ISSN NO. 2320-5407

Journal homepage: http://www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH

RESEARCH ARTICLE

Application of Electronic Spread Sheet and Water Balance Error Optimization Technique in Ground Water Model Study to Improve the Ground Water System in Restricted Area

Sivakumar SS

Head - Civil Engineering and Senior lecturer GrI, Faculty of Engineering in Jaffna University, Ariviyal Nagar, Kilinochchi, Sri Lanka, Phone-(94) 077 250 8730. E-mail: sssivakumar@jfn.ac.lk

Manuscript Info

Manuscript History:

Received: 19 April 2014
Final Accepted: 23 May 2014
Published Online: June 2014

Key words: Agriculture, Error minimization, Ground water model, Operational policy, Recharge coefficient, Simulation model, Withdrawal factor.

Corresponding Author

Sivakumar SS

Abstract

A study was carryout for a restricted ground water catchment about 160 sq. kilo meters in Vavuniya in Northern Sri Lanka to find out an operational policy of minor and medium Irrigation schemes, to recharge the ground water system to increase the economic pumping. Forty one wells were identified as observation wells within the study area of 160 sq. kilo meters to represent the aquifer. This study area was divided into forty one Thiession polygons by connecting the perpendicular bisectors of adjoining observation wells with four year seasonal collected (Oct.2000 - May.2004) water levels and three years seasonal historic (Oct.1997 - May.2000) water levels. A ground water simulation model was formulated for this polygonal network using integrated finite difference method in spreadsheet. The model was calibrated for the period from 1997 to 2001 having eight seasons. Since the initial values were taken as October 1997, the time step Δt was taken as 8 months followed by 4 months. These time steps were used alternatively throughout the calibration period from 1997 to 2001. The rainy season was taken from 1st October to 31st May of next year and non-rainy season was taken from 1st June to 30th September. By this calibration the hydrogeological stress parameters such as Transmissibility, Storage coefficient, Recharge coefficient for Irrigation scheme, Recharge coefficient for irrigation field, Recharge coefficient for rainfall and the Withdrawal factor for agro and domestic pumping were found using optimization technique. A complete water balance study for each polygon for each season was carried out. Forty one error models were prepared for the water balance, for each polygon for all the season. MATHCAD2000 was used for this optimization. Using the results obtained a validation of the model was carried out with three seasonal water level (Oct.2001 – May 2003). The model successfully predicted the water levels with very little error (less than three percent). This integrated finite difference model in spreadsheet & calibrated by error optimization technique, validated and was used to predict the system behavior for various operational policy of the Vavuniya restricted ground water catchment during this research. This article elaborates the use of electronic spread sheet and the use of optimization packages in this research work to formulate a ground water simulation model in any restricted catchment.

INTRODUCTION

1. Objective of the Research

OBJECTIVE of this research is formulating a model to represent a restricted catchment of 160 sq. meters area in Vavuniya District, incorporating five medium irrigation schemes, forty two minor Irrigation schemes and number of dug wells in spread sheet. A mathematical simulation model is formulated using integrated finite difference method in spread sheet. This model was calibrated for the period from 1997 to 2001 having eight seasons and used as the mathematical representation of the restricted catchment selected, after validation for another three seasons from October 2001 to May 2002, June 2002 to September 2002 and October 2002 to May 2003 and recalibrated up to May 2003 by using the same nonlinear water balance error optimization method, to find

- An economic policy in operating the minor medium irrigation scheme
- A technique of peripheral cut off or sub surface dam

2. Model Formulation and Water Balance

2.1Conceptual Model

Conceptually, the modeling techniques used for system representation can be very simply explained as below and schematically as in Fig.1.

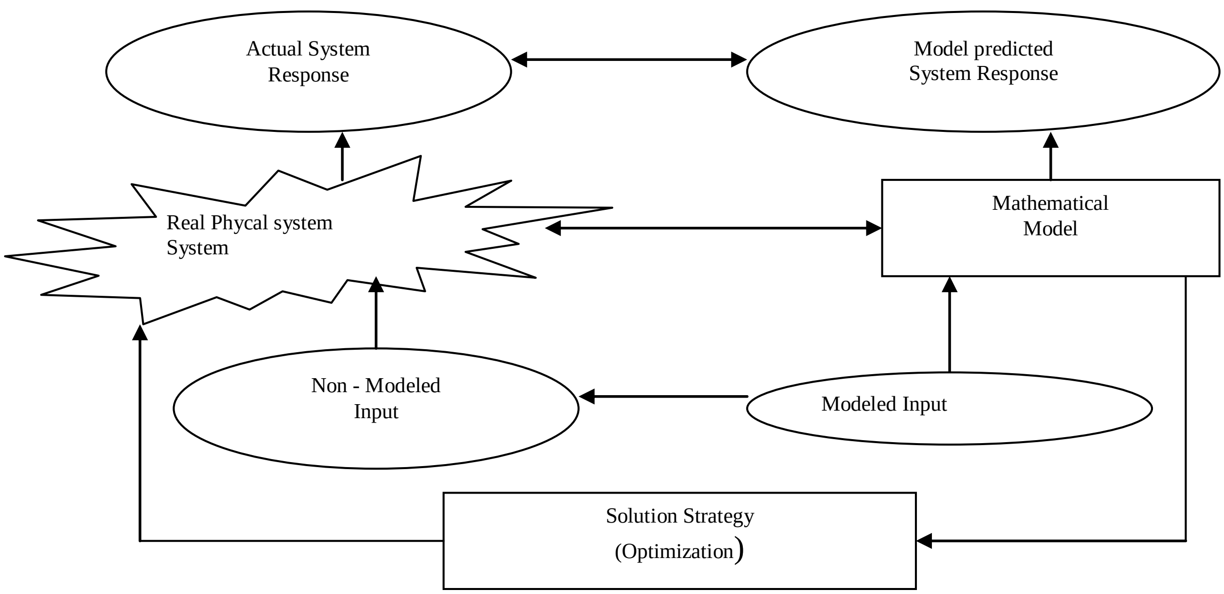


Fig1 Schematic representation of the process of system modeling and optimization

- Select or formulate a suitable model in electronic spread sheet
- Assume the important parameters approximately
- Adopt some error function to quantify the difference between measured and predicted responses
- Minimize the error function
- Determine the parameters accurately
- Predict system response

The equation of continuity of an unconfined aquifer in which there is no vertical variation of properties will be written as

$$-\frac{d}{dx}(km\frac{dh}{dx})-\frac{d}{dy}(km\frac{dh}{dy})+Sy\frac{dh}{dt}+Q=0$$

Where,

m - Thickness of saturated portion at the point of consideration.
h - Piezometric head
S_y - Specific yield
Q - Volumetric flow rate per unit area in vertical direction
t - Time
k - Permeability between polygonal boundaries
Transmissibility **T** will be equal to **k.m.**

Analytical solution of the equation is not possible for a complex natural system. Hence, numerical methods are necessary to solve the said equation. The integrated finite difference form of this differential equation for a typical node **B** and its association with its neighborhood nodes with particular reference to node **i** given in Fig.2 can be reduced by implicit numerical integration technique to the form at the time interval j and j+1 with time step Δt be written as

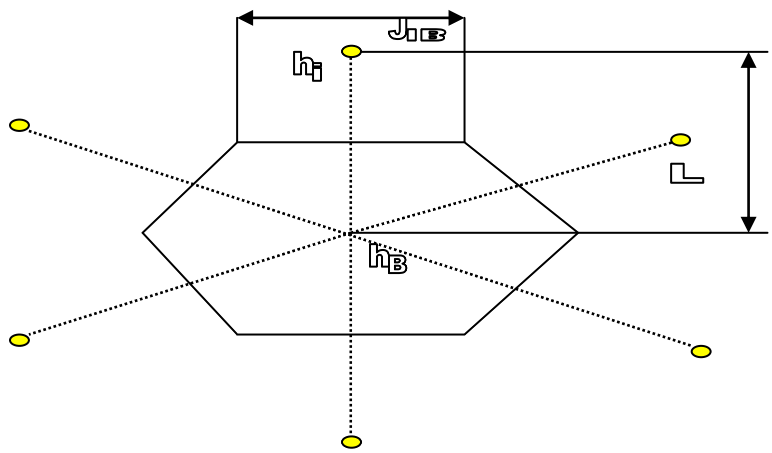


Fig 2-Typical polygon for node B with six observation wells surrounding

$$\sum_{i=1}^{M}(h_i^{j+1} - h_B^{j+1})Y_{iB}T_{iB} = \tfrac{S_B}{\Delta t}(h_B^{j+1} - h_B^{j})A_B + A_B Q_B^{j+1}.$$

Where,
h_i - Piezometric head of node i
h_B - Peizometric head at node B
$Y_{iB} = (J_{iB}/L_{iB})$ - conductance factor
T_{iB} - Transmissibility at mid-point between node B and i
J_{iB} - Length of perpendicular bisector associated with node B and i.
L_{iB} - Distance between nodes i and B
A_B - Polygonal area of node B
S_B - Shortage coefficient of node B
Q_B - Volumetric flow rate per unit area at node B.
M - No of observation wells surrounding node B
Δt - Time step between j and j+1

2.2 Water Balance

If we consider the water balance of this polygon for node **B,** Subsurface flow + Vertical flow will be equal to Change in storage. But there will be residue RES_B^{j+1}. This is due to the error in the assumed values of Transmissibility, Storage coefficients and Recharge coefficients.

$$RES_B^{j+1} = \sum_{i=1}^{M}(h_i^{j+1} - h_B^{j+1})Y_{iB}T_{iB} - \tfrac{S_B}{\Delta t}(h_B^{j+1} - h_B^{j})A_B + A_B Q_B^{j+1}$$

Objective of the calibration process is to determine the values of T_{ab}, S_B and recharge coefficients so as to minimize the square of this residue. Squaring is done to avoid cancellation of positive and negative errors.

2.3 Optimization Technique

In each of the error optimization model four variables for polygonal inputs, one variable for that particular polygonal Specific yield and five to seven variables for Transmissibility for every polygonal connection were formulated with constrains. Constrains were given as practicable ranges for the Recharge coefficients, Specific yield, and Transmissibility.
The objective function together with constrains below was used as error optimization models for each node.

$$Min\sum_{i=1}^{N}\left[\sum_{i=1}^{M}(h_i^{j+1}-h_B^{j+1})Y_{iB}T_{iB}-\tfrac{S_B}{\Delta t}(h_B^{j+1}-h_B^{j})A_B+A_BQ_B^{j+1}\right]^2$$

Where,

M - Number of observation wells surrounding node B

N - Number of seasons for calibration

Subject to

- $0.06 < S_B < 0.15$
- $15 < T_{iB} < 25$
- $0.075 < a < 0.15$
- $0.05 < b < 0.1$
- $0.15 < c < 0.25$
- $0.9 < d < 1.5$

Where a, b, c are the recharge coefficients of tank storage, field input, and rainfall respectively and d is the withdrawal factor.
For the entire study area altogether 164 variables for polygonal recharge coefficients, 41 variables for specific yield and 100 variables for transmissibility and 17 variables for the boundary lateral flow were found by error minimization using “GINO” / “MATCAD 2000”.

3. Formulation of Polygonal Network and Data Collection

The polygonal network was formulated by connecting the perpendicular bisector of the observation wells. Polygonal areas were planimetered. The conductance factors (J/L) of every connection were found by measuring the sides of the polygon (J) and distance between respective well points (L) and dividing them.

The following polygonal inputs were processed from the data available in Statistical handbook Vavuniya (1997 – 2005) and District Integrated Agriculture Development & Extension Program Vavuniya (1997 – 2005).

- Capacity of water stored in Irrigation scheme (m^3)
- Water issued for cultivation in irrigation scheme (m^3)
- Rainfall volume (m^3)
- Net pumping volume (m^3) that consists of the following
  - Pumping from domestic wells (m^3)
  - Pumping from agro wells (m^3)
  - Pumping from production wells (m^3).

4. Model Formulation in Spread Sheet and Matcad2000 for Calibration and Prediction

4.1 Spreadsheet Model Formulation for Calibration

4.1.1 Data entry in spreadsheet

4.1.1.1 Selection of season

Cell D7 is the identifier for the season for which the model data are to be updated. The season numbers is to be entered in Cell number D7 for running the model for that particular season. If the season number is entered the entire work sheet will update all the calculations for that season.

4.1.1.2 Nodal connectivity matrix

Every observation well is surrounded by few other observation wells in the polygonal network. This is called the nodal connectivity. The 100 nodal connectivities were given from B11 to AP51 in spreadsheet. This is a 41x41 square symmetric matrix. One was given for the connection and zero was given for the non-connection in this 41x41 square symmetric matrix.

4.1.1.3 Seasonal water level table

This is a rectangular matrix with 41 rows, for each observation well or polygonal identification and several columns for each nodal parameter such as nodal area and seasonal water levels at end of each season. These were given from B61 to K101 in the spreadsheet.

4.1.1.4 Conductance factor (J/L) matrix

The ratios of perpendicular bisectors to the distance between the connected nodes are called as conductance factors (J/L)**.** The conductance factor (J/L) of every connection was found by measuring the sides of the polygon (J) and distance between respective well points (L) and dividing J by L. The conduction factors calculated were given from B211 to AP251 as a 41x41 square symmetric matrix.

4.1.2 Model calculation in spreadsheet

The objective function together with the constraints below is used as error optimization models for each node**.**

$$Min\sum_{i=1}^{N}\left[\sum_{i=1}^{M}(h_i^{j+1}-h_B^{j+1})Y_{iB}T_{iB}-\tfrac{S_B}{\Delta t}(h_B^{j+1}-h_B^{j})A_B+A_BQ_B^{j+1}\right]^2$$

Here within the square brackets the value of transmissibility and storage coefficient are to be treated as constraint. Both components with these variables can be re grouped as below with transmissibility and storage coefficient.

- Lateral flow divided by Transmissibility
- Change in storage divided by Specific yield

4.1.2.1 Intermediate calculations

As the connectivity of the nodes were random in nature it is very difficult to utilize the water level in rows. Hence the water level matrix with connectivity is found essential.
For the same reason, the head difference matrix with connectivity was also found to be essential to precede the calculations of Lateral flow dived by Transmissibility and Change in storage divided by Specific yield.

4.1.2.1.1 Water level matrix for the season

If the season number is entered in cell D7 every row of this 41x41 square symmetric matrix shows the water levels of the observation wells representing the row under the column number where there is a connection with the respective row.

This was obtained by giving cell formulae connected with 'Nodal connectivity matrix' and 'Seasonal water level table'.
This is also a 41x41 square symmetric matrix which contains equation for any 8 seasons from B111 to PP151. By feeding seasonal water levels in slightly shifted from any number of seasonal calculations can be done with a slight change in the cell formula.

4.1.2.1.2 Head difference matrix for the season

This is also a 41 x 41 square matrix but not a symmetric matrix having cell equations from B141 to AP 201. This is a matrix having zero diagonal elements and the upper right elements are negative values of lower left elements.
This is giving the head difference (water level of column number minus water level of row number) for that particular observation well represented by column number and row number.

4.1.2.2 Final calculation

4.1.2.2.1 Matrix of lateral flow divided by transmissibility (M)

The lateral flow divided by transmissibility is part of a component in optimization model in MATCAD. Hence a 41x41 square non-symmetric matrix having zero as diagram elements with cell equations from B261 to AP301 was formulated to find these values for the prescription of the optimization model in MATCAD.
For all the 100 connections separate transmissibility variables were assigned and by error minimization using “MATCAD 2000” actual values were found.

4.1.2.2.2 Change in storage divided by specific yield

The change in storage divided by specific yield is also a part of a component in optimization model in MATCAD. Hence just a column result giving the seasonal change in storage divided by specific yield was calculated using suitable cell formula.

For the entire set of 41 polygons separate specific yield variables were assigned and by error optimization (error minimization) using “GINO” / “MATCAD 2000**”** actual values were found.

4.2 Error Optimization Model Formulation for Calibration in “GINO” / “MATCAD 2000”

4.2.1 Optimization (minimization) by “GINO”

The objective function is nonlinear and has large number of variables, the nonlinear optimization package GINO can handle variables up to 200 with constrains up to 100. It has therefore, not been possible to obtain optimal values for parameters so as to minimise total error in all the nodes. Optimal values of the parameters are to be determined for each node and its connection. These values are then to be taken up as initial values for further calibration.

Firstly for each node, models for minimization of the residue can be formulated. By GINO non-linear optimization package all the models can be minimized separately and the values of stress parameters and recharge coefficients can be found.
Taking these values of stress parameters and recharge coefficients as initial values to the groundwater model, residue in each node has to be found. Whenever the residue is not within the tolerance level, stress parameters and recharge coefficients have to be adjusted slightly, systematically and the residue for the first iteration can be found. By observing the trend of change in residue, within third or fourth iteration, the residues in all the nodes can be brought to the tolerance level.

This is a trial and error method. However MATCAD2000 which is much better than GINO (as MATCAD2000 is a user friendly package and require lesser computing time) was used in this study to minimize the iteration timing for non-linear error optimization.

4.2.2 Optimization (minimization) by “MATCAD 2000”

MATHCAD2000 is having the facility to optimize 1000 linear variables and 500 nonlinear variables.
As mentioned in the previous chapters the objective function together with the constrains below is used as error optimization models for each node.

$$Min\sum_{i=1}^{N}\left[\sum_{i=1}^{M}(h_i^{j+1}-h_B^{j+1})Y_{iB}T_{iB}-\tfrac{S_B}{\Delta t}(h_B^{j+1}-h_B^{j})A_B+A_BQ_B^{j+1}\right]^2$$

Where,
M - Number of observation wells surrounding node B
N - Number of seasons calibration is to be done
Subject to

- $0.06 < S_B < 0.15$
- $15 < T_{iB} < 25$
- $0.075 < a < 0.15$
- $0.05 < b < 0.1$
- $0.15 < c < 0.25$
- $0.9 < d < 1.5$

Where a, b, c are the recharge coefficients of tank storage, field input, and rainfall respectively and d is the withdrawal factor.
Entire 41 polygons were minimized using "MATCAD2000" one by one and the values of S_B, T_{iB}, a, b, c and d were found. While doing the 2nd node minimization, if it is connected to the 1st node the corresponding T_{iB} found from previous minimization was used

and that particular constrain was removed from the 2nd optimization model. By this method the entire 41 polygons were optimized and the hydro geological parameters for each polygon found.

While doing the 2nd node minimization, if it is connected to the 1st node the corresponding T_{iB} found from previous minimization was used and that particular constrain was removed from the 2nd optimization model. By this method the optimization models were run and the hydro geological stress parameters for each polygon were found as given in Table 4.1 and Table 4.2.

4.3 Prediction Model in Spreadsheet

For prediction, the water balance equation has been re arranged to have h_B^{j+1} in LHS with RHS as function of h_B^{j+1} as below.

$$h_B^{j+1} = h_B^j + \left[.A_B Q_B^{j+1} + \sum_{i=1}^{M} (h_i^{j+1} - h_B^{j+1}) Y_{iB} T_{iB}.\right] \Delta t / S_B A_B$$

In the Gauss-Seidal iteration method the value of h_B^{j+1} is found utilizing the function of GOALSEEK in spreadsheet.

As h_B^{j+1} is connected to M surrounding nodes, while finding the h_B^{j+1} the already found h_B^{j+1} will slightly vary. Hence after completing first iteration process for all the forty one nodes, the same process has to be repeated five to six times to get accurate results.

As explained in paragraph 4.1.2 the following items are formulated in spreadsheet.

- Time step Δt
- Nodal connectivity matrix
- Water level matrix for the selected time step
- Head different matrix
- Conductance factor matrix
- Transmissible matrix
- Calculation of trial h_B^{j+1}
- Error in water level

The function of GOALSEEK in spreadsheet with a small micro has been used in this prediction run, to do all the iteration in a few key strokes to predict the water level with zero error.

Even though the model is formulated season wise, prediction is possible monthly or even weekly by changing a few cell formulae and adding few more cell formulae.

5. Model Calibration

5.1 Model Validation

To test the validity of the model, using the calibrated parameters and using 8th season (Sept. 2001) water level as initial water level and the rest of the inputs, the 9th season (May 2002) water level was predicted using the prediction model. Where ever the predicted values were not matching with the observed values the stress parameters were systematically slightly adjusted to get a good match. In the same way, using 9th season (May 2002) water level as initial water level and the rest of the inputs, the 10th season (Sept. 2002) water level was predicted using the prediction model. In the same way, the water levels of May 2003, Sept. 2003, May 2004 and Sept. 2004 were predicted and compared with observed water levels.

5.2 Model Recalibration

The model was recalibrated as per the same optimization method using fourteen seasonal data. In each of the error optimization models, four variables for polygonal inputs, one variable for that particular polygonal Specific yield and five to seven variables for Transmissibility for every polygonal connection were formulated with constrains. These constrains were given as practicable ranges for the recharge coefficients, Specific yield, and Transmissibility. The results of the pumping test carried out by WRB in observation well number one was taken as a guide for giving ranges for Specific yield, and Transmissibility.

Recalibrated polygonal parameters such as recharge coefficients (rainfall, storage and field issue) and withdrawal factor, and hydro geological stress parameters such as transmissibility and storage coefficients fed in the model were used to run the prediction model. The recalibrated polygonal stress parameters are given in Table 5.3 and Table 5.4

5.3 Model Revalidation

The recalibrated model was run to test the validity of the recalibrated model, using the recalibrated parameters and using 14th season (Sept. 2004) water level as initial water level and the rest of the inputs, the 15th season (May 2005) water level was predicted using the prediction model.

The selection of tolerance level depends on the accuracy of the computation needed. In this study the accuracy in water level was taken as one centimetre. This led a good match in predicted water level and observed water level (refer Table 5.1 and 5.2). The comparison of the predicted water level with measured water level is given as figure 5.1 and 5.2.

Fig. 5.1 Validation of Groundwater Level - May-05

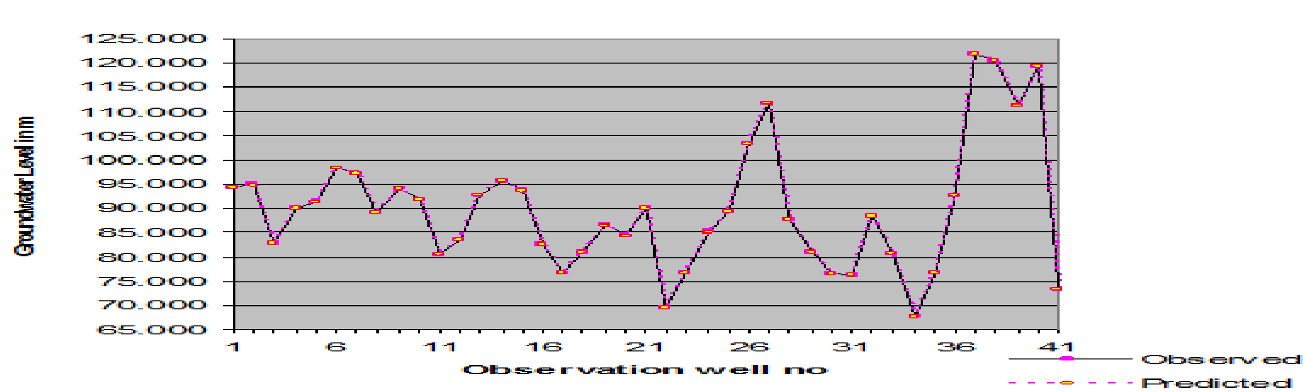
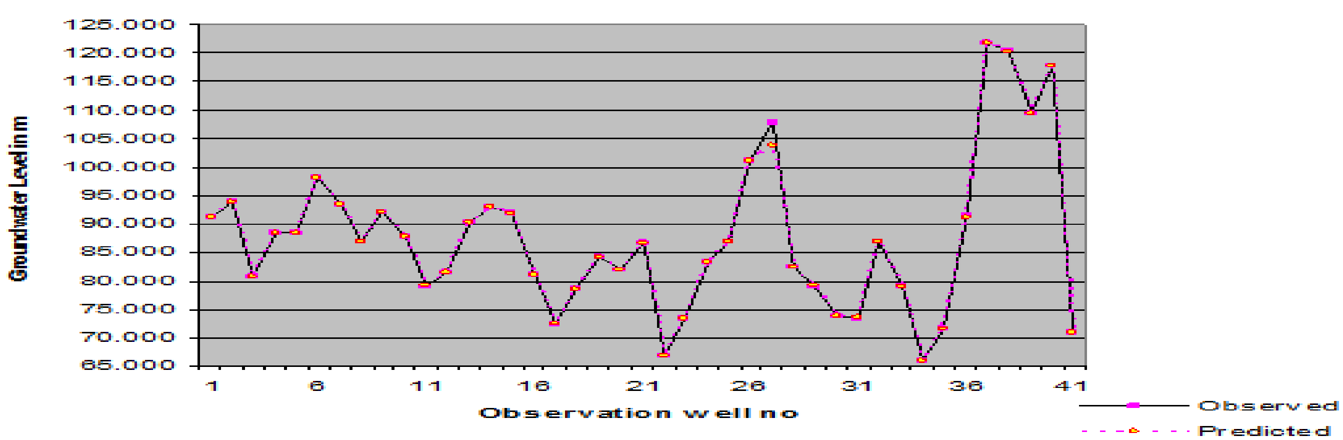


Fig 5.2 Validation of Groundwater Level -Sep-05



7. Conclusion

The function of GOALSEEK in spreadsheet with a small micro has been used in this prediction run, to do all the iteration in a few key strokes to predict the water level with zero error. Even though the model is formulated season wise, prediction is possible monthly or even weekly by changing a few cell formulae and adding few more cell formulae. This is a trial and error method. However MATCAD2000 which is much better than GINO (as MATCAD2000 is a user friendly package and require lesser computing time) was used in this study to minimize the iteration timing for non-linear error optimization. This led to an observed error in depth of water table of the magnitude ranging from -0.08% to +2.1%. For a groundwater simulation model in integrated finite difference method, an error of this magnitude may be regarded as acceptable depending on the scope and purpose of the project. The use of spread sheet and the optimization methods are very simple to use for even small catchment ground water simulation model. This was well tested in this research and yielding good reliable results in ground water development studies.

Annexures

Table 4.1 Optimized polygonal parameters - S,a,b,c,d,q

Polygon No	S	A	B	c	d	Q
1	0.09	0.080	0.07	0.16	1.3	0.0
2	0.09	0.075	0.06	0.16	1.5	0.0
3	0.09	0.078	0.07	0.16	1.5	0.0
4	0.09	0.080	0.06	0.15	1.5	0.0
5	0.09	0.076	0.07	0.17	1.5	0.0
6	0.10	0.081	0.07	0.17	1.5	0.0
7	0.10	0.080	0.06	0.16	1.3	0.0
8	0.10	0.077	0.06	0.18	1.5	0.0
9	0.08	0.080	0.06	0.19	1.4	0.0
10	0.09	0.079	0.06	0.18	1.5	0.0
11	0.10	0.078	0.08	0.19	1.4	0.0
12	0.08	0.080	0.08	0.17	1.3	0.0
13	0.08	0.081	0.06	0.17	1.5	0.0
14	0.08	0.080	0.08	0.15	1.5	0.0
15	0.08	0.080	0.08	0.16	1.4	0.0
16	0.10	0.080	0.08	0.19	1.4	0.0
17	0.10	0.081	0.07	0.21	1.5	0.0
18	0.08	0.078	0.07	0.18	1.5	0.9
19	0.10	0.076	0.06	0.17	1.5	0.0
20	0.08	0.090	0.06	0.18	1.3	0.0
21	0.08	0.075	0.05	0.17	1.3	0.0
22	0.09	0.075	0.07	0.19	1.4	0.9
23	0.10	0.077	0.08	0.21	1.4	0.0
24	0.09	0.082	0.08	0.18	1.5	0.8
25	0.08	0.079	0.07	0.17	1.1	0.0
26	0.08	0.080	0.07	0.19	1.2	0.0
27	0.08	0.076	0.07	0.21	1.2	0.0
28	0.08	0.081	0.06	0.19	1.5	0.7
29	0.08	0.087	0.07	0.21	1.5	0.7
30	0.09	0.092	0.06	0.20	1.4	0.8
31	0.10	0.090	0.06	0.16	1.4	0.7
32	0.08	0.088	0.07	0.17	1.5	0.7
33	0.08	0.089	0.07	0.15	1.5	0.8
34	0.10	0.087	0.07	0.15	1.5	0.8
35	0.08	0.087	0.07	0.21	1.4	0.7
36	0.08	0.091	0.07	0.20	1.3	0.8
37	0.08	0.076	0.05	0.15	1.1	0.9
38	0.08	0.076	0.06	0.17	1.2	1.0
39	0.08	0.080	0.06	0.18	1.1	1.1
40	0.08	0.081	0.06	0.18	1.1	0.6
41	0.09	0.093	0.07	0.21	1.4	0.8

Where **S** - Specified Yield
a - Recharge coefficient of tank storage
b - Recharge coefficient of tank issue
c - Recharge coefficient of rain fall
d - Withdrawal factor
q - Boundary head factor

Table 4.2 Optimized polygonal parameters- T (m^2 / day)

Txy denotes Transmissibility between node x and node y
(T0102indicates the value of T from node 01 to node 02)

Node 1	
T0102	15.1
T0103	24.8
T0104	15.6
T0105	24.9
T0106	16.0
T0107	17.5

Node 2	
T0102	15.1
T0203	23.5
T0207	15.4
T0208	23.8
T0209	24.7
T0210	21.5

Node 3	
T0103	24.8
T0203	23.5
T0304	16.0
T0310	15.6
T0311	21.3
T0312	15.9

Node 4	
T0104	15.6
T0304	16.0
T0405	17.1
T0412	21.6
T0413	18.0

Node 5	
T0105	24.9
T0405	17.1
T0506	15.1
T0514	24.3
T0515	15.8

Node 6	
T0106	16.0
T0506	15.1
T0607	24.8
T0615	15.2
T0616	24.9

Node 7	
T0107	17.5
T0207	15.4
T0607	24.8
T0708	15.1
T0716	22.1
T0717	24.0

Node 8	
T0208	23.8
T0708	15.1
T0809	15.9
T0817	16.8
T0818	24.6
T0819	15.5
T0830	21.0

Node 9	
T0209	24.7
T0809	15.9
T0910	24.6
T0919	20.8
T0920	24.8

Node 10	
T0210	21.5
T0310	15.6
T0910	24.6
T1011	24.7
T1020	15.1
T1021	23.8

Node 11	
T0311	21.3
T1011	24.7
T1112	24.9
T1121	15.2
T1122	15.6
T1134	16.0

Node 12	
T0312	15.9
T0412	21.6
T1112	24.9
T1213	15.1
T1222	24.9
T1223	22.5

Node 13	
T0413	18.0
T1213	15.1
T1314	24.9
T1323	16.0
T1324	15.1
T1325	21.8

Node 14	
T0514	24.3
T1314	24.9
T1415	18.6
T1425	15.1
T1426	16.7

Node 15	
T0515	15.8
T0615	15.2
T1415	18.6
T1516	22.0
T1526	24.8
T1527	24.3
T1528	15.2

Node 16	
T0616	24.9
T0716	22.1
T1516	22.0
T1617	15.1
T1628	24.8
T1629	21.0

Node 17	
T0717	24.0
T0817	16.8
T1617	15.1
T1730	24.9
T1741	23.0

Node 18	
T0818	24.6
T1819	15.1
T1830	15.6
T1831	24.9

T1641	21.8

Node 19	
T0819	15.5
T0919	20.8
T1819	15.1
T1920	21.0
T1931	23.0
T1932	24.7

Node 20	
T0920	24.8
T1020	15.1
T1920	21.0
T2021	15.3
T2032	16.2
T2033	24.6

Node 21	
T1021	23.8
T1121	15.2
T2021	15.3
T2133	15.1
T2134	15.1

Node 22	
T1122	15.6
T1222	24.9
T2223	15.4
T2234	15.1

Node 23	
T1223	22.5
T1323	16.0
T2223	15.4
T2324	20.0
T2335	15.1

Node 24	
T1324	15.1
T2324	20.0
T2425	24.3
T2435	15.3
T2436	24.9

Node 25	
T1325	21.8
T1425	15.1
T2425	24.3
T2526	16.7
T2536	24.9
T2537	15.4

Node 26	
T1426	16.7
T1526	24.8
T2526	16.7
T2627	15.2
T2637	24.1
T2638	21.0

Node 27	
T1527	24.3
T2627	15.2
T2728	24.9
T2739	23.5
T2740	16.0

Node 28	
T1528	15.2
T1628	24.8
T2728	24.9
T2829	19.8
T2840	15.1

Node 29	
T1629	21.0
T2829	19.8
T2941	20.0

Node 30	
T0830	21.0
T1730	24.9
T1830	15.6
T3041	23.7

Node 31	
T1831	24.9
T1931	23.0
T3132	24.7

Node 32	
T1932	24.7
T2032	16.2
T3132	24.7
T3233	24.4

Node 33	
T2033	24.6
T2133	15.1
T3334	24.4

Node 34	
T1134	16.0
T2134	15.1
T2234	15.1
T3334	24.4

Node 35	
T2335	15.1
T2435	15.3

Node 36	
T2436	24.9
T2536	24.9
T3637	22.0

Node 37	
T2537	15.4
T2637	24.1
T3637	22.0
T3738	24.3

Node 38	
T2638	21.0
T3738	24.3
T3839	24.0

Node 39	
T2739	23.5
T3839	24.0
T3940	15.2

Node 40	
T2740	16.0

Node 41	
T1641	21.8

T2840	15.1
T3940	15.2

T1741	23.0
T2941	20.0
T3041	23.7

Table 5.1 Comparison of predicted water levels

Node No.	**Water level in m**			
	May-05		**Sep-05**	
	Observed	**Prediction**	**Observed**	**Prediction**
1	94.26	94.254	91.08	91.086
2	94.95	94.879	93.88	93.879
3	82.91	82.931	80.77	80.703
4	90.07	90.104	88.39	88.386
5	91.47	91.463	88.39	88.412
6	98.45	98.452	98.15	98.148
7	97.23	97.229	93.42	93.423
8	89.15	89.143	86.87	86.871
9	94.06	94.101	92.13	92.128
10	91.74	91.743	87.78	87.793
11	80.54	80.541	79.10	79.114
12	83.52	83.526	81.53	81.528
13	92.81	92.793	90.37	90.359
14	95.63	95.629	92.96	92.957
15	93.88	93.712	91.90	91.903
16	82.60	82.547	80.92	80.918
17	76.66	76.673	72.39	72.384
18	80.92	80.918	78.49	78.487
19	86.56	86.539	84.12	84.118
20	84.43	84.428	81.84	81.843
21	90.07	90.069	86.56	86.558
22	69.49	69.482	66.90	66.903
23	76.81	76.808	73.46	73.457
24	85.19	85.179	83.21	83.212
25	89.46	89.471	86.87	86.867
26	103.33	103.334	101.19	101.185
27	111.71	111.71	107.82	103.852
28	87.78	87.792	82.30	82.329
29	81.08	81.081	79.10	79.103
30	76.50	76.504	73.76	73.754
31	76.35	76.358	73.46	73.462
32	88.39	88.374	86.87	86.859
33	80.85	80.851	79.10	79.047
34	67.82	67.813	65.99	65.983
35	76.66	76.653	71.48	71.473
36	92.81	92.803	91.29	91.274
37	121.92	121.883	121.92	121.919
38	120.40	120.481	120.40	120.321
39	111.25	111.257	109.42	109.413
40	119.35	119.347	117.81	117.807
41	73.38	73.3802	70.87	70.841

Table 5.2 Recalibrated optimized polygonal parameters - S,a,b,c,d,q

Polygon No	S	a	b	c	D	Q
1	0.100	0.080	0.070	0.160	1.400	0.0
2	0.090	0.075	0.065	0.160	1.550	0.0
3	0.085	0.078	0.070	0.160	1.500	0.0
4	0.090	0.080	0.069	0.150	1.530	0.0
5	0.098	0.076	0.075	0.170	1.500	0.0
6	0.100	0.081	0.070	0.170	1.490	0.0
7	0.105	0.080	0.068	0.160	1.300	0.0
8	0.180	0.077	0.060	0.180	1.500	0.0
9	0.080	0.080	0.072	0.190	1.400	0.0
10	0.090	0.079	0.060	0.180	1.520	0.0
11	0.095	0.078	0.080	0.205	1.480	0.0
12	0.085	0.080	0.084	0.170	1.300	0.0
13	0.080	0.081	0.060	0.170	1.500	0.0
14	0.091	0.080	0.082	0.150	1.590	0.0
15	0.080	0.087	0.080	0.160	1.510	0.0
16	0.095	0.080	0.080	0.180	1.40	0.0
17	0.100	0.081	0.075	0.210	1.490	0.0
19	0.100	0.076	0.060	0.170	1.570	0.0
20	0.080	0.090	0.065	0.180	1.300	0.0
21	0.085	0.075	0.050	0.174	1.380	0.0
22	0.090	0.075	0.070	0.190	1.470	0.917
23	0.106	0.082	0.083	0.215	1.400	0.0
24	0.092	0.082	0.084	0.180	1.600	0.800
25	0.080	0.079	0.078	0.170	1.100	0.0
26	0.080	0.085	0.074	0.195	1.410	0.0
27	0.078	0.076	0.070	0.210	1.280	0.0
28	0.080	0.081	0.065	0.190	1.470	0.810
29	0.087	0.087	0.070	0.210	1.500	0.732
30	0.090	0.092	0.064	0.260	1.450	0.800
31	0.960	0.090	0.060	0.160	1.460	0.700
32	0.080	0.088	0.073	0.170	1.590	0.700
33	0.080	0.089	0.070	0.150	1.482	0.800
34	0.095	0.091	0.070	0.158	1.500	0.800
35	0.080	0.087	0.071	0.210	1.480	0.700
36	0.080	0.091	0.070	0.236	1.425	0.850
37	0.080	0.076	0.058	0.150	1.185	0.900
38	0.080	0.076	0.060	0.176	1.225	1.095
39	0.080	0.080	0.060	0.180	1.180	1.100
40	0.080	0.098	0.064	0.184	1.100	0.650
41	0.093	0.100	0.070	0.210	1.450	0.825

Table 5.4 Recalibrated optimized polygonal parameters- T (m^2 / day)

Txy denotes Transmissibility between node x and node y
(T0102indicates the value of T from node 01 to node 02)

Node 1	
T0102	15.2
T0103	24.6
T0104	15.6
T0105	25.1
T0106	16.3
T0107	17.4

Node 2	
T0102	15.2
T0203	23.5
T0207	15.5
T0208	23.8
T0209	25.1
T0210	21.5

Node 3	
T0103	24.6
T0203	23.1
T0304	16.3
T0310	15.5
T0311	21.3
T0312	15.7

Node 4	
T0104	15.6
T0304	16.3
T0405	17.3
T0412	21.5
T0413	18.0

Node 5	
T0105	25.1
T0405	17.3
T0506	15.1
T0514	24.5
T0515	15.8

Node 6	
T0106	16.3
T0506	15.1
T0607	25.0
T0615	15.1
T0616	24.7

Node 7	
T0107	17.4
T0207	15.5
T0607	25.0
T0708	15.1
T0716	22.1
T0717	24.1

Node 8	
T0208	23.8
T0708	15.1
T0809	15.7
T0817	16.8
T0818	24.5
T0819	15.6
T0830	21.0

Node 9	
T0209	25.1
T0809	15.7
T0910	24.6
T0919	21.0
T0920	24.8

Node 10	
T0210	21.5
T0310	15.5
T0910	24.6
T1011	24.8
T1020	15.2
T1021	23.8

Node 11	
T0311	21.3
T1011	24.8
T1112	24.9
T1121	15.6
T1122	15.7
T1134	16.1

Node 12	
T0312	15.7
T0412	21.5
T1112	24.9
T1213	15.4
T1222	24.9
T1223	22.5

Node 13	
T0413	18.0
T1213	15.4
T1314	24.9
T1323	16.2
T1324	15.1
T1325	21.8

Node 14	
T0514	24.5
T1314	24.9
T1415	18.6
T1425	15.3
T1426	16.7

Node 15	
T0515	15.8
T0615	15.1
T1415	18.6
T1516	22.0
T1526	24.7
T1527	24.4
T1528	15.2

Node 16	
T0616	24.7
T0716	22.1
T1516	22.0
T1617	15.1
T1628	24.5
T1629	21.2
T1641	21.6

Node 17	
T0717	24.1
T0817	16.8
T1617	15.1
T1730	25.1
T1741	23.1

Node 18	
T0818	24.5
T1819	15.1
T1830	15.6
T1831	24.8

Node 19	
T0819	15.6

Node 20	
T0920	24.8

Node 21	
T1021	23.8

T0919	21.0
T1819	15.1
T1920	21.0
T1931	23.1
T1932	24.9

T1020	15.2
T1920	21.0
T2021	15.3
T2032	16.1
T2033	24.6

T1121	15.6
T2021	15.3
T2133	15.4
T2134	15.2

Node 22	
T1122	15.7
T1222	24.9
T2223	15.4
T2234	15.1

Node 23	
T1223	22.5
T1323	16.2
T2223	15.4
T2324	20.0
T2335	15.1

Node 24	
T1324	15.1
T2324	20.0
T2425	24.3
T2435	15.4
T2436	24.9

Node 25	
T1325	21.8
T1425	15.3
T2425	24.3
T2526	16.7
T2536	24.9
T2537	15.4

Node 26	
T1426	16.7
T1526	24.7
T2526	16.7
T2627	15.3
T2637	24.1
T2638	21.3

Node 27	
T1527	24.4
T2627	15.3
T2728	24.9
T2739	23.4
T2740	16.0

Node 28	
T1528	15.2
T1628	24.5
T2728	24.9
T2829	19.8
T2840	15.2

Node 29	
T1629	21.2
T2829	19.8
T2941	20.0

Node 30	
T0830	21.0
T1730	25.1
T1830	15.6
T3041	23.8

Node 31	
T1831	24.8
T1931	23.1
T3132	24.7

Node 32	
T1932	24.9
T2032	16.1
T3132	24.7
T3233	24.4

Node 33	
T2033	24.6
T2133	15.4
T3334	24.5

Node 34	
T1134	16.1
T2134	15.6
T2234	15.1
T3334	24.5

Node 35	
T2335	15.1
T2435	15.4

Node 36	
T2436	24.9
T2536	24.2
T3637	22.0

Node 37	
T2537	15.4
T2637	24.1
T3637	22.0
T3738	24.3

Node 38	
T2638	21.3
T3738	24.5
T3839	24.0

Node 39	
T2739	23.4
T3839	24.0
T3940	15.2

Node 40	
T2740	16.0
T2840	15.2
T3940	15.2

Node 41	
T1641	21.6
T1741	23.1
T2941	20.0
T3041	23.8

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