therefore, the maximum allowable pumping rate of Q = $0.01m^3$/s were assumed as a conservative case. This can be pumped up using two wells installed in one cell if one well can produce 300 liters/minute.

3-c: Maximum allowable groundwater drawdown in Angkor heritage area

The maximum allowable groundwater drawdown in Angkor Hertage area was assumed to be 0.30m. Judging from the result of land subsidence monitoring near Angkor Wat, the drawdown of 0.30m by new production wells would cause the land subsidence of less than 1.0mm.

4) Other Considerations

4-a: Groundwater development area

The groundwater development area was limited in the area where the groundwater has low iron content and low clay content, based on the water quality and VLF sounding tests performed in this study.

4-b: Along the National Road No.6

The best access place along the National Road No.6 was selected for a planned well field from practical viewpoint.

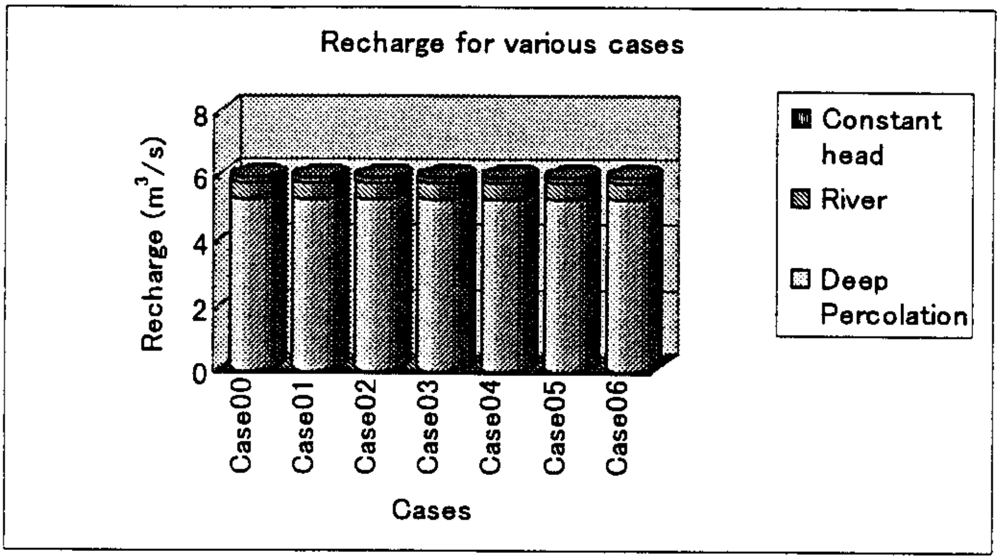
7. Optimization Results

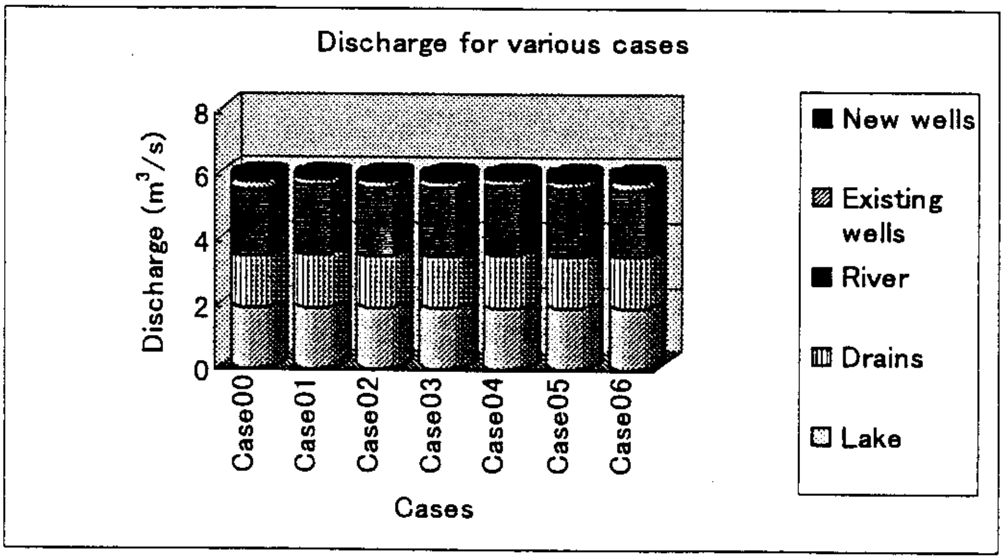
Seven cases are considered for various upper bounds on head and pumping at the pumping location. The optimal total pumping rates for 7 cases are summarized in Table 7.1. Figure 7.1 shows the water balance for all the cases. For all the cases, the ratio of pumping from the existing newly planned wells to the total discharge is 5%.

Table 7.1 Optimization Results

	GWL drawdown in Angkor area	GWL drawdown in the well field	Upper bound on allowable discharge (m^3/sec/well)	Daily Maximum allowable discharge in total	Number of pumping cells (number of wells)
Case-0	0.30 m	3.00 m	0.20	16,330	6(12)
Case-1	0.30 m	1.00 m	0.01	9,850	31(62)
Case-2	0.30 m	2.00 m	0.01	14,170	18(36)
Case-3	0.30 m	3.00 m	0.01	14,342	17(34)
Case-4	0.30 m	1.00 m	0.02	9,850	31(62)
Case-5	0.30 m	2.00 m	0.02	14,947	10(20)
Case-6	0.30 m	3.00 m	0.02	15,638	10(20)

The total of 31 wells in Case-1 and Case-4 is not economically practical because of well construction cost and land acquisition. In addition, due to more drawdown than other cases, Case-3 and Case-6 may cause stopping or less production of the shallow wells and increasing irrigation requirement in for the paddy fields near the production wells. In conclusion, the Case-5 is the best groundwater plan at present. However, the maximum allowable pumping rate should be considered around 10,500m^3 per day (70% of the pumping rate obtained from the model) since some planned production wells in the Case-5 have more discharge than that of the WT4





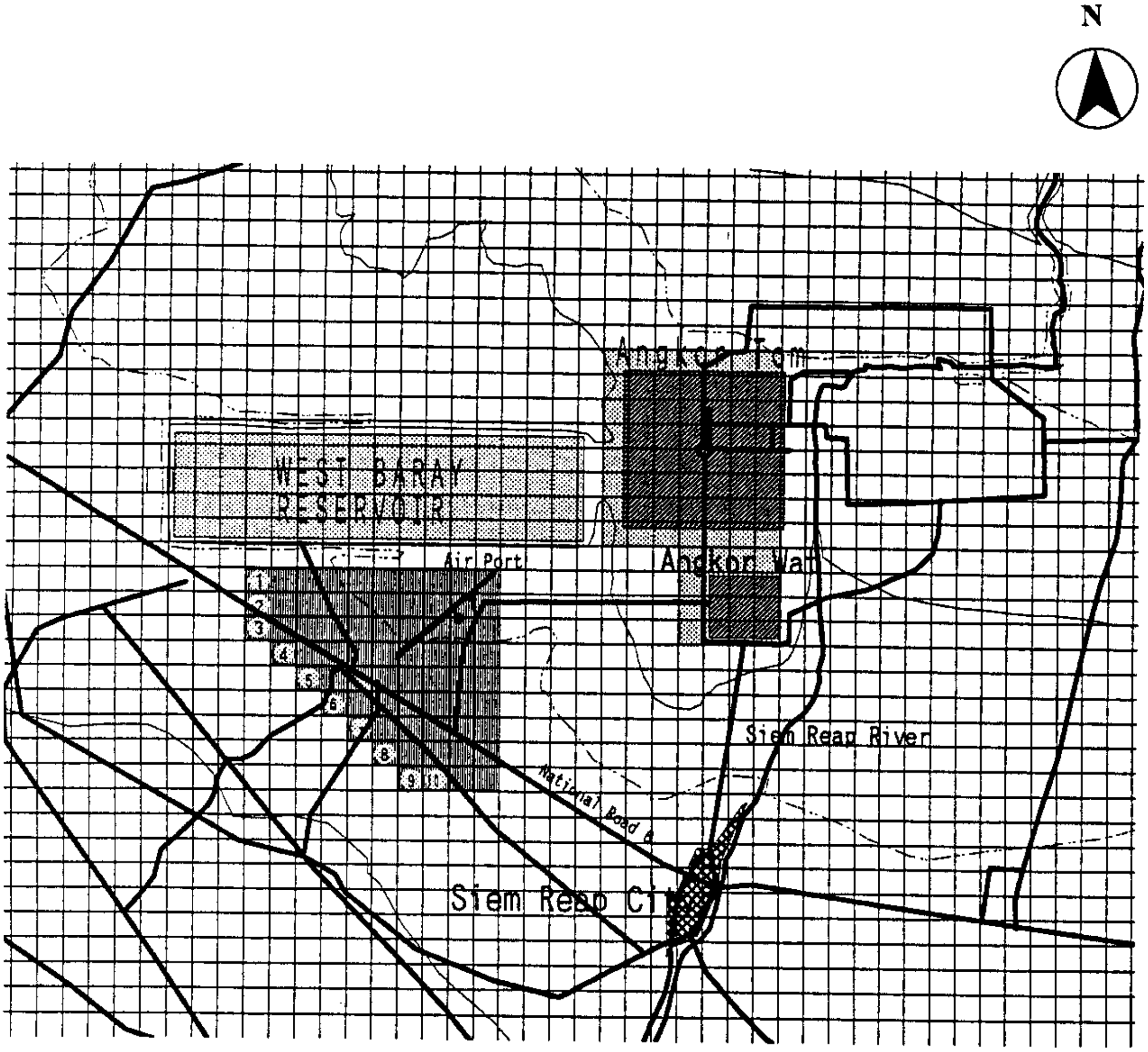
The Study on Water Supply System for Siem Reap Region in Cambodia	Figure 7.1 Water Balances for Various Cases
Japan International Cooperation Agency	

testing well). Further, more detail examination such as the production (discharge) rate and actual groundwater drawdown should be done for pilot wells, which will be constructed in the next study stage.

The details such as selected well locations and pumping rates for Case-5 are shown in Figures 7.2 and Table 7.2, respectively. The details for other cases are also shown in Attachment 6. Figure 7.3 shows the drawdowns for Case-5, comparing with the present condition (no groundwater development). In the figure, the drawdowns around the Angkor heritage and the pumping locations are less 0.30m and less than 2.0m, respectively.

Table 7.2 Spatial Distribution of Wells for Case-5 (Pumping Rate)

Well Location number	Pumping rate per second(m^3/s)	Pumping rate per minutes(m^3/min)	Pumping rate per day(m^3/day)
1	0.020	1.20	1,728
2	0.012	0.72	1,037
3	0.017	1.02	1,469
4	0.016	0.96	1,382
5	0.018	1.08	1,555
6	0.018	1.08	1,555
7	0.020	1.20	1,728
8	0.020	1.20	1,728
9	0.020	1.20	1,728
10	0.012	0.72	1,037
Total	0.173	10.38	14,947

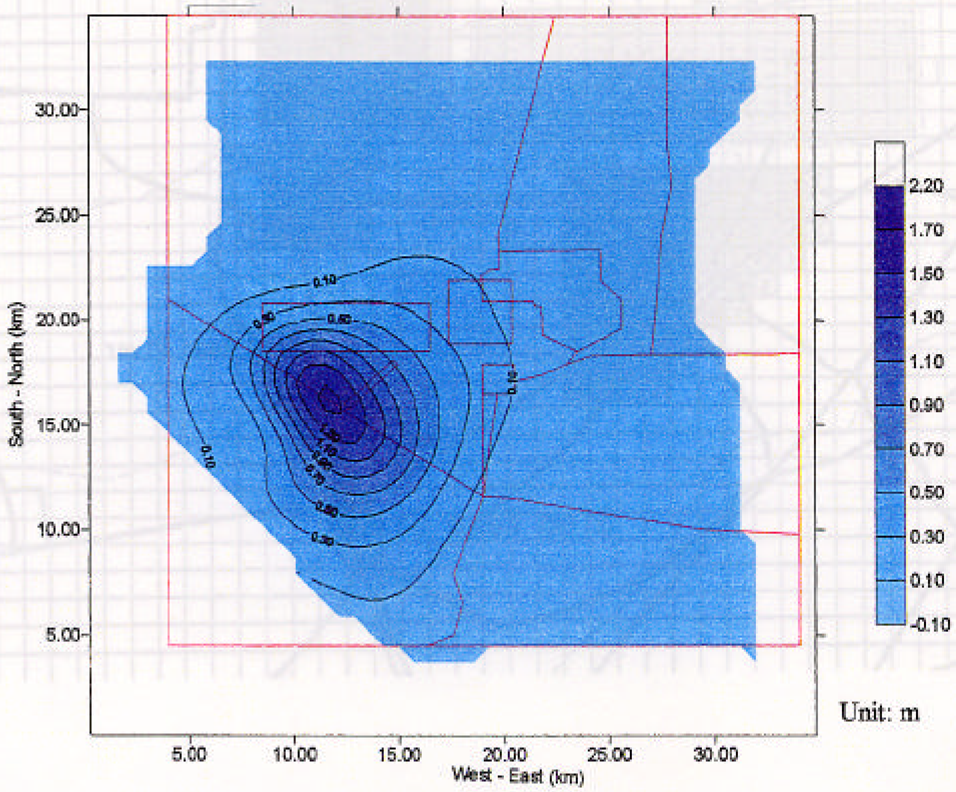


Selected well sites

Angkor Heritage area (groundwater lowering level < 0.30m)

Candidate sites for groundwater development

The Study on Water Supply System for Siem Reap Region in Cambodia	**Figure 7.2** Optimal Spatial Distribution of Wells for Case-5
Japan International Cooperation Agency	



The Study on Water Supply System for Siem Reap Region in Cambodia	**Figure 7.3 Drawdowns for Case-5**
Japan International Cooperation Agency	