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Inverse Analysis on Regional Groundwater by Tank Model: A Case Study of Osaka Plain Aquifer

タンクモデルによる地域地下水の逆解析：大阪平野地下水のケース・スタディー

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Knowledge of regional groundwater flow behavior is important in water management. However, modeling and estimation of aquifer parameters for very complex aquifer system, like the one considered here for Osaka area, by mathematical models is notoriously difficult. This paper concerns with such complex aquifer system by relatively simple model that is the tank model, so as to understand the major mechanism of such aquifer system. The major difficulty in developing such model is the trade-off between the fit of the observed data to the model response and reliability of the parameter estimation. Random start optimization procedure together with Akaike's Information Criterion, AIC, has been employed to overcome this problem. A stable model is established which is believed to be reliable to simulate the groundwater flow pattern of the Osaka plain aquifer. The results also suggest disconnection of some regional aquifers as well as inflow of seawater to the deeper layers in the studied period. A tank model associated with the optimization technique and statistical procedure proposed in the study offers a promising approach in reliably understanding the mechanism of a complex regional groundwater flow system such as studied in this paper, Osaka plain aquifer system.
***Key Words**: regional groundwater flow, tank model, AIC, parameter estimation*

1. Introduction

A common use of groundwater flow models is to predict the response of an aquifer for planned pumping and to identify the aquifer flow behavior. While the mathematical and computational aspects of such responses are reasonably well developed, the question of how to choose appropriate aquifer model and estimate reliable parameter values for such model has not been completely resolved. Measurement of parameters like transmissivities in three dimensional space and at each point of the aquifer are difficulty to obtain, especially when one is dealing with regional study[1].

Therefore the focus of this paper is the practical implementation of the tank model method for regional groundwater flow analysis. Tank model in water resources was originally developed by Sugawara[2] for rainfall-runoff modeling. The advantage of the tank model lies on its simplicity and does not require much information of the catchment or aquifer. Difficulties in the tank model exist in the optimization of the parameters. However, optimization techniques are well developed and one needs to select a method and procedures to solve the problem of local optima[3].

1.1. Description of the Osaka Plain Aquifer

Osaka area is located in the Osaka plain as shown in Figure 1. The plain is surrounded by Rokko mountains and Senri hills in the north. The Ikoma mountains that stretch to the south to join with the Kongo mountains and Sensyu hills bind the eastern part. The plain is divided into two basins by Uemachi upland running south from the north, this was formed by fault movements.

The geology of the region is one of the typical Quaternary basins in Japan. The first layer below the ground surface is an Alluvial layer. The average thickness of this Alluvial layer is about 25-30 (m) as presented in Figure 2. The thickness becomes greater as it approaches the coastal zone. Below the Alluvium is a bed of Clay layer of about 10-15 (m) followed by very thick Diluvial deposits of Pleistocene age, which consist of alterations of sand and clay. Both Alluvium and Diluvium layers form a rich aquifer in this region. Hydrology of the region consists of the two main rivers, namely: the Yodo river in the north and Yamato river in the south. The two rivers discharge the water in the Osaka Bay [4][5].

1.2. Data and Location of Observation Wells

Monthly precipitation and pumping data including observed groundwater levels of 1987 through 1991 were collected. The groundwater levels were obtained from Research Committee on Groundwater Geo-environment (RCGG)[6] and the pumping data from Osaka Prefecture[7]. Precipitation data were collected from Annual Reports on Amedas Observation (2003) of the Japan Weather Association (JWA)[8].

Groundwater heads in the region were collected from 26 observation wells. The wells are numbered from 1 to 26 without a circle as shown in Figure 1, some of them are located at the same place but at different depths. The wells that were observed at depth more than 150 (m) below the Osaka Point (O.P) and those showed very different behavior from the average behavior of the nearby observation wells were excluded in the analysis. Exceptions to some observation wells with depth more than 150 (m) were been

¶ Dedicated to the memory of Prof. Michihiro KITAHARA

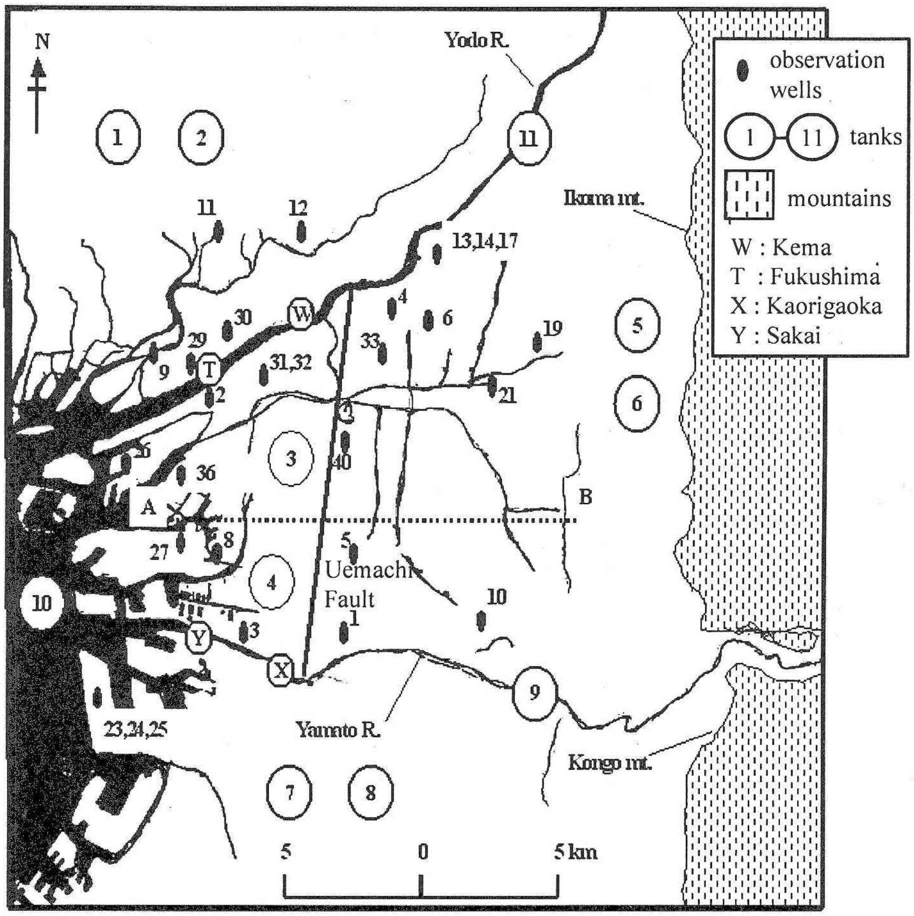

Fig. 1 Location of observation wells in the Osaka area

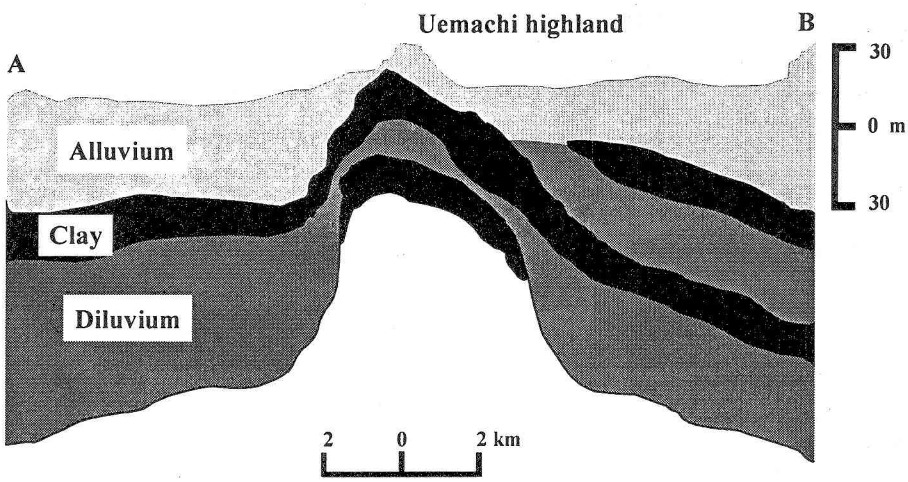

Fig. 2 Section A-B, alluvium and diluvium layers

Table 1. Location of tanks in the region

Region	Tank number	Description	Area (m^2)
North	1	Top aquifer	275.00E+06
	2	Bottom aquifer	275.00E+06
Center	3	Top aquifer	118.75E+06
	4	Bottom aquifer	118.75E+06
East	5	Top aquifer	298.75E+06
	6	Bottom aquifer	298.75E+06
South	7	Top aquifer	232.50E+06
	8	Bottom aquifer	232.50E+06
	9	Yamato river	
	10	Sea	
	11	Yodo river	

Table 2. Observation wells in each tank

Tank number	Well number
1	12
2	9,11,29,30
3	2,3,8,27
4	26,31,32,36
5	1,4,5
6	6,10,13,14,17,19,21,33
7	23,24
8	25

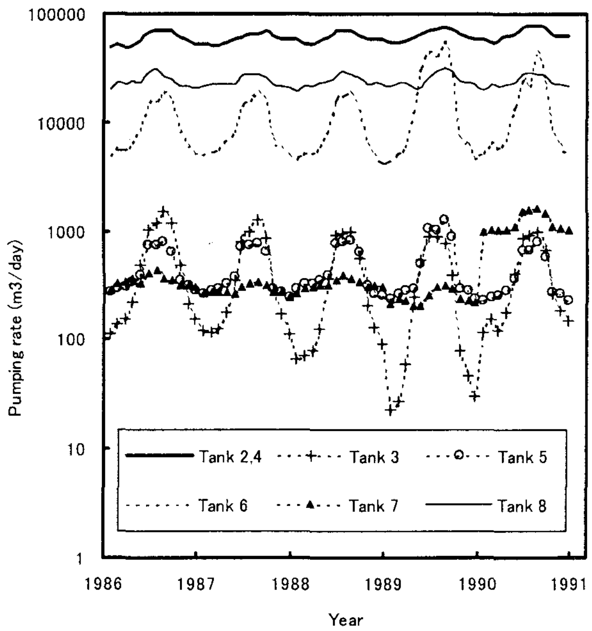

Fig. 3 Monthly pumping rate (m^3/day) 1987-1991

considered where the depth of the aquifer from geological maps was reasonable to be included, especially those near the sea.

For the purpose of implementing the tank model, the basin was divided into four zones with regards to the hydrological and geological features of the region. The tanks are numbered from 1 to 11 with a circle as shown in Figure 1. The region between Yodo river and Yamato river was divided into two zones through the Uemachi fault. North of Yodo river was one zone and the other in the south of Yamato river. In each zone we have the top and bottom aquifer. As a result, the region was divided into 11 tanks including the sea, Yamato river and Yodo river as shown in Table 1 and Figure 1. The odd number in each zone represents the top aquifer and even number for the bottom. Observation wells for the top and bottom aquifer in each zone are given in Table 2 and their locations are given in Figure 1.

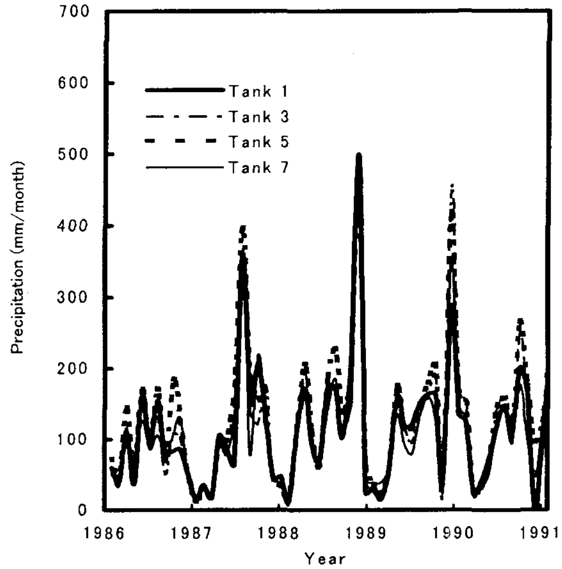

Fig. 4 Monthly precipitation 1987-1991

The datum of the observation heads was taken 100m below the O.P. The mean value of all observed heads in each month from the observation wells in the tank was considered to be the representative head of the tank in the particular month of the year. The representative head of the Yodo river is the mean of the observed heads at Fukushima and Kema gauging stations, while the mean of the observed heads at Sakai and Kaorigaoka gauging stations represents the observed heads of the Yamato river. Tank 2 and 4 were combined since the aquifers have high connectivity and they show strongly the same head fluctuation. The total amount of monthly pumping rates in each tank and the monthly precipitation in the top aquifers are presented in Figure 3 and 4 respectively.

1.3. Background and Purpose of this Research

The regulation of pumping in Osaka plain groundwater has started in 1960's for the purpose of controlling ground subsidence of the area. Since then, the groundwater level has recovered about 30 (m). The recovery of the groundwater still continues in 1990's although there was some decline of the level due to large scale pumping by some factories in the early 1990's. As a result, there are some concerns for effects of groundwater to deep excavations and risk of liquefaction during earthquakes. There are needs to establish management and usage policies of groundwater based on sound scientific knowledge.

Osaka prefecture has developed 'regional ground subsidence prediction model' based on the analyses of groundwater cycle and flow in the plain (Osaka Prefecture, 1983). A quasi three dimensional model was employed to model the groundwater flow. Groundwater Recharge Committee of Groundwater Geo-environmental Research Conference has continued this work, where three dimensional finite element method is going to be introduced. On the other hand, Uno et al[9] and Kamiya et al[10] have analyzed various factors affecting the behavior of the aquifer

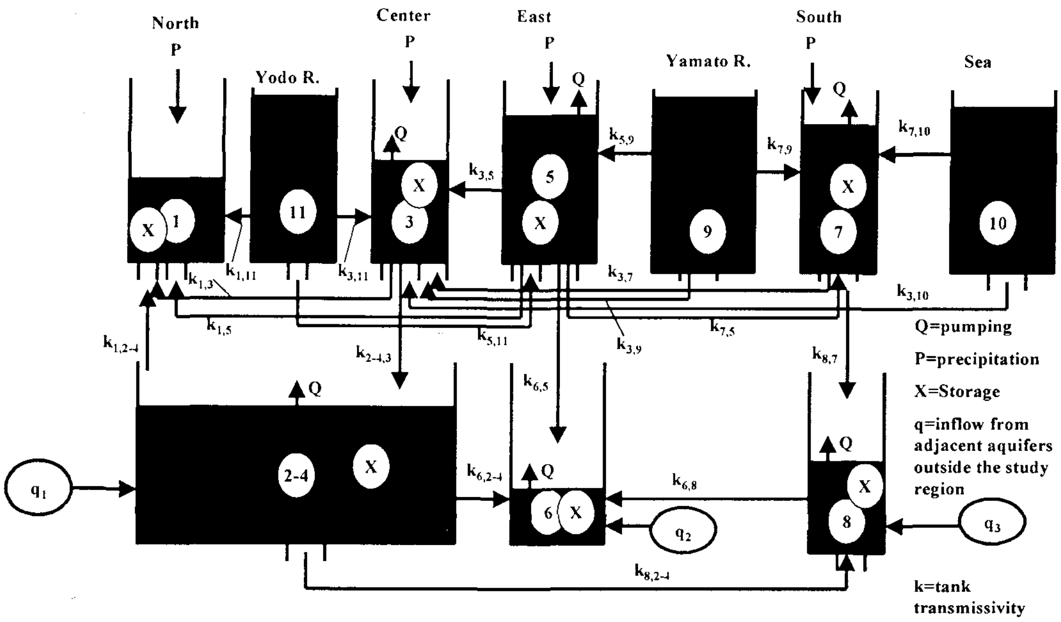

Fig. 5 Tank model for the Osaka plain aquifer

based on observed fact, such as groundwater level, pumping rate, precipitation, river water level etc., by some statistical methods including so called 'simplified model'. However, it is fair to say, in spite of all these efforts, groundwater cycles and flow mechanism of aquifer system under Osaka plain has not yet been elucidated fully.

The purpose of this study is to model the aquifer system under Osaka plain by a tank model so as to obtain a general picture of the groundwater cycle and flow. Mainly statistical means are used to obtain a simple model that can describe the macro mechanism of the aquifer.

2. Methodology

2.1. Tank Model

The tank model was proposed and developed by Sugawara[2] and originally used to explain the mechanism in which rainfall brings flood. In order to resolve the mechanism, it is necessary to identify many parameters in the tank model, such as the coefficient of discharge at the outlet of each tank and the height of outlet.

The proposed groundwater flow tank model for the Osaka area is given in Figure 5. It consists of eleven tanks and 23 parameters, i.e., 20 tank transmissivity parameters and 3 parameters of the inflow from adjacent aquifers outside the study region. We consider the water mass balance in the region, where rainfall, pumping, river and sea levels are measured. Using the tank model, the governing equations are as follows:

$$X_i(t+\Delta t)=\left\{I_{ij}(t)+x_{ij}(t)+P_i(t)-Q_i(t)+q_i\right\}\Delta t + X_i(t) \qquad (i\neq j) \tag{1}$$

where

$$I_{ij}(t)=\sum_{j=1}^{\ell} k_{ij}\left(H_j(t)-\frac{X_i(t)}{\eta_i A_i}\right) \tag{2}$$

$$x_{ij}(t)=\sum_{j=1}^{M-\ell} k_{ij}\left(\frac{X_j(t)}{\eta_j A_j}-\frac{X_i(t)}{\eta_i A_i}\right) \tag{3}$$

$$P_i(t)=c_i A_i R_i(t) \tag{4}$$

$X_i(t+\Delta t)$ is the storage (m^3) in tank i at time $t+\Delta t$, Δt is time step, t is time in months, $X_i(t)$ is storage (m^3) at time t, $I_{ij}(t)$ is the inflow ($m^3/month$) to tank i from tank j (river or sea) at time t, $x_{ij}(t)$ is inflow ($m^3/month$) to tank i from tank j at time t, $P_i(t)$ is precipitation volume ($m^3/month$) in tank i at time t and $Q_i(t)$ is pumping rate ($m^3/month$) in tank i. q_i is inflow ($m^3/month$) to tank i from adjacent aquifers outside the study region, parameter k_{ij} is a tank transmissivity ($m^2/month$) connecting tank i and j, η_i is soil porosity of tank i, A_i is the catchment area (m^2) of tank i. While $H_j(t)$ is observed head (m) of river or sea number j at time t, ℓ is total number of sources (sea and rivers), M is the total number of tanks in the model, c_i is coefficient of infiltration of tank i and $R_i(t)$ is rainfall expressed in $m/month$. The calculated head, $h_i(t\,|\,\theta)$, in tank i at time t given parameter vector θ, is defined as:

$$h_i(t\,|\,\theta)=\frac{X_i(t\,|\,\theta)}{\eta_i A_i} \tag{5}$$

where $X_i(t\,|\,\theta)$ is the storage in tank i at time t given the parameter vector θ.

2.2. Model Selection and Parameter Estimation

Using the tank model every observation can be modeled as:

$$h_{ir}^* = h_{ir}(\theta) + \xi_{ir} \tag{6}$$

where h_{ir}^* is the observed head in tank i in month r and $h_{ir}(\theta)$ is calculated head in tank i in month r given parameter vector, θ , ξ_{ir} is error assumed to follow $N(0,\sigma_\xi^2)$.

Based in the model introduced in Eq. (6), it is derived that the maximum likelihood estimator of $\underline{\theta}$, i.e. $\hat{\underline{\theta}}$, can be obtained by minimizing the following objective function:

$$J(\theta) = \sum_{r=1}^{L}\left[\sum_{i=1}^{M-\ell}(h_{ir}(\theta) - h_{ir}^*)^2\right] \tag{7}$$

where L is the number of months in the observation period and ℓ is number of sources (sea and rivers).

The goodness of fit of the model to the observations is measured by $RMSE$, the root mean square error, which is define as:

$$RMSE = \sqrt{\frac{J(\theta)}{n}} \tag{8}$$

where n is total number of observations given by

$$n = L(M - \ell) \tag{9}$$

It is well known fact that there is a trade-off between goodness of the fit of a model to the observation data and stability or reliability of estimated parameter values: A model with more number of parameters usually gives better fit to the observations but has less stability in the estimated parameter values. On the other hand, a simpler model, i.e. a model with less number of parameters, gives more stable estimation of the parameter values. One of the criterion to overcome this difficulty was proposed by Akaike (1972)[11] which is known as AIC, Akaike's Information Criterion given by:

$$AIC = -2(Maximum\ Loglikelihood) + 2(number\ of\ parameters) \tag{10}$$

It is explained that the first term in Eq. (10) mesuares the fit of the model to the data whereas the second term works as a penalty to the model by introducing more number of parameters. A model which minimizes AIC is the best model to be used for the prediction.

Eq. (10) in present formulation of the problem as presented in Eq. (6), is given as follows:

$$AIC = n.ln(2\pi) + n.ln\frac{J(\hat{\theta})}{n} + 2(n_p + 1) \tag{11}$$

where n_p is number of parameters to be optimized.

2.3. Optimization Procedure

We start our optimization from a tank model with 11 tanks and 23 parameters: 20 tank transmissivities, and 3 parameters of inflows from adjacent aquifers outside the study region q_1 to q_3. The average soil porosity of the region was known to be 0.3 and optimization runs to determine coefficient of infiltration were carried out starting with 10% to 1% of precipitation and finally it was fixed at 3%.

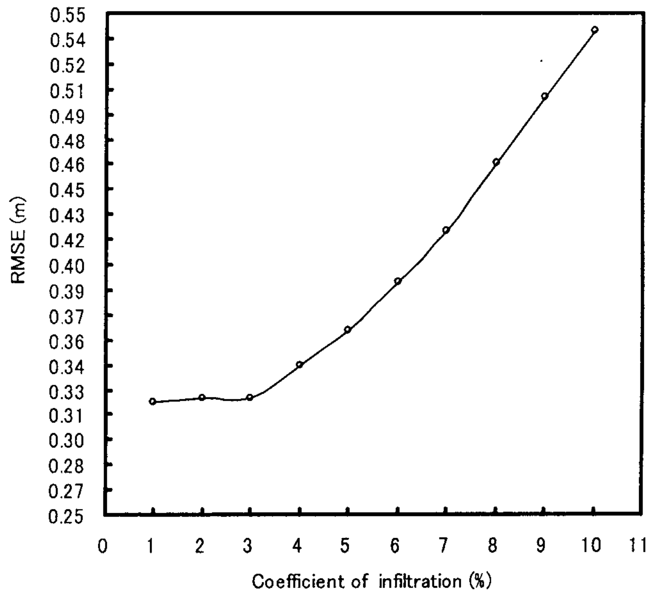

Fig. 6 RMSE at different levels of infiltration coefficient determined during priliminary analysis by using 7-parameter tank model.

This is because a good fit between observed heads and calculated heads was obtained at that percentage of infiltration. Decreasing the infiltration below 3% could not make any significant improvement in the RMSE as shown in Figure 6. All tank models tested could show the same trend as given in Figure 6. Furthermore other regional studies done in the area by Yokoo et al[12] also showed that the infiltration coefficient is about 3%.

It was found in the initial stage of the calculation, the tank model we had set, i.e. M23, (model defined here implies that a model with some fixed number of parameters, for example M23 means a model with 23 parameters), was far more complex for the given amount of observations: the estimated parameter values are so unstable that different results are obtained for different initial set of parameters during optimization.

Based on this fact the following procedure of random start optimization are taken to reduce the number of parameters introduced in the model:

Step 1: 600 sets of candidate initial parameters are generated using random number generator. Each parameter is assumed to follow an appropriate lognormal distribution whose mean and standard deviation are set in the preliminary analysis.

Step 2: Among the 600 parameter sets, the one that gives the minimum objective function value was chosen by running the tank model. This set was used as an initial parameter values in the optimization. The Quasi –Newton method was employed to solve this problem[13].

Step 3: For each model step *1* and *2* are repeated 10 times[3]. If a model is unstable, the optimized solutions exhibit instability of model parameter values. The results presented in the next section for each model is the one that gave the minimum $J(\hat{\underline{\theta}})$ values among the 10 cases.

Step 4: The reduction of parameter number was done as follows:

(i) List up candidate parameters that can be eliminated in the next step, the candidate parameters are the ones that give relatively low tank transmissivity or inflow.

(ii) For each candidate parameter, reduced model was formed, which was then put to optimization analysis described in S*tep 1, 2 and 3.*

(iii) The parameter that gave minimum value of $J(\hat{\underline{\theta}})$ was chosen as a parameter to be eliminated in this step. In this way the reduced model was produced.

Step 5: Step 4 was repeated until minimum AIC was reached.

After obtaining the optimum *AIC*, two model stability tests were carried out. First the conditional number, CN, defined as the ratio between the maximum and minimum eigenvalues obtained from singular value decomposition of the sensitivity matrix, A, expressed as

$$A(i,j) = \frac{h_i(\theta_j) - h_i(\theta_j + \Delta\theta_j)}{\Delta\theta_j}$$
$$\text{for } i = 1,\ldots,n \text{ and } j = 1,\ldots,n_p \qquad (12)$$

The lower the conditional number the model is stable.

The second test for model stability is the plot of the parameter value obtained in each of the 10 trial cases against case number. A model is said to show stability if among the 10 trial cases of random start optimizations performed by using the model, most of the trials produce a value almost equal to the optimum value of the parameter considered, otherwise it is unstable.

After obtaining the optimum parameter values, the total flow volume, V_T (m^3), from tank number j to tank number i during the period of record, in our case 1987-1991, is computed as:

$$V_T = k_{ij}\sum_{r=1}^{L}(h_{jr}(\theta) - h_{ir}(\theta)) \qquad (13)$$

The total flow volume, V_H (m^3), from the river or sea number j to tank number i is given by:

$$V_H = k_{ij}\sum_{r=1}^{L}(H_j - h_{ir}(\theta)) \qquad (14)$$

And the total flow volume V_q (m^3) from adjacent aquifers outside the study region to tank i is determined as:

$$V_q = q_i \mathrm{L} \qquad (15)$$

All other parameters as defined in the previous sections, i.e. 2.1 and 2.2.

3. Results and Discussion

3.1. Model Selection and Parameter Estimation

The model selection procedure to minimize the AIC was carried out starting with 23 parameter model, M23, to 6 parameter model, M6, as shown in Figure 7 and Table 3.

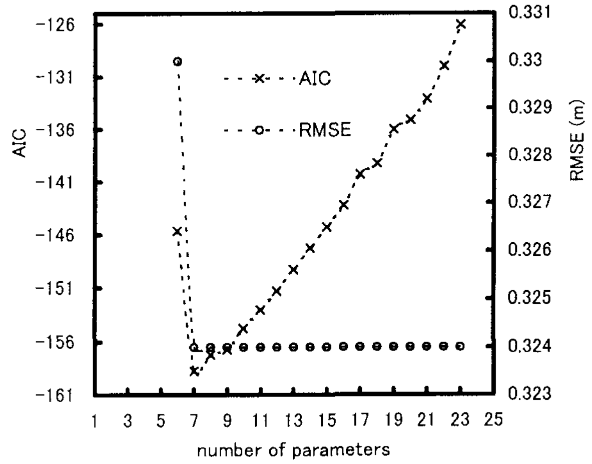

Fig. 7 AIC and RMSE versus number of parameters for the alternative tank models

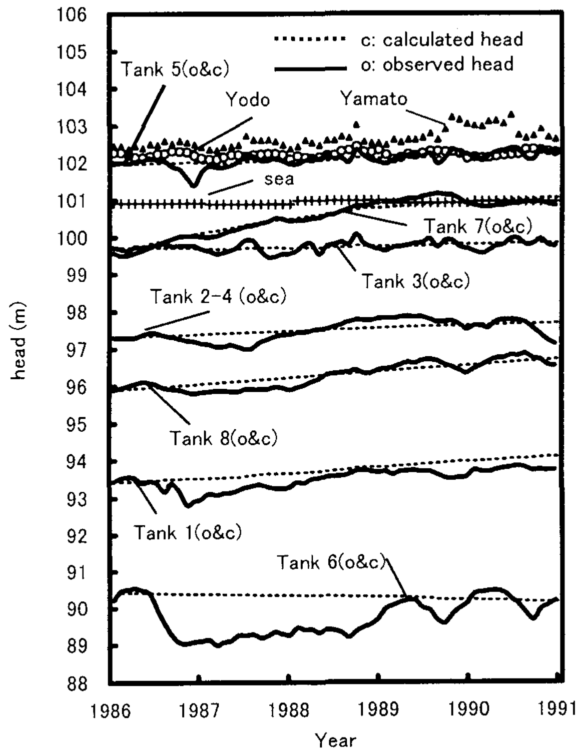

Fig. 8 Observed heads and calculated heads by M7 model (1987-1991)

Reduction of a parameter from a model was done by the procedure explained in the previous section that resulted to the reduction process presented in Table 3.

A little modification of the reduction procedure was done when moving from M8 to M7. After some trials, it was found that to remove $k_{7,5}$ and $k_{8,7}$ and add $k_{5,11}$ again gives the minimum AIC among the possible cases we have considered.

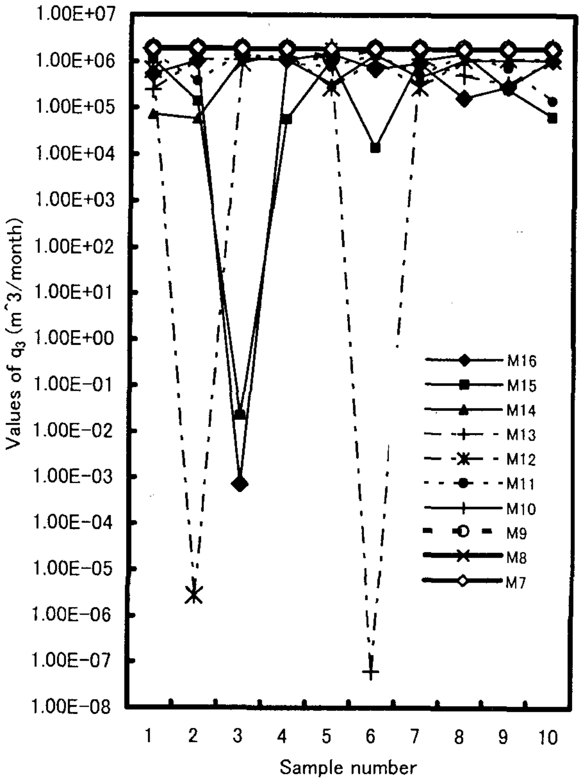

Fig. 9 Stability of parameter q_3

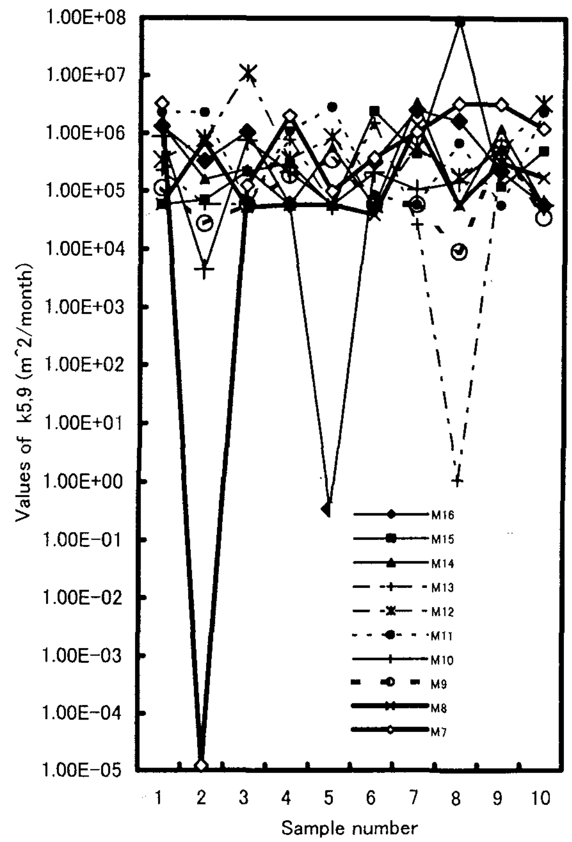

Fig. 10 Stability of parameter $k_{5,9}$

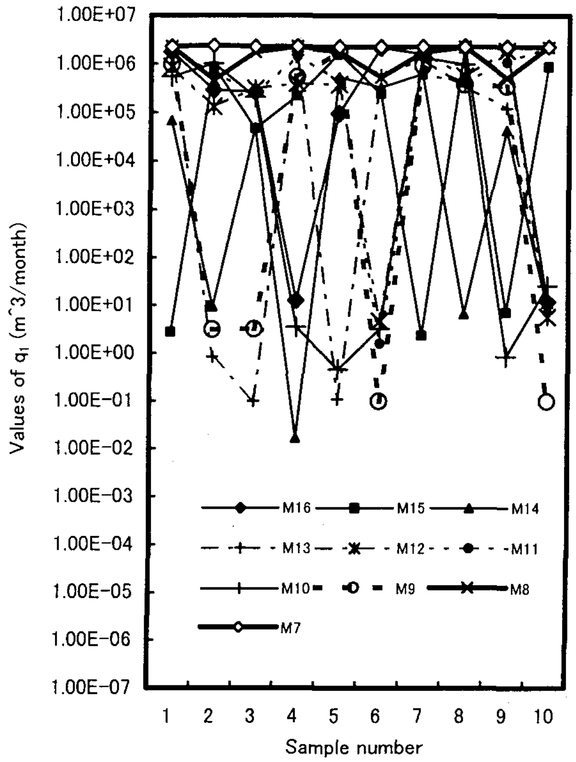

Fig. 11 Stability of parameter q_1

All the models presented in Table 3 have the same *RMSE* of 0.324 (m) except M6. A 7-parameter model, M7, reached the optimum level of AIC. Figure 8 shows fitness between the observed heads and the computed heads by model M7. Although the results of M7 are shown, all other models has almost equal fit to the observation data as can be expected from *RMSE* 's in Table 3.

3.2. Stability of Parameter Values

In order to illustrate the stability or instability of the estimated parameters, estimated results of 10 cases for each model for parameter q_3, $k_{5,9}$ and q_1 are presented in Figure 9 through 11. Model M7 to M11 in Figure 9 show stability in the estimated parameter values of q_3 because most of the trial cases produce values of q_3 almost equal to the optimum parameter values presented in Table 3. Model M12 to M16 show instability in the estimated parameter values because most of the 10 trial cases produce results that are different from the optimum parameter values of q_3 given in Table 3.

The plot of parameter $k_{5,9}$ and q_1 in Figure 10 and 11 respectively, model M7 and M8 indicate more stable results compared to the results of other models.

Since model M8 is stable and the difference in the AIC from model M7 is relatively small as indicated in Figure 7 and Table 3, M7 and M8 models are not different from statistical point of view. On the other hand M8 describes more hydro-geological features studied in the region and it is hard to believe that tank 7 and tank 8 are isolated from other tanks. With these regards M8 is considered to be the best model for prediction of flow pattern in the region.

3.3. Hydro-geological Considerations

After determining the optimum parameter values of each model, the total flow volumes from one tank to another

Table 3. Optimum parameters for 16 tank models

Parameter and tank connectivity		M6	M7	M8	SM8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M23
n_p		6	7	8	8	9	10	11	12	13	14	15	16	17	18	19	23
$k_{1,2-4}$	(1-2,4)												1.12E-05	9.78E-06	2.00E-06	1.43E-05	3.78E-07
$k_{1,3}$	(1-3)													1.20E-07		1.09E-05	1.79E-04
$k_{1,5}$	(1-5)															6.15E-06	6.02E-08
$k_{1,11}$	(1-11)																3.87E-04
$k_{2-4,3}$	(2,4-3)	1.52E+05	1.52E+05	1.52E+05	1.52E+05	1.52E+05	3.19E+05	1.16E+06	1.16E+06	1.16E+06	1.16E+06	3.65E+05	1.16E+06	1.16E+06	1.08E+06	1.16E+06	1.16E+06
$k_{6,2-4}$	(6-2,4)																5.01E-08
$k_{8,2-4}$	(8-2,4)									1.43E-01	2.32E-04	1.55E-05	1.92E-05	1.56E-03	3.35E+05	1.21E+00	3.42E+05
$k_{3,5}$	(3-5)											1.30E-03	2.20E-05	5.09E-04	8.99E-02	2.03E+00	6.05E-05
$k_{3,7}$	(3-7)										2.44E-05	4.62E-06	8.01E-06	6.50E-05	1.70E+05	5.49E+01	1.83E-06
$k_{3,9}$	(3-9)								5.78E-05	1.97E-02	1.00E-05	6.88E-05	1.03E-05	1.49E-05	8.21E-05	3.38E+00	1.12E-01
$k_{3,10}$	(3-10)						5.10E+04	1.79E-04	1.91E+06	1.91E+06	1.91E+06	4.03E+05	1.91E+06	1.91E+06	1.65E+06	1.91E+06	6.88E+04
$k_{3,11}$	(3-11)					1.65E-06	1.92E+05	1.91E+06	2.95E-05	2.79E-01	5.25E-01	3.76E-02	1.10E-01	4.51E-02	1.37E+01	2.05E+01	8.77E+05
$k_{6,5}$	(6-5)														7.09E-07		2.85E-06
$k_{7,5}$	(7-5)			4.42E+05	4.45E+05	4.42E+05	6.74E+05	4.42E+05	4.42E+05	4.42E+05	4.42E+05	4.41E+05	4.42E+05	2.98E+05	2.73E+05	3.06E+05	4.23E+05
$k_{5,9}$	(5-9)	9.07E+05	2.20E+06	5.40E+04	4.52E+05	5.40E+04	7.46E+05	5.39E+04	5.40E+04	5.39E+04	5.40E+04	5.16E+04	5.40E+04	1.93E+05	8.79E+05	1.55E+05	1.04E+06
$k_{5,11}$	(5-11)	1.05E+06	1.67E+06					8.27E+01	1.74E-05	5.21E-01	1.37E+00	1.35E+00	7.28E-01	2.83E+05	6.36E+05	2.47E+05	5.33E+05
$k_{6,8}$	(6-8)																1.84E-09
$k_{8,7}$	(8-7)			1.29E+05	8.44E+04	1.29E+05	2.58E+05	1.29E+05	1.29E+05	1.29E+05	1.29E+05	1.29E+05	1.29E+05	1.03E+05	1.79E+05	7.16E+04	2.69E+05
$k_{7,9}$	(7-9)	6.02E+05	7.23E-05	1.42E+00	4.00E+05	2.36E+00	1.55E+05	1.25E+00	9.48E-01	1.87E+00	9.13E-01	3.27E-01	1.11E+00	5.43E-04	6.31E+05	9.10E+00	3.68E+05
$k_{7,10}$	(7-10)		2.50E+06	2.15E+06	6.48E+05	2.15E+06	1.81E+06	2.15E+06	2.15E+06	2.15E+06	2.15E+06	2.15E+06	2.15E+06	2.41E+06	5.09E+05	2.11E+06	1.76E+06
q_1	(2,4)	2.28E+06	2.28E+06	2.28E+06		2.28E+06	1.90E+06	1.45E+01	8.92E-01	3.40E-01	3.40E+00	1.80E+06	7.25E+00	1.75E+00	6.21E+05	3.77E+02	4.43E+05
q_2	(6)														1.49E-06	4.61E-02	1.20E-07
q_3	(8)	1.68E+06	1.68E+06	1.14E+06		1.14E+06	6.00E+05	1.14E+06	1.14E+06	1.14E+06	1.14E+06	1.14E+06	1.14E+06	1.25E+06	5.00E+05	1.38E+06	1.13E+05
$k_{2-4,10}$	(2,4-10)				1.58E+06												
$k_{8,10}$	(8-10)				1.90E+02												
J		45.709	44.093	44.041	44.093	44.093	44.066	44.038	44.038	44.038	44.038	44.041	44.142	44.039	44.171	44.053	44.162
RMSE		0.330	0.324	0.324	0.324	0.324	0.324	0.324	0.324	0.324	0.324	0.324	0.324	0.324	0.324	0.324	0.324
AIC		-145.63	-158.75	-157.25	-156.75	-154.75	-153.01	-151.28	-149.28	-147.28	-145.28	-143.25	-140.29	-139.27	-136.01	-135.13	-126.10
CN		300	341	270	220	387	434	671	670	602	807	970	826	1900	2856	2900	9675

Units: k (m^2/month), q (m^3/month), J (m^2), RMSE (m)

8

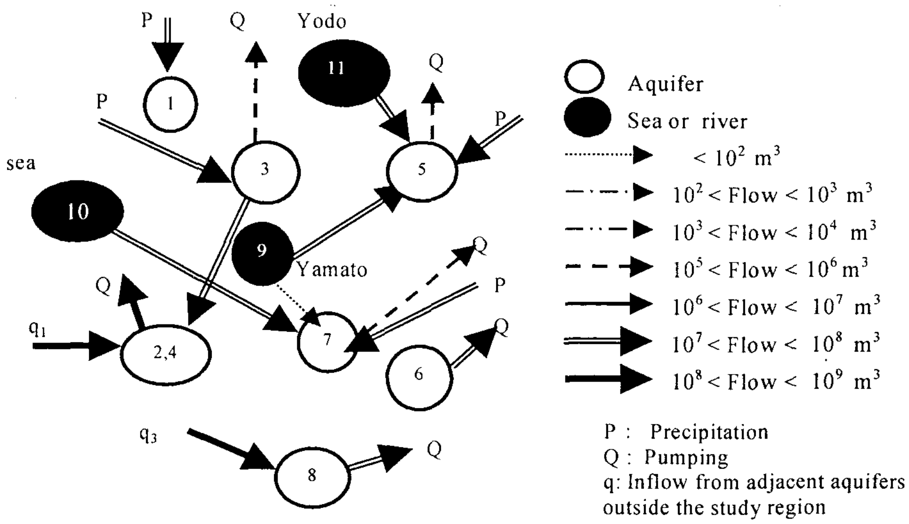

Fig. 12 Pattern of total flow volume (1987-1991) by model M7

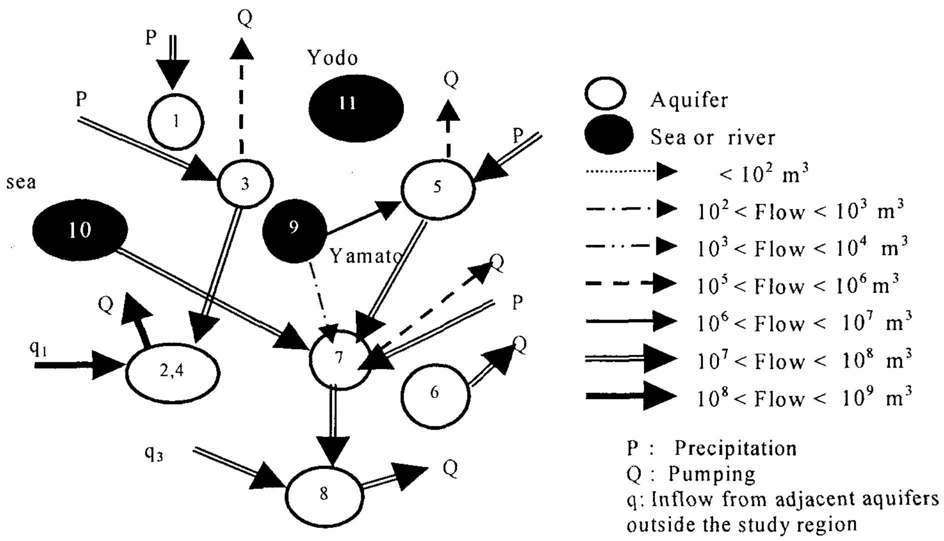

Fig. 13 Pattern of total flow volume (1987-1991) by model M8

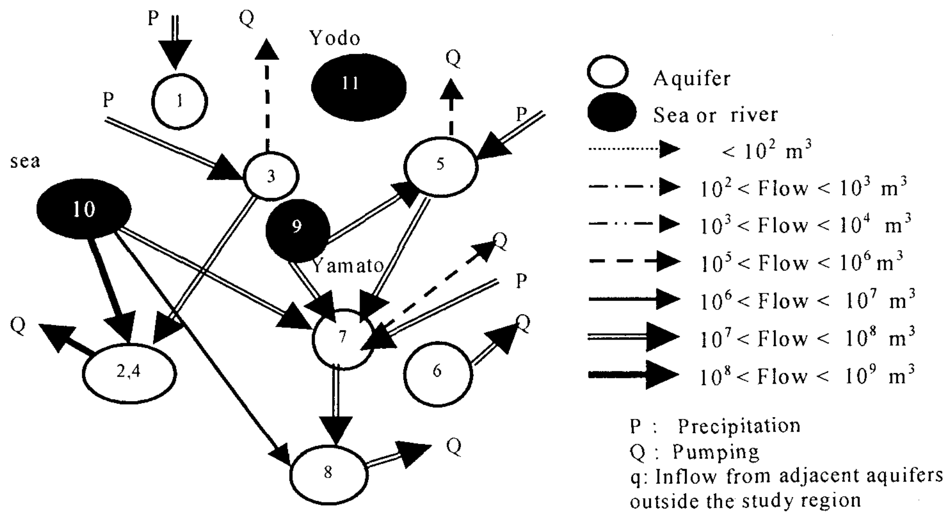

Fig. 14 Pattern of total flow volume (1987-1991) by model SM8

during the period of study were calculated by using Equations (13) through (15) so as to understand the groundwater flow patterns.

The groundwater flow pattern computed by using M7 and M8 are presented in Figure 12 and 13 respectively. Considering Figure 13, the flow pattern from model M8 that is considered to be the best model, shows much inflow from adjacent aquifers outside the study region to tank 8 and tank 2-4. With regards to the geology of the region that is bound by mountains, it is difficulty to conclude that such huge amount of water can be supplied by adjacent aquifers outside the study region in the short period of record (1987-1991).

In this case, the only source that could be in contact with the bottom aquifers, i.e. tank 2-4 and tank 8, is the sea. The second type model of 8 parameters, SM8, that connects tank 2-4 and tank 8 to the sea was proposed to be used to estimate the groundwater flow behavior. Figure 14 shows the pattern of total flow volume after the bottom aquifers of the center of the Osaka area and that of the south were connected to the sea. Model SM8 replaces parameter q_1 with $k_{2\text{-}4,10}$ and that of q_3 by $k_{8,10}$ in M8 model as shown in Figure 14 and Table 3. Model SM8 is as good as M8 as far as statistical indices are concern.

The pattern shows that there is higher seawater inflow to the center of the Osaka area than to the southern part. Yamato river has higher interaction with the top aquifer while the Yodo river has no contribution. This may be due to differences in some geological conditions between the two rivers. The results also suggest that there is disconnection of aquifers of tank number 1, 3 and 6 from other aquifers.

4. Conclusions

Modeling and estimation of aquifer parameters for very complex aquifer system like the one considered here for Osaka area by mathematical models is notoriously difficult. This paper concerns with such complex aquifer system by relatively simple model that is the tank model, so as to understand the macro mechanism of such aquifer system.

The major difficulty in developing such model is the trade-off between the fit of the observed data to the model response and reliability of the parameter estimation.
Random start optimization procedure together with Akaike's Information Criterion, AIC, have been employed to overcome this problem. The followings are the outcomes of this research.

1) A stable model is established which is believed to be able to reliably simulate the groundwater flow cycles and flow of the aquifer system under Osaka plain. The whole process clearly exhibited the procedure proposed works well in achieving the objective described above.
2) The results suggest disconnection of some of major regional aquifer as well as inflow of seawater to the deeper layers in the studied period. The result coincides with speculations made on the groundwater flow based on hydro-geological views[9)10)].
3) A tank model associated with the random start optimization technique and the statistical procedure proposed in the study offers a promising approach in reliably understand the mechanism of a complex regional groundwater flow mechanism such as one studied in this paper, Osaka regional aquifer system.

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