ESTIMATION OF NET GROUNDWATER RECHARGE IN LARGE AQUIFER SYSTEMS BY GENETIC ALGORITHM: A CASE STUDY

K. Lakshmi Prasad[1] and A. K. Rastogi[2]

[1]Professor, Department of Civil Engineering, Bapatla Engineering College, Bapatla, Andhra Pradesh, India
[2]Professor, Department of Civil Engineering Indian Institute of Technology, India

Abstract: Present study deals with the development of a numerical model for the estimation of net annual recharge by coupling the Galerkin's finite element flow simulation model with the Gauss-Newton-Marquardt optimization technique. The developed coupled numerical model is applied for estimating net annual recharge for Mahi Right Bank Canal (MRBC) project area, Kheda and Anand Districts, Gujarat. The net recharge is also estimated by water balance approach, which adopts the norms of Groundwater Resources Estimation Committee (1984, 1997) and Indian Agricultural Research Institute (1983). It is observed that the estimated net recharge by inverse modeling is closer to the net recharge estimated using the water balance approach. Further it is observed that the computed head distribution from the estimated recharge agrees closely with the observed head distribution. The study concludes that the developed model for inverse modeling can be successfully applied to large groundwater systems involving regional aquifers where reliable recharge estimation always requires considerable time and financial resources.

Key words: Inverse modeling, genetic algorithm, FEM, recharge, unconfined aquifer

1. INTRODUCTION

The problem of estimating aquifer parameters with the aid of a numerical model using limited geologic and hydrogeologic data is often referred to as inverse modeling. The fundamental benefit of inverse modeling is its ability to automatically calculate parameter values that produce the best fit between observed and simulated hydraulic heads. Inverse modeling involves system simulation and optimization. Optimization algorithms of gradient, conjugate gradient, quasi Newton, Gauss-Newton, or modified Gauss-Newton methods are largely used for computing optimum parameters. Yeh (1986) and Sun (1994) have discussed relevant aspects of these inverse modeling techniques in greater detail. Recharge from rainfall, seepage from canal distribution system and deep percolation from irrigated fields are the normal inputs to a large aquifer system. It is infact very difficult to correctly quantify the net recharge into an aquifer because except pumping, the other contributions to the aquifer can not be estimated with exactness. Consequently, in many countries often the values recommended by the ministry of water resources or various irrigation offices, water research centres and water resources bulletins are used to assess the quantum of the other recharge terms. Alternatively, empirical formulae are also used to estimate these quantities which are checked and modified by actual on site measurements and small-scale experimentation. For example in India, such recharge quantities are estimated using recommendations of the "Groundwater Estimation Committee of Ministry of Irrigation" and "Groundwater Resources Estimation Committee of Ministry of Water Resources". Net quantity of the recharge can be estimated from the various components that constitute the inflow, outflow and withdrawals from the groundwater basin.

In the present study, the inverse modeling procedure require the formulation of an objective function (2) the parameterization which reduces the number of parameters to be identified inorder to stabilize the inverse problem and (3) the optimization algorithm which estimates the parameter set. The objective function involves weighted least squares (WLS) method and the required flow simulation model for computing the head distribution is based upon Galerkin's finite element approach. The aquifer domain is parameterized using zonation and Gauss-Newton-Marquardt (GNM) method is used for estimating the optimal zonal recharge values.

2. THE STUDY AREA

The present study region of MRBC project area situated in Kheda and Anand districts in Gujarat state (Fig. 1) covers an area of 2997 sq. km and is bounded by Shedi river in the north, Mahi river in the east and south and Alang drain in west direction. The MRBC command area lies between north latitudes 22^0 26′- 22^0 55′ and

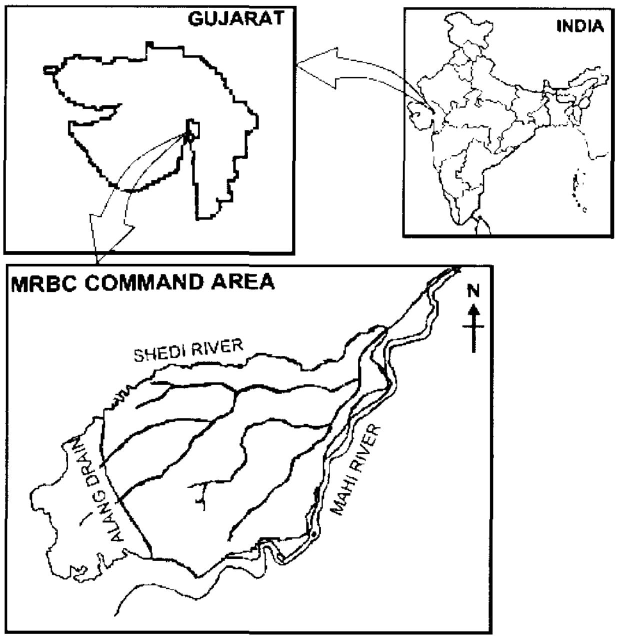

Fig. 1. MRBC project area location map

east longitudes 72^0 49'- 73^0 23' and climate of the area is arid to semi arid with an average rainfall of 823 mm. About 96% of rainfall occur in the monsoon season (June-Sept.) and there is substantial variation in the monthly and annual rainfall. Detailed field investigations of the region were carried out by Gujarat Water Resources Development Corporation (GWRDC), Gandhinagar. Lithological cross sections of selected regions of the area have indicated the presence of a main water table aquifer consisting mostly of a mixture of gravel and sand which exhibits a large variation in the conductance properties. The applicable value of specific yield within the aquifer region is 0.15. Analysis of water table maps of the past few years suggested that the recharge to the aquifer from rainfall, canal seepage, and irrigation return flows exceeds the groundwater withdrawals from the region resulting in a steady rise of water table. For simulation purposes net annual recharge values over the area were considered. It is also assumed that in the present model the average annual inflow is almost negligible compared to average annual outflow across the boundaries, which is computed by subtracting pumping withdrawals and aquifer storage from the net annual recharge. The no inflow assumption is justified inview of a continuously rising trend of the water level suggesting aquifer storage and outflows.

3. FLOW SIMULATION MODEL

The governing equation for the groundwater flow in the MRBC command area can be given as

$$\frac{\partial}{\partial x}\left\{k_x(h-\eta)\frac{\partial h}{\partial x}\right\}+\frac{\partial}{\partial y}\left\{k_y(h-\eta)\frac{\partial h}{\partial y}\right\}+R=s_y\frac{\partial h}{\partial t} \tag{1}$$

where h (x, y, t) is the hydraulic head (m), s_y is the specific yield, η (x, y) is the elevation of aquifer bottom (m), k_x and k_y are the hydraulic conductivity values (m/d) in the principal axes direction and R (x,y,t) is the net nodal recharge (m/d).

The initial and boundary conditions for the problem are given as,

$$\begin{aligned} &h(x, y, 0) = H(x, y) \text{ for all } x, y \in \Omega \\ &h(x, y, t) = H_R(x, y, t) \text{ for all } x, y \in \Omega_1 \end{aligned} \tag{2}$$

where, H is the initial groundwater head (m) in the aquifer domain Ω and H_R is the known head (m) along the Alang drain and the river boundaries Ω_1.

The solution of the above governing equation (Eq. 1) is obtained by Galerkin's finite element approach. The study area is discretized into 171 nodes and 294 triangular elements (Fig. 2). The resulting system of linear equations can be finally written in the matrix form as,

$$\left([G]+\frac{1}{\Delta t}[P]\right)\left\{h_L^{t+\Delta t}\right\}=\frac{1}{\Delta t}[P]\left\{h_L^t\right\}+\{F_L\} \tag{3}$$

where **[G]** is the conductance matrix containing hydraulic conductivity terms, **[P]** is the storage matrix with specific yield terms, Δt is the size of timestep, vector $\{F_L\}$ is the net flux at node L, $\{h^{t+\Delta t}\}$ is the unknown head vector and $\{h^t\}$ is the known head vector at time t. The solution is then carried out iteratively and during each timestep the right hand side known vector and the conductance matrix is updated with the latest head values to take care of the transient nature of the problem. The objective function is weighted least squares function where the functional to be minimized is

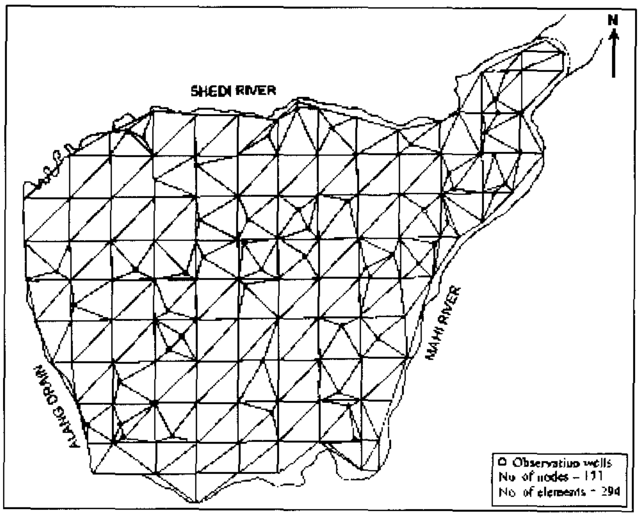

Fig. 2. Finite element discretization of the study area

$$\underset{T_1,\dots,T_M}{\text{Min}}\ J = \sum_{L=1}^{L}\sum_{t=t_0}^{t=t_f}\omega_{L,t}\left[h^C_{L,t} - h^{OB}_{L,t}\right]^2 \tag{4}$$

subject to the lower and upper bounds of the parameters

$$ZR_i^l \le ZR_i \le ZR_i^u \tag{5}$$

where, $h^C_{L,t}$ and $h^{OB}_{L,t}$ are computed and observed heads at observation well L and at time t, ZR_i is recharge at homogeneous zone i, M are number of recharge zones, L are number of observation wells, t_0 and t_f are beginning and ending times of observations, l and u are superscripts used to denote lower and upper bounds of parameters and $\omega_{L,t}$ is weighting matrix. Presently in the absence of any reliable information regarding the quality of measurements, equal weightage is assumed for all the observations first, then weight matrix is derived based upon observed head and also computed as the inverse of error covariance $(\sigma H)^2$ matrix.

4. INVERSE MODELING FOR ESTIMATING NET RECHARGE

The field data of 1984 and 1985 is used to estimate net annual recharge in the study area. The observation heads at 57 observation wells in the aquifer domain are used in the present study. The study region is parameterized into 10 zones (Fig. 3) based upon the geological mapping, topography and prior information on parameters. Based upon field information the lower and upper bounds for the zonal recharge parameters is chosen as 5×10^{-5} to 10^{-3} for all the ten zones. The zonal recharge is estimated considering different initial estimates and in all cases the parameters converged to same recharge values. The estimated zonal recharges for different weighting coefficients are tabulated in Table 1.

It is observed that the estimated net annual recharge by inverse modeling is closer to the estimated annual recharge from the field data considering the inflows and outflows of the aquifer region. From the estimated zonal recharges,

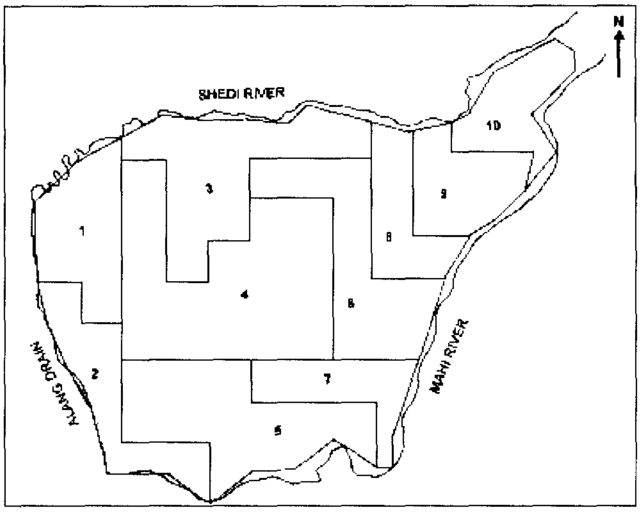

Fig. 3. Zonation pattern of the aquifer domain (10 zones)

Table 1. Estimated zonal recharge ($R\times10^{-5}$ m/d) by Inverse Modeling

Zone No	ESTIMATED RECHARGE (10^{-5} m/d)					
	$\omega_{i,j}=1$	$\omega_{i,j}=\frac{1}{h^{ob}_{i,j}}$	$\omega_{i,j}=\left(\frac{1}{h^{ob}_{i,j}}\right)^{1.5}$	$\omega_{i,j}=\left(\frac{1}{h^{ob}_{i,j}}\right)^{1.75}$	$\omega_{i,j}=\left(\frac{1}{h^{ob}_{i,j}}\right)^{2}$	$\omega_{i,j}=\left(\frac{1}{\sigma_H}\right)^{2}$
1	29.486	27.536	26.723	26.360	26.013	29.486
2	64.901	62.777	62.151	61.903	61.692	64.901
3	71.619	71.113	70.848	70.704	70.548	71.619
4	96.073	88.717	85.093	83.298	81.561	96.073
5	33.773	33.118	32.733	32.531	32.316	33.773
6	81.752	75.225	72.253	70.756	69.339	81.752
7	65.894	66.089	66.073	65.969	65.890	65.894
8	89.727	93.147	94.658	95.342	95.542	89.727
9	17.835	19.954	21.203	21.833	22.942	17.835
10	5.000	5.000	5.000	5.000	5.000	5.000

the net annual recharge in the aquifer domain is computed as

$$\sum_{i=1}^{\text{No. of zones}} \left\{(\text{Zonal recharge})_i\ (\text{Zonal area})_i \times 365\right\} \quad (6)$$

Thus, the estimated net annual recharge by inverse modeling using GNM method is 688.45 MCM. These values are in close agreement with the estimated net annual recharge (741.97 MCM) by the water balance approach (Table 3)

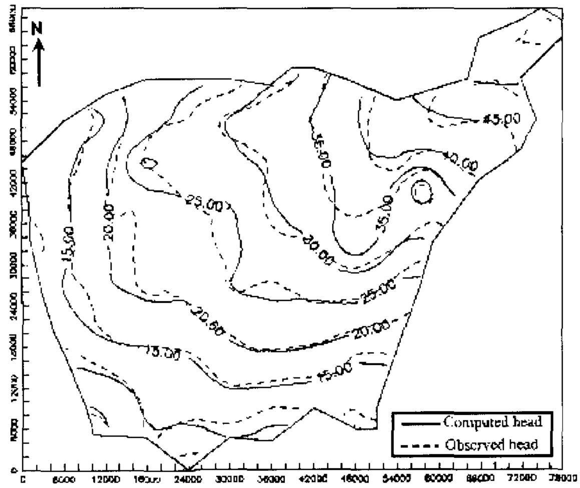

Fig. 4. Comparison of computed head from inversemodeling and observed head for 1985

considering the various inflow and outflow data collected from the field. It is observed that the weights have not improved the solutions in the present study. Further the resulting rise in water table is determined using a specific yield value of 0.15. These values are compared well with the observed values of water table rise which indicate that the regional groundwater recharge estimates are realistic. Further, the computed head distributions using the zonal recharges estimated by inverse modeling are in close agreement with the observed head contours (Fig.4).

5. NET RECHARGE BY WATER BALANCE APPROACH

The net regional recharge (R_n) to groundwater during any time period is estimated as

$$R_n = R_g \pm Q_g - Q_p \quad (7)$$

where R_g = Gross recharge to groundwater basin, Q_g = Groundwater inflow or outflow to neighbouring areas and Q_p = Groundwater extraction through wells.

The gross recharge (R_g) to the groundwater basin is given by:

$$R_g = R_p + R_c + R_d + R_{ci} + R_{wi} \quad (8)$$

where R_p = recharge from rainfall occurring in the command area, R_c = seepage from main canal and branches, R_d = seepage from distributaries, R_{ci} = return flow from the canal irrigated areas and R_{wi} = return flow from the area irrigated by wells.

The terms on the right hand side of the Eq. (8) are estimated using the recommendations of Groundwater Estimation Committee of Ministry of Irrigation (1984), Groundwater Resource Estimation Committee of Ministry of Water Resources (GWREC, 1997) and Indian Agricultural Research Institute (IARI) research bulletin (1983).

Following recharge and discharge terms were considered to compute the net recharge in the flow domain:

[a] Recharge from rainfall: The average annual rainfall for the year 1984-85 was 833.86 mm. The area has large coarse textured soil for which GWREC (1984) has recommended 12 to 18% of the annual rainfall. Considering 17% as recharge, thus the annual average recharge due to rainfall = $0.83386 \times 0.17 \times 2.997 \times 10^9/10^6$ = 424.84 MCM (million cubic meter).

[b] Seepage from the main and branch canals: According to the data available from the department of irrigation, MRBC project, Nadiad 2034 MCM water was delivered into the canal system during the study period. Based on recommendations of IARI (1983), 2.6% of the total water is considered as seepage. Therefore the applicable recharge due to canal seepage losses = $1872.6 \times 0.026 = 48.688$ MCM.

[c] Seepage from distributories: Distributories in the region are unlined and seepage losses amount to 7% of the total water available from the lined canal system - IARI (1983) (ie. water remaining after accounting for seepage losses from the lined main and branch canals). Thus for the period under study, seepage losses from the distributories = (1872.6-48.69) =1823.91 × 0.07 = 127.674 MCM.

[d] Return flow from canal irrigated areas: 30% of the water delivered at the outlet for application in fields is considered as return flow from irrigation IARI (1983). Therefore, return flow from canal irrigated areas for the year 1984-85 = (1823.91-127.67) = 1696.24 × 0.30 = 508.87 MCM. In wetland paddy fields there is continuous deep percolation. This is to be accounted separately in addition to the above estimates. IARI recommended additional percolation losses to be 3 mm/d for 100 days of paddy cultivation. The average area under paddy during the kharif season was 71123 hectares for the period of 1984-85. Thus, additional recharge to groundwater = $71123 \times 0.003 \times 10^4 \times 100/10^6$ = 213.37 MCM. Thus, total return flow from canal irrigated areas = 508.87 + 213.37 = 722.24 MCM.

[e] Ground water draft: As per the records of GWRDC, Gandhinagar the groundwater draft for 1984-85 was 214.79 MCM.

[f] Return flow form well irrigated areas: Following the recommendations of the Ground water Recharge Estimation Committee Report (1984, 1997), the deep percolation from areas irrigated by wells is 15 % of the pumping well water applied to the field. Thus return flow for the period under study = 214.79 × 0.15 = 32.22 MCM.

[g] Groundwater outflow or inflow from the basin to neighboring areas (Q_s): Groundwater outflow was worked out from the annual water balance of the MRBC project area for which all the required data are available. The water balance equation can be written as,

$$(P + I) = Q_g + Q_p + Q_s + ET + E \pm \Delta S_c \pm \Delta S_g \pm \Delta S_m \pm \Delta S_s \quad (9)$$

where P = Total precipitation during the study period (June 1 to May 31) i.e. one year, I = Total amount of irrigation from all sources, Q_g = Out flow of groundwater across basin boundaries, Q_p = Quantity of water pumped (draft), Q_s = Surface runoff outflow across the basin boundaries, ΔS_c = Change in capillary storage, ΔS_g = Change in groundwater storage, ΔS_m = Change in soil moisture storage, ΔS_s = Change in sur-

Table 2. Annual water balance of MRBC Project area (1984-85) in mm

Year	Input				Output						Groundwater outflow
	Rainfall	Irrigation		Total	Q_p	ET	E	ΔS_g	Q_s	Total	
		Canal	Well								
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1984 -85	833.86	703.69	71.67	1609.22	71.67	530	315	267.67	291.85	1475.22	133.10

face water storage.

All the above quantities are expressed in depth (mm) over the gross command area of 2997 sq. km. Since the MRBC system doesn't have a significant natural surface water body within the system, at the beginning of June every year it is considered practically dry for the purpose of annual water balance computations. Therefore the change in surface water storage (ΔS_s) is assumed to be zero. Since the water balance computations are done on an annual basis, it is assumed that there will be no significant change in soil moisture storage (ΔS_m) and soil capillary storage (ΔS_c). The annual rainfall (P) over the MRBC command area for the year 1984-85 was computed as arithmetic mean of rainfall occurrence at various stations and found to be 833.86 mm. Irrigation from other independent sources such as tanks, local streams etc., is negligibly small. The total volume of irrigation water delivered, expressed in depth of water in mm over the gross command area (2, 99, 700 ha) amounts to: canal irrigation: 703.69 mm, well irrigation: 71.67mm, groundwater draft (Q_P) was 71.67mm. Evapotranspiration (ET) for the years 1984-85 is considered as 535 mm as per the available information. The average values of evaporation (E) for the years 1984-85 is 315 mm, when distributed uniformly over the gross command area of 2, 99, 700 ha from the available information. Average rise is calculated based on the groundwater levels for the pre-monsoon and post-monsoon periods over 57 wells, which are distributed uniformly over the command area. The average annual rise in water table was found to be 1.784 m for the year 1984-85. The volume of water stored accounting for this average rise was computed by using a value of 0.15 for the specific yield. The quantity of increase in groundwater storage expressed as mm depth over the gross command area of 2, 99, 700 ha. Thus, Change in groundwater storage (ΔS_g) for year 1984-85 = $0.15 \times 1.784 \times 299700 / 299700$ = 267.67 mm. For the MRBC system, it was considered that 35% of the annual rainfall as runoff as the annual rainfall is between 600 and 1000 mm. Accordingly, the surface runoff outflow (Q_s) from the command area for 1984-85, was (833.86×0.35) 291.85 mm. As mentioned earlier, this quantity was sought to be computed as a residual of the water balance. Computations of groundwater outflow from the MRBC area are given in Table 2. The average annual groundwater flow for the year 1984-85 is 133.10mm depth over the gross command area 2, 99, 700 hectares or 398.90 MCM. The net annual groundwater recharge considering the inflows and outflows of the project area is found to be (Table 3) 741.97 MCM.

Table 3. Net annual groundwater recharge(1984-85) in MCM

Year	Rainfall	Seepage from main canal and branches	Seepage from dis-tribut-aries	Return flow from canal irrigation	Return flow from well irrigation	Ground water extraction	Ground-water outflow	Aquifer storage or Net recharge (1)+(2)+(3)+(4) +(5)-(6)-(7)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1984-85	424.84	48.69	127.67	722.24	32.22	214.79	398.90	741.97

6. CONCLUSIONS

The developed coupled numerical model based upon Gauss-Newton-Marquardt method and Galerkin's finite element approach can be successfully used for estimating net recharge in case of distributed parameter system such as regional aquifers where reliable recharge estimation is always a major problem in real system simulation.

ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance of GWRDC, Gandhinagar, S.E, MIC, Nadiad and GERI, Vadodara for providing the necessary data for the present study.

REFERENCES

IARI Research Bulletin- 42. Resource analysis and plan for efficient water management- A case study of Mahi Right Bank Canal Command area, Gujarat. Water Technology Centre, Indian Agricultural Research Institute, New Delhi (1983).

Ministry of Irrigation. Report of the groundwater estimation committee- Groundwater resource estimation methodology, Govt. of India, New Delhi (1984).

Ministry of Water Resources. Report of the groundwater resource estimation committee- Groundwater resource estimation methodology, Govt. of India, New Delhi (1997).

Sun Ne-Zheng. (1994). *Inverse Problems in Groundwater Modeling*. Kluwer academic publishers, Netherlands

Yeh WW-G. (1986). Review of parameter identification procedure in groundwater hydrology: The inverse problem. *Water Resour. Res*, 19. pp. 225-233

K. Lakshmi Prasad, Department of Civil Engineering, Bapatla Engineering College, Bapatla, Andhra Pradesh, India
(E-mail: kolalapudi_2000@yahoo.com)

K. Rastogi, Department of Civil Engineering Indian Institute of Technology, Bombay MUMBAI - 400 076, India