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지하수위 자료를 이용한 대수층의 수리상수 추정과 추정오차 분석

Aquifer Parameter Identification and Estimation Error Analysis from Synthetic and Actual Hydraulic Head Data

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요약/Abstract

최대우도법(maximum likelihood method)을 이용하여 정류상태의 지하수위 자료로부터 불균질성과 비등방성을 가지는 대수층의 수리상수를 추정하는 반전모델을 개발하였다. 반전모델을 이용하여 추정된 수리상수의 추정오차를 분석하기 위하여 Fisher information matrix분석법을 도입하고, 수리상수의 추정을 위한 Parameterization의 방법으로 소유동영역화 방법(zonation method)을 사용하였다. 개발된 반전모델을 이용하여 세가지 경우에 대해서 대구지역의 투수량계수를 추정하였다. 또한, 대구지역의 지하 수함양률을 각 소유동영역의 값으로 추정하였다. 각 추정에서 수반되는 추정오차의 특성을 Fisher information matrix를 구하여 살펴보았다.

A method is proposed to estimate aquifer parameters in a heterogeneous and anisotropic aquifer under steady-state groundwater flow conditions on the basis of maximum likelihood concept. Zonation method is adopted for parameterization, and estimation errors are analyzed by examining the estimation error covariance matrix in the eigenspace. This study demonstrates the ability of the proposed model to estimate parameters and helps to understand the characteristics of the inverse problem. This study also explores various features of the inverse methodology by applying it to a set of field data of the Taegu area. In the field example, transmissivities were estimated under three different zonation patterns. Recharge rates in the Taegu area were also estimated using MODINV which is an inverse model compatible with MODFLOW. The estimation results indicate that anisotropy of aquifer parameters should be considered for the crystalline rock aquifer which is the dominant aquifer system in Korea.

Key Words : parameter estimation, inverse problem, heterogeneity, anisotropy

Introduction

In recent years, a large number of mathematical and computational models have been developed and used to analyze or predict various phenomena associated with the groundwater system. Forward groundwater flow models require aquifer parameters as input data for prediction of the system states. Therefore, the accurate information on unknown aquifer parameters plays an important role in making prediction closer to the real system.

During the past three decades there have been numerous studies to identify the aquifer parameters in distributed-parameter systems. Stallman (1956) was the first to determine aquifer properties based on measured heads. Stallman (1956) considered transmissivity as a constant over every large segment of the aquifer (zone) in order to overcome instability in numerical solutions. After Stallman's work many researches associated with the inverse problem have been reported (Jacquard and Jain, 1965, Nelson, 1968, Emsellem and de Marsily, 1971, Cooley, 1977, 1979, Neuman and Yakowitz, 1979, Jacobson, 1984). Chavent (1971) first developed the adjoint state theory for obtaining sensitivity coefficient more efficiently and Carrera and Neuman (1986a, b, c) estimated aquifer parameters under transient and steady-state conditions on the basis of a maximum likelihood concept. Geostatistical approaches have also been proposed extensively for solving the inverse problem (Kitanidis and Vomvoris, 1983, Dagan, 1985).

In this study a method for estimating aquifer parameters under steady-state conditions is presented, and the concerned hydraulic parameters are limited only to values of hydraulic conductivities (or transmissivities), K, in isotropic or anisotropic media, which are the most influencing parameters on groundwater flow or contaminant transport. The problem is posed in the framework of nonlinear maximum likelihood (ML) estimation by adopting a log-likelihood criterion which only includes head measurements. The theoretical and algorithmic foundations for this study are based upon Carrera and Neuman (1986a, b), Lee et al. (1993), and Lee and Cushman (1993). The principal objective of this study is to propose a method to identify aquifer parameters from hydraulic head data and analyze the characteristics of inverse estimation problems.

Problem Statement

This work is concerned with the problem of steady-state groundwater flow in a heteroge neous and anisotropic aquifer which is described by the Poisson equation

$$\nabla \cdot (\mathbf{K} \cdot \nabla h) + q = 0 \qquad \text{on } R \qquad (1)$$

subject to the boundary condition of the following generalized type :

$$-\mathbf{K} \cdot \nabla h \cdot \mathbf{n} = \alpha(H - h) + Q \qquad \text{on } \Gamma \qquad (2)$$

where R is the spatial domain of the aquifer, Γ is its boundary, ∇ is the gradient operator, K is the hydraulic conductivity tensor, h is the hydraulic head, q represents the internal sources, S_S is the storage coefficient, n is the unit vector normal to Γ pointing out of the aquifer, H is the specified boundary head, Q is the specified boundary flux, and α is the parameter controlling the type of boundary condition and leakage coefficient. When the flow is horizontal, K can be replaced by the transmissivity tensor, T, and S_S by the storativity, S. A numerical scheme is required to solve the governing equation, provided that parameter values are properly estimated. In this study the governing equation is solved by using the finite element method (FEM).

To obtain a good agreement between the measured and computed heads by (1), the model parameters in (1) must be calibrated. This is, what is so-called, 'the inverse problem' of which some more details are extended to next section. If there is sufficient prior information on estimated parameters, it can yield more accurate estimates incorporating prior information. If parameter measurements are contaminated seriously by noise, much attention should be required because they can cause erroneous results. This study adopts the zonation method for parameterization. Pameter identification in this study uses only hydraulic head data for the parameter estimation, which is due to the fact that hydraulic head data can be obtained easily and sufficiently over the region while there is lack of prior information on parameters.

Maximum Likelihood Method

There are two representative approaches to the estimation of parameters. One is the Bayesian approach, which regards parameters as random variables and hydraulic head measurements or hydraulic parameters are considered as samples of two different random fields, the other is the likelihood-concept approach, in which the uncertainty of hydraulic model parameters is not due to their random characteristics, but due to insufficient and corruped data by irregular noise. This study adopts the maximum likelihood concept, and develops the algorithm to estimate parameters by relying on hydraulic head measurements obtained in a set of observation wells.

A few aspects of maximum likelihood method for this study are now discussed. Let z^* be the vector of measurable variables including heads, h^*, and auifer parameters, p^*, i.e., $z^*=(h^*, p^*)$, and β be the vector combining model parameters, p, and the parameters defining the underlying error structure, θ, i.e., $\beta=(p,\theta)$. Let us designate a "true" value by naked letter, e.g., z, h, and p, a "measured" value by superscript star (*), e.g., z^*, h^*, and p^*, and a "computed" value by tilde (^), e.g., $\hat{z}$, $\hat{h}$, and $\hat{p}$. As mentioned above, according to the likelihood concept, uncertainty in the model parameters is not due to their random nature (β being deterministic) but due to insufficient data and their corruption by noise. Since h^* and p^* are usually obtained by independent method (e.g., water level measurements and pumping tests), the prior errors associated with them are mutually independent. That is to say, the prior head errors and the prior parameter estimation errors are assumed to have weak cross-correlation. Only the posterior estimation errors, $\hat{h}$-h and $\hat{p}$-p, are cross-correlated due to the fact that $\hat{h}$ and $\hat{p}$ are obtained from the same numerical model.

In the maximum likelihood approach, one maximizes $f(z^*/\beta)$, the conditional probability of z^*, given a set of parameters, β. The probability density function (p.d.f.) $f(z^*/\beta)$ is sometimes termed "likelihood function" and designated by $L(\beta/z^*)$, i. e., the likelihood of β, given z^*. The likelihood function is proportional to $f(z^*/\beta)$, the probability to $f(z^*/\beta)$, the probability density of observing z^* if β is true. Edwards (1972) proposed likelihood axiom, which provides theoretical support for the maximum likelihood (ML) estimates. In the ML approach, the distribution of parameters is assumed to be Gaussian, and so is that of prior errors with zero mean. The likelihood function which is a function of parameters can then be written as

$$L(\beta/z^*) = f(z^*/\beta) = \left(2\pi|\mathbf{C}_z|\right)^{-1/2} \cdot \exp\left[\frac{1}{2}(z^*-z)^T \mathbf{C}_z^{-1}(z^*-z)\right] \tag{3}$$

Here C_z is the covariance matrix of the prior errors,

$$\mathbf{C}_z = \begin{bmatrix} \mathbf{C}_h & 0 \\ 0 & \mathbf{C}_p \end{bmatrix} \tag{4}$$

where C_h and C_p are the covariance matrices of the prior head and model parameter errors given as following equations, respectively.

$$\mathbf{C}_h = \sigma_h^2 \mathbf{V}_h \tag{5}$$

$$\mathbf{C}_l = \sigma_l^2 \mathbf{V}_l \tag{6}$$

where C_i is the covariance of the prior errors associated with parameter type p_i ($i = K, S_s, q, H, Q$ and α), which is block diagonal component of the global covariance matrix of all the model parameters, C_p, σ_i^2 is either a known or unknown positive scalar, and V_i is a known symmetric positive-definite matrix.

In practice, parameter estimation problem adopting the ML concept, generally, has a solution which minimizes the "negative log-likelihood" or "support" criterion

$$
\begin{aligned}
S &= -2\ln\left[L(\beta/\mathbf{z}^*)\right] \\
&= (\mathbf{h}^* - \mathbf{h})^T \mathbf{C}_h^{-1}(\mathbf{h}^* - \mathbf{h}) + (\mathbf{p}^* - \mathbf{p})^T \mathbf{C}_p^{-1}(\mathbf{p}^* - \mathbf{p}) \qquad (7) \\
&\quad + \ln(|\mathbf{C}_h|) + \ln(|\mathbf{C}_p|) + n\ln(2\pi)
\end{aligned}
$$

Note that if the error structure is fully prescribed (i.e., θ is known and need not be estimated), only the first two terms in (7) include unknown parameters. Then the maximization of (3) is equivalent to the minimization of the generalized non-linear least squares functional

$$
\begin{aligned}
J &= (\mathbf{h}^* - \mathbf{h})^T \mathbf{C}_h^{-1}(\mathbf{h}^* - \mathbf{h}) + (\mathbf{p}^* - \mathbf{p})^T \mathbf{C}_p^{-1}(\mathbf{p}^* - \mathbf{p}) \\
&= \frac{J_h}{\sigma_h^2} + \sum_{i=1}^{M} \frac{J_p}{\sigma_p^2} \qquad (8)
\end{aligned}
$$

Where M is the total number of parameter types. In a special case where there are only head measurements and no parameter measurements, or when one intends to estimate hydraulic parameters using only head data, the objective function J_h for parameter estimation problem is represented by

$$
\begin{aligned}
J_h &= (\mathbf{h}^* - \mathbf{h})^T \mathbf{V}_h^{-1}(\mathbf{h}^* - \mathbf{h}) \\
&= \int_R \int_R \left[\mathbf{h}(x')^* - \mathbf{h}(x)\right]^T \mathbf{V}^{-1}(x', x)\left[\mathbf{h}(x')^* - \mathbf{h}(x)\right] dx'dx \qquad (9)
\end{aligned}
$$

In this research, (9) is taken as an objective function to obtain the parameter estimates that maximize the probability of observing the measured data.

Inverse Methodology

In order to minimize the negative log-likelihood function arising from maximum likelihood theory, the general iterative approach is used in this study. Theories for minimization algorithm are obtained from Carrera and Neuman (1986a, b) and Lee et al. (1993). Conjugate gradient iterative approaches combining adjoint state method are proposed. Under the maximum likelihood concept, the covariance matrix of estimated parameters is given as the inverse of the Fisher information matrix, F. The inverse methodology proposed in this study can estimate aquifer parameters as well as the covariance matrix of parameter estimate for the estimation error analysis. The flow chart of the proposed model is shown in Figure 1.

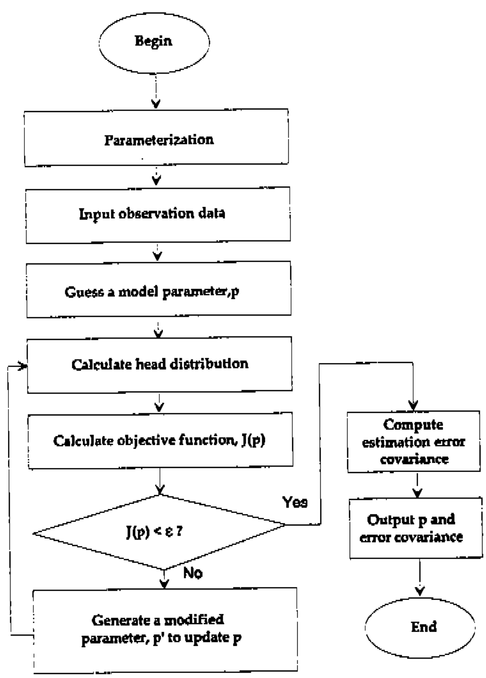

Fig. 1 Flow chart illustrating optimization procedure.

Application to Hypothetical Problem

A hypothetical problem was designed in order to test the performance of the proposed inverse algorithm because in synthetic examples the nature of the "hydrologic system" is known with precision and the characteristics of any noise superimposed on the "data" is fully specified. Here a numerical example that estimates anisotropic hydraulic conductivities and analyzes the estimation errors is presented. Let us consider a 1,200m by 1,200m square confined aquifer as shown in Figure 2a. Its left boundary is given as a constant head, and a specified flux boundary is set at the bottom. The recharge rate is equally assigned to the entire domain, and its value is 0.0001 m/day. The aquifer is assumed to consist of four hydraulic conductivity zones, and different hydraulic conductivity values are given to the zones. Thereof particularly zones 1 and 3 are assumed to have anisotropic hydraulic conductivities as shown in Figure 2b. There are two pumping wells and ten observation wells in this region. The location of wells are depicted in Figure 2a. Measured head values are generated by giving random noise with zero mean and 0.1 standard deviation to calculated head values. From generated data isotropic or anisotropic hydraulic conductivities of all zones have simultaneously been estimated. The estimated hydraulic conductivitities are listed in Table 1. The covariance matrix of the estimation errors, the eigenvectors and corresponding eigenvalues are thus calculated in order to analyze the uncertainty of the estimated hydraulic conductivities (Table 2a, 2b). The covariance matrix of the estimation errors can provide some information on the relative worth of data. The covariance matrix of the estimation errors can provide some information on the relative worth of data. The covariance matrix indicates that the x-directional hydraulic conductivity of zone 3 is the most likely reliable in that it has the largest component of the eigenvector related to the smallest eigenvalue. On the contrary, the hydraulic conductivity of zone 4 is likely to be least reliable because the largest component of the eigenvector associated with the largest eigenvalue corresponds to the estimate for zone 4. This fact is consistent with the results listed in Table 1.

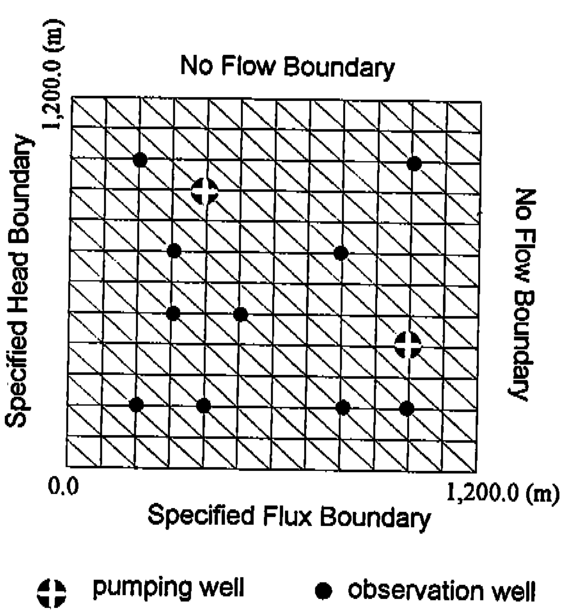

Fig. 2a Aquifer configuration and finite element discretization for a synthetic example.

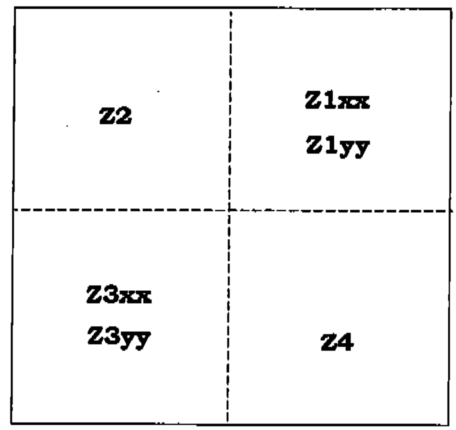

Fig. 2b Zonation pattern of a synthetic example(anisotropy is given for zones 1 and 3).

Table 1. Isotropic and anisotropic hydraulic conductivity estimates in a synthetic example.

Zone		True Hydraulic Conductivity	Estimated Hydraulic Conductivity
1	Kxx	5.30	5.28
	Kyy	4.50	4.52
2		3.00	2.96
3	Kxx	4.50	4.49
	Kyy	3.50	3.48
4		6.00	6.22

Hydraulic conductivities are in m/day. (Initial values = 10.0)

Table 2a. Estimation error covariance matrix in a synthetic example.

	K1xx	K1yy	K2	K3xx	K3yy	K4
K1xx	1.103	-1.087	-1.821	0.111	-2.120	-0.644
K1yy	-1.087	7.291	-2.210	1.633	7.583	-1.880
K2	-1.821	-2.210	-1.060	3.065	-1.370	0.719
K3xx	0.111	1.633	3.065	0.194	3.014	1.304
K3yy	-2.120	7.583	-1.370	3.014	27.14	0.212
K4	-0.644	-1.880	0.719	1.304	0.212	27.78

($\times 10^{-7}$)

Table 2b. Matrix of eigenvectors and corresponding eigenvalues in a synthetic example.

Eigenvectors					
0.4598	0.0350	0.8655	-0.1738	0.0830	0.0338
0.3177	-0.3529	0.0383	0.8166	-0.3219	0.0510
-0.2011	-0.9267	0.0800	-0.2950	0.0711	-0.0472
-0.8008	0.1159	0.4929	0.2929	-0.1222	-0.0417
0.0281	0.0410	0.0060	-0.3524	-0.9280	-0.1104
0.0722	0.0177	0.0062	0.0771	0.0915	0.9900
Eigenvalues					
3.244×10^{-10}	2.742×10^{-8}	8.572×10^{-7}	5.457×10^{-7}	3.108×10^{-6}	2.737×10^{-6}

Application to the Taegu Area

While the information obtained from such synthetic tests may be extremely valuable, it is not sufficient to conclude that the method will perform with a similar degree of success when applied to real data. Hence, let us turn to the problem of estimating the hydraulic parameters of an aquifer in the Taegu area in order to demonstrate that the proposed method can indeed handle real systems successfully. For the purpose of comparison hydraulic conductivities in the Taegu area are estimated by using both a proposed inverse methodology and an inverse model MODINV. Net-infiltration rates in the Taegu area are also estimated by using MODINV.

Descriptions of Site and Configuration of the Aquifer

The Taegu area is mainly composed of sedimentary materials and represents the typical stratigraphy of the Kyongsang supergroup (Figure 3). The aquifer system in this area is considered as one hydrostratigraphic unit. The hydrostratigraphic unit is basically a confined aquifer with the thickness range from 10m to 97m. The measured data available for the Taegu area are hydraulic head data at 64 observation wells. The locations of the observation wells are shown in Figure 4. A specified head boundary is set along the boundaries of the Taegu area which seems to act as the water divide.

Estimation of hydraulic conductivities

The purpose of parameter estimation in this problem is to identify the transmissivity of the aquifer in this area. Two zonation models for estimating transmissivities in the Taegu area are constructed based upon the lithology of this area. One, referred to as model 1 (Figure 5), has three zones : 1) granitic zone including Palgongsan Granite, 2) sedimentary zone including Chinju, Chilgok, Silla Conglomerate, Haman, and Panyaweol Formations, and 3) andesitic zone including Hakpong Volcanic Formation. The other model, referred to as model 2 (Figure 6), has four zones. In model 2, the sedimentary zone in model 1 is divided into two subregions : the northwestern part, and the southeastern part of Hakpong Volcanic Formation. The remainder is the same as that of model 1. With the two zonation models, this study deals with three cases; in cases 1 and 2 the isotropic transmissivities corresponding to models 1 and 2 are estimated, respectively, and in case 3 the anisotropic transmissivities are estimated for model 1. In case 3, transmissivities with an anisotropic ratio 100 to 1($T_{xx}/T_{yy}=100/1$)are to be estimated.

The recharge rates are given nonuniformly over the region. The recharge rate for urban area in the region is given as 5.5% of the total precipitation (Sung, 1991), and in the other areas, their land

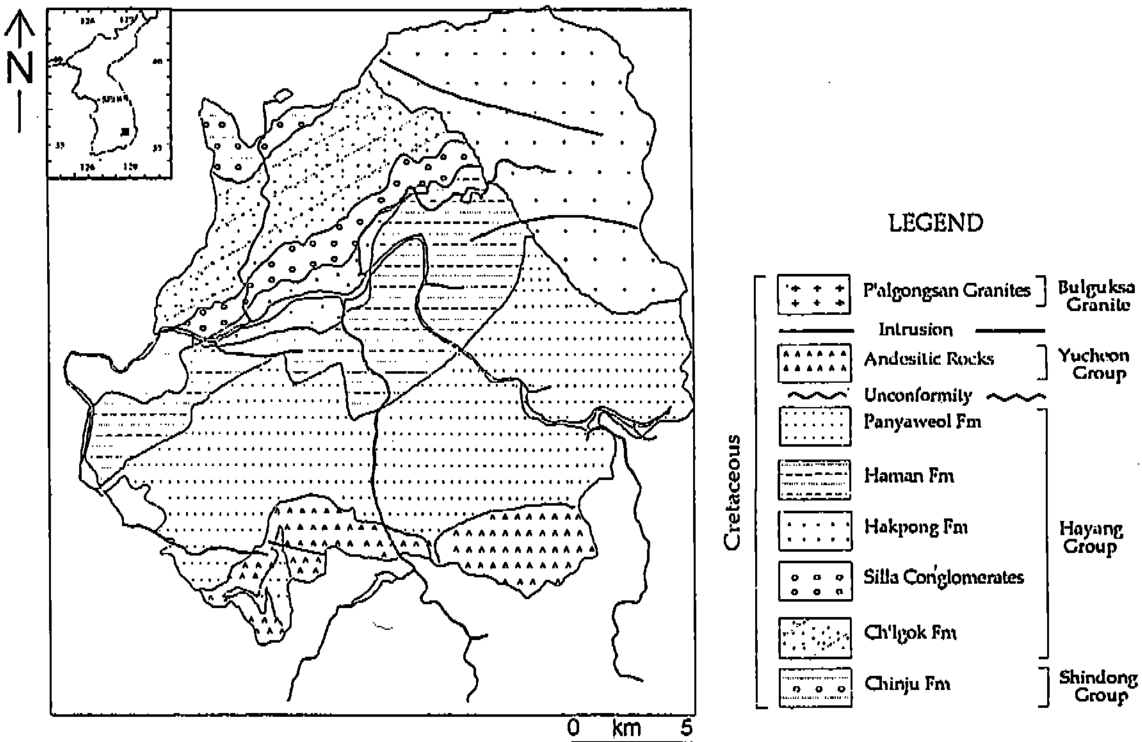

Fig. 3 Geologic map of the Taegu area(After Chang, 1975 : Choi, 1986).

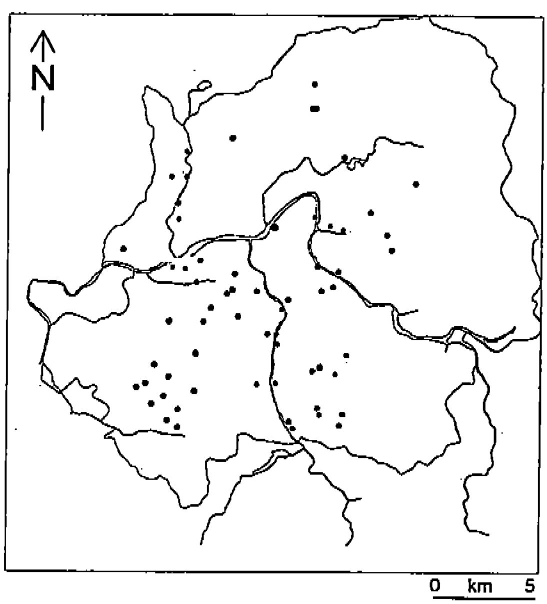

Fig. 4 Location map of head measurements.

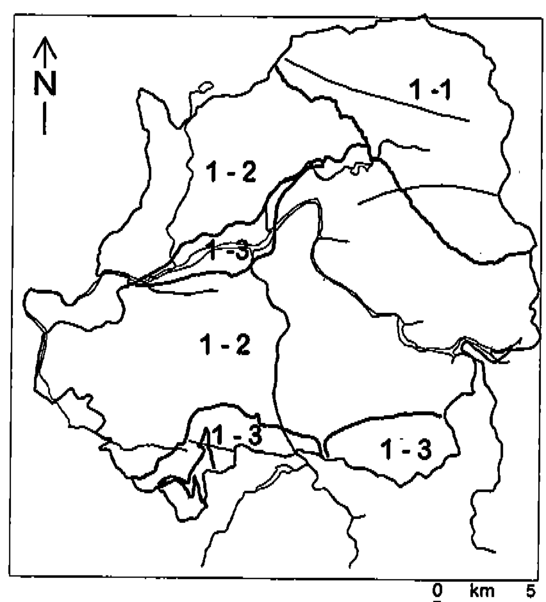

Fig. 5 Transmissivity zonation model 1 for the Taegu area.

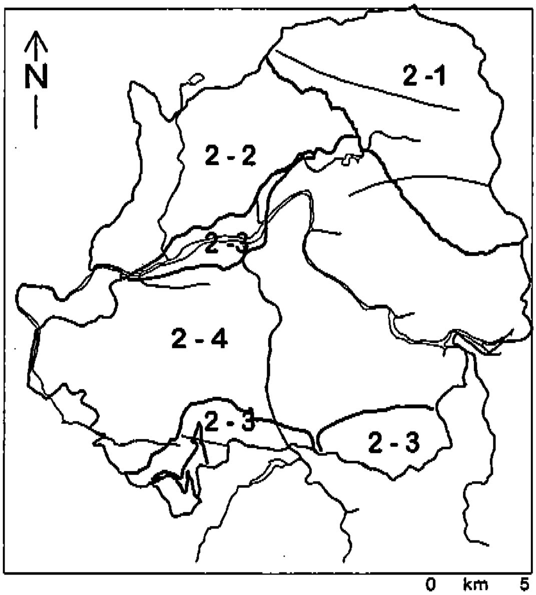

Fig. 6 Transmissivity zonation model 2 for the Taegu area.

Table 3. Recharge rates according to the land use in the Taegu area.

Land use	SCS CN	Recharge rates (m/sec)
Urban	82	0.241×10^{-9}
Forest	77	0.257×10^{-9}
Paddy	56	0.657×10^{-9}
Industry	95	0.208×10^{-9}
	Total	1.363×10^{-9}

use and corresponding Soil Conservation Service (SCS) curve numbers(CN) are considered to assign the recharge values. The total amount of precipitation is 1,382mm/year, which has been estimated from April, 1985 to March, 1986. The assigned recharge rates are listed in Table 3. The initial transmissivity for the iterative inverse solution is equally given to all zones by $2{,}961 \times 10^{-4}$ m^2/sec based upon the analysis of pumping test data in Haman Formation(Sung, 1991). For three cases described above, transmissivities are estimated by using both the proposed inverse model and MODINV, and the results are compared. The resulting transmissivity estimates for the three cases are given in table 4a, 5a, and 6a, respectively. Eigenvectors and the corresponding eigenvalues are also computed for the estimation error analysis. Two transmissivity estimates for each zone are listed. The former estimated value is obtained by using the proposed inverse model, and the latter by using MODINV. In case 1, the transmissivities estimated for zone 1-1 are 0.8961×10^{-5} and 0.1470×10^{-4} m^2/sec, where the transmissivity range corresponds to the typical range of transmissivity in fractured media. For zone 1-3, the transmissivities are estimated to be 0.3667 and 0.1470×10^{-1}m^2/sec. These are rather small, but reasonable estimates for basaltic rocks. For zone 1-2, the transmissivities are estimated to be 0.3526×10^{-2} and 0.8455×10^{-3}m^2/sec. These values are somewhat different than prior information on transmissivity obtained from pumping tests in this zone. This can be explained that zone 1-2 composed of sedimentary materials is large enough to give heterogeneous transmissivities due to the spatial heterogeneity in grain size distribution, alluvium thickness, and the other possible factors. This reasoning becomes clear when examining the eigenvectors and eigenvalues. Tables 4b and 4c show that the estimated transmissivities for zone 1-2 are the least reliable.

In order to represent the spatial heterogeneity of zone 1-2 more suitably in the above case zone 1-2 having the largest uncertainty is divided into two subregions in case 2. Let us designate these two subregions by zones 2-2 and 2-4. This is model 2 as stated earlier(Figure 4). Case 2 is expected to yield better results compared to case 1 according to the above reasoning. When using the proposed model, the result seems more reasonable as long as the transmissivities in zones 2-2 and 2-4 are concerned. The estimated transmissivity in zone 2-2 is a little higher than zone 2-4 as shown in Table 5a. However, the transmissivity estimates in zones 2-2 and 2-4 are quite acceptable as well as smaller eigenvalues were obtained. When using MODINV, the same results were obtained, too. The results ars consistent with the corresponding lithology. For zone 2-3, very similar values are estimated by the two models. Comparing eigenvalues, the estimates

Table 4a. Transmissivity estimate in the Taegu area for case 1.

Zone	Estimated Transmissivity	Estimated Transmissivity by MODINV
1	0.8961×10^{-5}	0.1470×10^{-4}
2	0.3526×10^{-2}	0.8455×10^{-3}
3	0.3667	0.1470×10^{-1}

Transmissivities are in m^2/day.

Table 4b. Matrix of eigenvectors and the corresponding eigenvalues by using the proposed inverse model for case 1.

	Eigenvector	
0.8519	-0.0072	-0.0375
0.0758	-0.0843	0.8553
0.5181	0.9964	0.5168
	Eigenvalue	
1.890×10^{-3}	3.375×10^{-1}	5.663×10^{1}

Table 4c. Matrix of eigenvectors and the corresponding eigenvalues by using MODINV for case 1.

	Eigenvector	
0.9984	-0.0399	-0.0394
0.0362	-0.0787	0.9962
0.0429	0.9961	0.0771
	Eigenvalue	
2.389×10^{-3}	1.183×10^{-1}	1.382×10^{2}

Table 5a. Transmissivity estimate in the Taegu area for case 2.

Zone	Estimated Transmissivity	Estimated Transmissivity by MODINV
1	0.7314×10^{-4}	0.2940×10^{-4}
2	0.8921×10^{-4}	0.8270×10^{-4}
3	0.5274	0.7986
4	0.3444×10^{-4}	0.1688×10^{-4}

Transmissivities are in m^2/day.

Table 5b. Matrix of eigenvectors and corresponding eigenvalues by using the proposed inverse model for case 2.

	Eigenvector		
0.0810	-0.0171	0.9266	0.3669
-0.9886	0.0605	0.1165	-0.0732
0.1109	0.0027	0.3575	-0.9273
0.0610	0.9980	0.0079	0.0132
	Eigenvalue		
4.571×10^{-2}	5.678×10^{-1}	1.322×10^{-1}	1.196

Table 5c. Matrix of eigenvectors and corresponding eigenvalues by using MODINV for case 2.

	Eigenvector		
0.0372	-0.5026	0.8636	-0.0128
-0.9990	-0.0044	0.0402	-0.0202
0.0196	0.0002	-0.0155	-0.9997
-0.0165	-0.8645	-0.5023	0.0072
	Eigenvalue		
1.390×10^{-2}	9.423×10^{-2}	2.623×10^{-1}	3.867×10^{1}

for zone 2-3 are found the most uncertain. Lastly, in case 3 where all the conditions are the same as in case 1 only except that anisotropy is given. In this case, the x-directional transmissivity can be estimated by using the proposed model. MODINV cannot estimate each component of anisotropic transmissivity. Results are listed in Table 6a. The estimated transmissivity in each zone is accepted as reasonable one. Table 6b shows the transmissivity estimate for zone 3-3 which has the most uncertainty like what appeared in the result of case 2. Transmissivity for zone 3-2 is rather reliable.

Table 6a. Transmissivity estimate in the Taegu area for case 3.

Zone	Estimated x-directional Transmissivity
1	0.5150×10^{-5}
2	0.1481×10^{-4}
3	0.1030

Transmissivities are in m^2/day.

Table 6b. Matrix of eigenvectors and corresponding eigenvalues for case 3.

	Eigenvector	
0.7887	-0.0074	-0.6148
0.1098	-0.9822	0.1527
0.6049	0.1879	0.7738
	Eigenvalue	
2.624×10^{-3}	9.955×10^{-1}	4.512×10^{1}

Estimation of recharge rates

As stated earlier, the proposed inverse model can estimate the hydraulic conductivities(or transmissivities)by using head data, and other aquifer paramerers are not concerned. However, the inverse problem can deal with not only aquifer parameters, but initial conditions, boundary conditions, and sink or source terms. For the purpose of illustration, the recharge rates are to be estimated by using MODINV. The hydraulic conductivities are assumed to be known, and the estimates in the case 3 are assigned. The zonation model for estimating recharge rates is designed on the basis of the land use map in the Taegu area as shown in Figure 7. Zone 1 includes urban area, and zone 2 represents forest area. Paddy area is represented as zone 3, and the industry area is referred to as zone 4. The estimated recharge rates are very similar to the assigned values in case 3(Table 3), and are listed in Table 7.

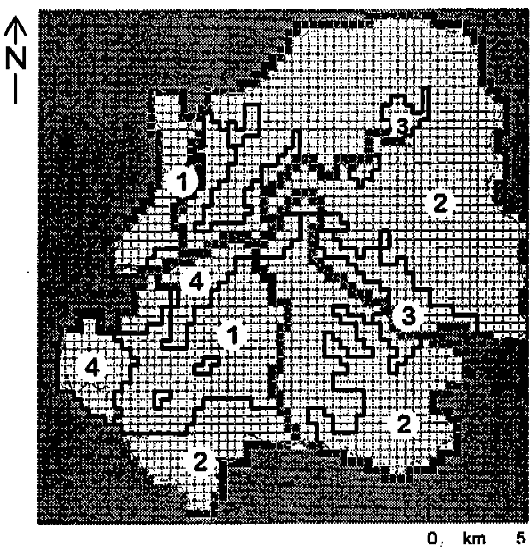

Fig. 7 Recharge rate zonation for the Taegu area.

Table 7. Recharge rate estimate in the Taegu area.

Zone	Estimated Recharge Rate
1	0.1942×10^{-9}
2	0.2250×10^{-9}
3	0.2399×10^{-9}
4	0.6105×10^{-9}

Recharge rates are in m/sec

Conclusions

1. An inverse method based upon a maximum likelihood concept and an adjoint state method with several conjugate gradient techniques is developed to identify aquifer parameters by using hydraulic head data.
2. The proposed model can analyze the estimation errors in eigenspace by adopting Fisher information concept, and computing the covariance matrix, eigenvectors, and corresponding eigenvalues. According to this theory, large eigenvalues correspond to linear combinations of parameters estimated with less confidence than combinations associated with smaller eigenvalues.
3. The ability of the proposed model for the estimation of anisotropic conductivities and the analysis of estimation error structure is demonstrated through application of the model to a synthetic example.
4. As a field example, the inverse methodology is applied to head data of the Taegu area. This study estimated the transmissivities in the Taegu area for three cases by using the proposed model and MODINV, and compared the results. Both results are acceptable, and consistent with those of lithology in this region.
5. Net infiltration rates in the Taegu area are estimated by using MODINV. Estimated net infiltration rates are somewhat consistent with the values assigned on the basis of the land use map in this area and Soil Conservative Service (SCS)curve number.

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