Groundwater Flow Modeling of Gundal Sub-basin in Kabini River Basin, India

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Abstract: Accurate estimation of groundwater recharge is extremely important for proper management of groundwater system especially in semi-arid regions. Many different approaches exist for estimating recharge. This study deals with groundwater modeling for assessing the groundwater balance and estimating the recharge in the Gundal sub-basin, which is located in a semi-arid portion of the Kabini river basin. A two-dimensional fully distributed groundwater model on the concept of predominantly lateral flow conceptualized as an unconfined aquifer has been used in this study. The modeling is supported through remote sensed data and GIS. The different modeling approaches used here gave consistent set of specific yield, transmissivity and rainfall recharge factor with the assumption of zero flow condition specified along the basin boundary. However, these parameters are found to be lower than what is usually known to occur in this geo-climatic context. The results of groundwater modeling, further supported through the groundwater chemistry analyses, show the impact of pumping resulting in regional groundwater flows influencing the hydrogeological regime in the recharge zone. The study also indicates that water levels in the excessive groundwater depletion zones in the Gundulpet area are sustained at the present level due to the inflows from the adjacent Nugu river basin.

Key words: Groundwater, numerical modeling, recharge, water balance, gneissic aquifer, semi-arid zone.

Introduction

Regional groundwater modeling efforts for assessing recharge and groundwater flow have been made through several studies during the last two decades. Numerical modeling is routinely employed for analyzing the problems associated with groundwater flow at watershed, sub-basin and basin scales. The nonlinear interactions among various processes in these models make solutions to these problems difficult to resolve without the careful accounting of all the system parameters and their geographical distribution, which are inputs to a groundwater model (Sanford, 2002). In order to represent recharge effectively in a groundwater model, it is required to consider the processes that control the rate of recharge. These factors are related to the hydrologic landscape of the aquifer system (Winter, 2001). Analysis of recharge and groundwater models is important in semi-arid and arid regions, where the unsaturated zone in general is relatively thick (Krishnamurthi et al., 1977). In regions with semi-arid climates, the climate controls the rate of recharge, whereas in relatively humid climates the geologic framework controls the rate of recharge (Sanford, 2002). Similarly analyses of artificial recharge
schemes have been improved by groundwater modeling exercises (Latinopoulos, 1981; Peters, 1998).

Most of the groundwater models are distributed models and parameters used are not directly measurable. Parameter estimation through the solution of inverse model is most suitable approach in such a situation. In the regional groundwater systems, estimation of parameters like transmissivity, specific yield and recharge factor will be of great interest. The ability to use groundwater models to estimate recharge has been made easier by the development of inverse modeling techniques, where nonlinear regression algorithms are used to automatically obtain a best fit between observed and simulated observations (Cooley, 1977; Yeh, 1986). This type of approach not only has the advantage of producing a mathematical best fit between the observations of the model, but also produces information on the sensitivities of the observations to the model parameters. The sensitivities yield information on the relative certainty with which parameters are estimated given the specific observations (e.g., water levels) that are present and the uncertainties in their measurements. This type of modeling approach has been incorporated into groundwater models (e.g., Hill, 1992; Hill et al., 2000). During inverse modeling exercises, recharge and transmissivity values are usually estimated simultaneously. However such an approach can have higher uncertainties in the estimates of recharge and transmissivity due to correlations among each other resulting from presence of water level measurements alone. This uncertainty can be decreased, if base flow to streams is considered in addition to the water level observations. Alternately, in the absence of such flux measurements a two-step approach, wherein the transmissivity and recharge factor are estimated using a sequential approach, provides better estimates of these parameters and decreased correlation among them (Nagaraj, 1999). Variability of topography, soil and geologic framework within the flow system may cause different controls to operate in different regions. It is required to translate these controls into mathematical conditions in a suitable way to represent the recharge in regional groundwater models. This is feasible by combining the groundwater flow modeling with the inputs from the thematic layers of geomorphology, lithology, structures, land use/land cover, soil, and drainage network (Sridharan et al., 2002). Such an approach may offer an improved distributed recharge estimation and groundwater balance assessment.

The present study attempts to model a regional groundwater system to analyze groundwater flow in a hard rock aquifer in the Gundal sub-basin of the Kabini river basin, which is very important for groundwater assessment and management in this area. In this application groundwater modeling is combined with remote sensing and GIS approaches for calibrating the groundwater flow model. A two-dimensional fully distributed groundwater model on the concept of predominantly lateral flow conceptualized as an unconfined aquifer has been used in this study. An attempt is made to explore the possibility of supporting the regional groundwater dynamics with the help of detailed examination of groundwater chemistry.

### Description of the Study Area

The Gundal sub-basin is located in the South West of Karnataka state. The location map of study area is shown in Figure 1. The Gundal sub-basin lies almost entirely in Gundulpet taluk of Chamrajnagar district and partly in Nanjangud taluk of Mysore district and occupies an area of 1270 km². The basin stretches from 76° 30' to 76° 51' 47" longitude and 11° 40' 13" - 12° 7' 13" latitude. The Gundal river is the main tributary of Kabini river, which originates in Himavad Gopalaswamy Betta and flows over a distance of 59 km and its confluence with Kabini river is near Nanjangud town. There are nearly 45 tanks, which are seasonal. The major source of water for irrigation in this sub-basin is groundwater. Temperature is lowest during December and January with mean minimum temperature varying in the range of 17 °C to 37 °C respectively. The main rainfall period is from June to November. The SOI topomaps of 1:50,000 scale are used for delineating the basin boundary, base map preparation, drainage network etc. The different thematic maps prepared for the present study are drainage, land use/land cover, hydrogeomorphology, structure and soil (Narayana, 2003).

The drainage pattern of the study area reflects the soil and geology. The pattern of drainage is arranged from dendritic to sub-parallel to linear moving from top of the mound, which is representing the higher contour. The Gundal watershed flows in generally S-N direction and joins Kabini river in the north tip of the basin. The stream pattern is angular reflecting a strong structural control. The drainage pattern is characterized by a single main stream joined by a number of tributaries and is only dendritic at the lower stream order. The drainage network of the Gundal basin is shown in Figure 2. The study area mainly consists of one major rock type. Granitic gneiss covers maximum area of the sub-basin. A number of dykes traversing in east-west direction occur in the study area. The length of the dykes range from 0.5 to 1.5 km
Figure 1: Location map of Gundal sub-basin in Kabini and Cauvery river basin.
with width varying from 5 m to 15 m. Most of these dykes are doleritic in composition. It is observed that the lineaments in this area are drainage oriented and fracture controlled. Many of the lineaments in this basin are rectilinear type and trend north-south or NNE-SSW and range from 2.5 to 7.5 km in length (Subhashchandra and Narayanachar, 1997). The soils in the basins are deep red loams and clayey. The loams are derived from igneous rocks, principally granitic gneisses. The soil represents the running slopes, plains and undulating uplands with gentle lowlands. The red soils are characterized by light texture (loams), weak granular structure, porous, sticky and plastic, non-gravelly and sub-soil with clay. The soil depth varies from 50 cm to several metres depending on the undulating terrain. In addition, brown clayey alluvium deposits mixed with kankar are seen on either bank of Gundal river extending to about 100 m on either side of the river, and the thickness often ranges from 2 m to 6 m. The vegetation in Gundal watershed is characterized by agriculture activity. Traditionally crops are grown during Kharif and Rabi season. Main crops in Kharif seasons are ragi (finger millet) and pulses whereas paddy is grown in the command areas of tanks and canals. As a result of increased irrigation by bore wells, irrigated crops like sugarcane and cash crops replace crop pattern.

Rainfall and Draft  Daily rainfall data for 17 years during 1980-1997 was collected from Department of Economics and Statistics, Bangalore. The mean annual rainfall calculated for past 15 years (1980-1995) amounts to be 620 mm for Gundal sub-basin but variation exists between each year and among each station. Data of the groundwater level for nine observation wells that exist in the Gundal watershed from 1973 to 1999 have been collected from Department of Mines and Geology (DMG), Karnataka State. The location of various rain gauge and groundwater monitoring wells is shown in Figure 3. The annual draft estimates are obtained from the Department of Mines and Geology (DMG), Karnataka. This average draft is available every five years in both the taluks and is observed to be increasing each year.

Groundwater Quality  The concentration of total dissolved solids (TDS) (Premchandra, 1998), calcium and carbonate are available at select spatial locations in the Gundal sub-basin. The TDS concentration is obtained at approximately 80 wells. The concentration varies from 300 to 2000 ppm. The TDS concentrations are shown in Figure 4. Further the water quality parameters in many villages of the sub-basin are measured during the period 1988-89 by Department of Mines and Geology, Karnataka and made available for this study.

Groundwater Flow Model  The groundwater model (Nagaraj, 1999) was suitably modified to take into account the recharge components
along with the transmissivity and specific yield parameters. Modifications are made in this model to incorporate the recharge components such as return flows from irrigation and recharge from tanks. The typical groundwater flow equation for two dimensional, anisotropic, nonhomogeneous system is considered. It is assumed that the study region can be described by an unconfined groundwater flow at a regional scale. The general equation for flow in such an aquifer is given by

$$\frac{\partial}{\partial x} \left( T_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( T_y \frac{\partial h}{\partial y} \right) = S_y \frac{\partial h}{\partial t} + Q_g - Q_r - Q_t - Q_i$$

(1)

where \( h \) is the piezometric head, \( T_x \) and \( T_y \) are the transmissivities in \( x \) and \( y \) directions respectively, \( S_y \) represents the specific yield, \( Q_g \) is the net pumping rate per unit area, \( Q_r \) is the recharge rate from rainfall per unit area, \( Q_t \) is the recharge from tank water, \( Q_i \) is the return flow due to irrigation, \( x \) and \( y \) are the Cartesian coordinates and \( t \) is the time. The solution to above equation can be obtained by using the Galerkin Finite Element Method which is the most commonly used weighted residual method. The above governing equation is parabolic in nature and it requires open boundary along with initial and boundary conditions for solving it. The water level at all nodes at the start of simulation period is taken as the initial condition. The external boundary of the study area is assumed as a zero flux condition.

Recharge is limited to some extent by the amount of infiltration that is available at the land surface. For this situation the boundary condition in the groundwater model is effectively represented by specifying the recharge flux. The approach for the estimation of recharge in this manner is by using mass balance calculations at each model cell. Fluxes between each model cell are calculated based on the transmissivity and water table gradients. The difference between these fluxes in a two dimensional framework must then amount to recharge or discharge entering the cell. Limitations using such an approach are that errors in water table gradients or the transmissivity distribution leads to errors in recharge estimates. However, it is observed that uncertainties associated with estimates of transmissivity distribution are large in comparison to the uncertainties of recharge rates (Nagaraj, 1999).

In this application a simple rainfall recharge relationship assuming recharge as a linear function of rainfall is used. A simple rainfall recharge relationship is given by

$$Q_r = F_r R_f$$

(2)

where \( F_r \) is recharge factor for rainfall and \( R_f \) is rainfall rate. For the recharge component from return flows due to surface and groundwater irrigation areas, recharge is assumed as a percentage of the amount of irrigation depending on the type of crop and type of irrigation based on the norms provided in the Groundwater Resource Estimation Committee Report (GEC, 1998). For modeling recharge from the major tanks, the tank water spread area and the water levels are used as boundary conditions in the model. The location of the tanks and other ancillary data for this purpose are obtained using field surveys. A weighted least square method with Gauss Newton algorithm for minimization is used and the approach for parameter estimation is similar to that employed in the earlier studies (Yeh, 1986; Sekhar et al., 1994)

**Results and Discussion**

The flow model discussed above is applied to the study area combining the inputs from the field data collected as well as from the thematic layers generated for simulating the groundwater levels.

**Modeling the Groundwater Flow Dynamics**

The regional groundwater model is applied to the study area for calibration and validation. The region is discretized into 329 elements with 184 associated nodes in the finite element model (Narayana, 2003). The thematic layers of the study area are integrated in GIS to produce a composite zonation layer of aquifer parameters. The present study area has one single lithological unit of
granitic gneisses and other small areas of amphibolite schists, hence soil classification has been integrated with hydrogeomorphology maps to produce an integrated zonation layer for aquifer parameters (Narayana, 2003). The groundwater balance is obtained for sub-zones shown in Figure 3.

Figure 5 shows the variations of water table level in four observation wells located in the southern part of the Gundal basin. In three wells (OW5, OW8 and OW9), the water table level is quite shallow (between 5 and 15 m), and does not seem to represent any decreasing trend between 1972 and 1999. Seasonal variations are of the order of 5 to 10 m and hence are important. In contrast, one well (OW7) exhibits a very steep decline in groundwater levels from 1985 to 1990. The water level depth ranges between 5 and 15 m before 1985 and seems to stabilize between 20 and 25 m after 1992. This trend of higher decline in water levels in the zone surrounding OW7, which is located close to the town of Gundulpet, is due to the higher draft.

The depth to groundwater in the observation wells in the discharge, intermediate and recharge areas are 4-5 m, 8-11 m and 11-15 m respectively. The average annual water level changes in the discharge, intermediate and recharge areas are 0.2-0.5 m, 3-5 m and 4-6 m respectively. As the number of observation well network is not very dense, it is likely that the reliability in parameter estimation may be poor if enough seasonal redundancy of data is not considered (Nagaraj, 1999). Hence to overcome this difficulty, water level observations over a period of large number of years (at least five years) is proposed here for model calibration to keep a reasonably high redundancy factor (ratio of number of measurements to the parameters).

The water level contours in May 1989 are used for prescribing the initial condition. This contour map was prepared using the water level data at all the observation wells distributed over the watershed. However, since these observations are very few, Kriging method available in GIS is used for interpolating the contours in the domain of the watershed based on the actual point measured water levels. Similarly, since the water levels are correlated to the topography, during the interpolation this aspect was used to obtain them. In spite of this exercise, the water level contours may not fully confirm the groundwater flow of the basin. Hence, using these interpolated water levels the groundwater model is simulated for a few time steps, which results in obtaining water level contour map confirming to the groundwater drainage in this watershed.

It is observed that such a procedure resulted in obtaining a good initial condition for the water levels at each node of the numerical model. The model boundary is assumed to be a no flow boundary. In the present study, a time step of 15 days is used for the inverse problem. It is observed during field surveys that the Gundal river is dry in many reaches while one can observe base flow in some reaches especially in the upland region forming the recharge areas of the watershed due to the presence of forest area of Bandipur national park and in the discharge area of the watershed close to Kabini river where there is considerable irrigation both from canal command and from groundwater irrigation. The length of the river reach for applying this boundary condition was made possible by using Global position system (GPS) during the field surveys. The water level observed in select locations in the Gundal river in various seasons are directly used in the model while for the remaining nodes forming the river nodes suitable interpolation is made. The water levels in the river in the discharge area is found to be constant throughout the year due to return and seepage flows and a value of 1 m above the bed of the river is used which is observed in the field. However, the river water levels in the recharge area were found to vary from monsoon to non-monsoon season. The highest water level above the bed of the river during base flow is found to be 0.75 m during the month of October and no flow is found during February to June.

The basin comprises large number of small and big tanks and store runoff from their catchments (Narayana, 2003). The largest and smallest tank areas are 3.35 km² and 0.08 km² respectively. These are suitably incorporated into the model by considering a tank area and
The return flow due to irrigation is calculated as a percentage of the applied irrigation water based on the GEC (1998) norms. The values used are 30% and 25% for surface irrigation and groundwater irrigation respectively, when depth to water table is 5-10 m. For depths greater than 10 m the values are 20% and 15% respectively. The transmissivity is estimated considering the field situation could be characterized by an isotropic situation. The transmissivity estimated under these circumstances is equivalent transmissivity of $x$ and $y$ directions. Such an assumption will not affect the estimates of specific yield and rainfall recharge factor and also parameters are likely to be better estimated owing to a higher data redundancy factor (Nagaraj, 1999).

The model is calibrated for a period of five years starting from May 1989 to April 1994. The aquifer parameters estimated are used to calibrate the model for the period of 1989-1994. The parameter estimation method uses a two-step approach wherein transmissivities are estimated in the first step, assuming specific yield and rainfall recharge factor to be constant. In the second step, the transmissivity is kept constant and estimation of specific yield and rainfall recharge is made. This procedure of sequential estimation of parameters during each parameter iteration is used to eliminate the correlation between transmissivity and recharge factor. These estimated parameters are used to compute the water levels at all the nine observation wells and are compared with the observed water levels. The comparison of observed and computed water levels at different observation wells are shown in Figure 6. The degree of match between observed and computed water levels are compared using $R^2$ norm, which is found to be 0.918. The degree of match is said to be good if $R^2$ is in the range of 0.9 to 1.0.

Figure 6: Observed and simulated water levels in observation wells.
For the sake of clarity, only pre-monsoon and post-monsoon water levels are plotted for three wells. These three wells are representative of discharge zone (OW3), intermediate zone (high draft) (OW7) and recharge zone (OW8). The model simulated inter annual trend reasonably well in all the wells. However, in the recharge zone (OW8) the average water level is underestimated both during pre and post monsoons, which suggests that there is a need to look at the boundary condition hypothesized in the recharge zone. The parameters estimated for the various zones are given in Table 1. Transmissivity estimates ranged between 70 and 172 m².day⁻¹. The range of these regional estimates of transmissivity is in good agreement with the pump test data (CGWB, 1999) in this region. The specific yield values estimated varied approximately an order (0.2-3%). The smaller specific yield values estimated (0.2%) correspond to the discharge zones of 1-3, which are characterized by black soils, while higher specific yield corresponds to red soils in the intermediate and recharge zones of the sub-basin. The uncertainty in the parameter estimates, which are obtained using a posteriori error statistics, ranged from 10-15%.

Groundwater Balance Components
The annual average groundwater balance of the basin is shown in Table 2. The balance for zone 1 is not presented due to the higher uncertainty in these values. It should be noted that this zone comprises surface water irrigation through canal systems of Nugu and Kabini rivers in addition to the groundwater discharges from the Gundal basin, due to which the annual water level fluctuations are very small resulting in high uncertainty in the estimates of water balance from groundwater modeling alone. The recharge is found to vary from 5 to 10% of the rainfall in various zones, which is in conformity with the recharge estimates for this region in the studies of CGWB (1999). The recharge factor for zones 2-5 varied from 5 to 8%, while in the zones of 6 and 7 it is approximately 10%. The higher recharge factor in the intermediate zones of 6 and 7 is due to the additional induced recharge from tanks apart from the rainfall recharge. The recharge factors in zones 8 and 9 are in the range of 5%, indicating an underestimation of these values especially in the recharge areas. One of the possible reasons, which can explain the lower values of the recharge factor, is due to the errors in the estimation of groundwater fluxes in these zones. Based on the assumption of no flow across the boundaries in the modeling, the recharge in zones 8 and 9 support the net groundwater fluxes from the recharge zone as well as the draft in these zones. In Table 2, the net groundwater flux in these zones is shown negative, indicating an outflow from this region. However, if one were to relax

<table>
<thead>
<tr>
<th>Zone</th>
<th>Transmissivity, m²/day</th>
<th>Specific Yield</th>
<th>Rainfall recharge factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>145.6</td>
<td>0.002</td>
<td>0.078</td>
</tr>
<tr>
<td>2</td>
<td>119.4</td>
<td>0.003</td>
<td>0.055</td>
</tr>
<tr>
<td>3</td>
<td>95.5</td>
<td>0.0033</td>
<td>0.065</td>
</tr>
<tr>
<td>4</td>
<td>83.6</td>
<td>0.012</td>
<td>0.085</td>
</tr>
<tr>
<td>5</td>
<td>105.8</td>
<td>0.0074</td>
<td>0.069</td>
</tr>
<tr>
<td>6</td>
<td>171.7</td>
<td>0.022</td>
<td>0.102</td>
</tr>
<tr>
<td>7</td>
<td>145.2</td>
<td>0.007</td>
<td>0.101</td>
</tr>
<tr>
<td>8</td>
<td>70.8</td>
<td>0.021</td>
<td>0.054</td>
</tr>
<tr>
<td>9</td>
<td>79.9</td>
<td>0.03</td>
<td>0.049</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Recharge</th>
<th>38.5</th>
<th>42.9</th>
<th>47.6</th>
<th>47.1</th>
<th>70.9</th>
<th>78.9</th>
<th>58.3</th>
<th>45.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return flow</td>
<td>4.8</td>
<td>8.6</td>
<td>9.3</td>
<td>8.4</td>
<td>7.9</td>
<td>18.6</td>
<td>8.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Net flow</td>
<td>-14.0</td>
<td>-11.9</td>
<td>-1.8</td>
<td>-9.5</td>
<td>-10.0</td>
<td>5.2</td>
<td>-21.1</td>
<td>-11.7</td>
</tr>
<tr>
<td>Draft</td>
<td>-24.0</td>
<td>-34.5</td>
<td>-46.5</td>
<td>-42.0</td>
<td>-52.7</td>
<td>-93.2</td>
<td>-42.5</td>
<td>-33.9</td>
</tr>
<tr>
<td>Storage change</td>
<td>-1.2</td>
<td>-2.4</td>
<td>-6.7</td>
<td>-3.0</td>
<td>-15.4</td>
<td>-6.9</td>
<td>-2.1</td>
<td>-5.3</td>
</tr>
<tr>
<td>Error</td>
<td>4.2</td>
<td>2.7</td>
<td>1.9</td>
<td>1.0</td>
<td>0.7</td>
<td>2.6</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Rainfall</td>
<td>701</td>
<td>660.2</td>
<td>560</td>
<td>681.8</td>
<td>693.9</td>
<td>781.2</td>
<td>1078.9</td>
<td>907.3</td>
</tr>
</tbody>
</table>
the no boundary condition along the basin boundary near the recharge zones, the modeling will result in a lesser outflow from this region, which will result in a higher recharge factor for modeling the measured groundwater fluctuations. The issues regarding the no-flow boundary condition will be discussed in the later sections. The net groundwater flow in Table 2 is negative for all the zones except zone 7, indicating the groundwater outflow from the basin. A positive net flow here indicates that there is more groundwater inflow than the outflow in this zone, which results from relative decline in water levels in this zone due to excessive groundwater pumping. The storage change in all the zones (Table 2) indicate that groundwater is depleting in the sub-basin. The change in storage corresponds to a water level decline of 0.3 to 0.5 m per year in zones 2-5, while in zones 6 and 7, it is 0.7 to 1.0 m per year. Zones 8 and 9 have lower values of storage change and correspond to water level declines in the range of 0.1 to 0.2 m per year. The annual average groundwater balance of the basin (Table 2) shows some discrepancy in the estimates in the recharge zone as discussed above, and hence to verify the budget an alternate approach was attempted to assess the hydrologic parameters in each of the zones. For zones 8 and 9, the following terms are computed:

**Draft:** Draft is a major responsible factor for the water level fluctuation in this area. Hence based on the water level fluctuations occurring in that zone, the draft is calculated from the slope of the water level fluctuations over a large period of years while assuming 20 mm as the initial draft prior to 1975.

**Specific yield:** The method suggested by GEC (Groundwater estimation committee, 1997) has been used for the estimation of the specific yield. According to the above method, the groundwater balance equation for the non-command area in non-monsoon season can be used for the estimation of the specific yield using

\[ S_y \Delta z = Q_g + D \]  

(3)

where \( \Delta z \) is the difference in the pre-monsoon water level of consecutive years, \( S_y \) is the specific yield, \( Q_g \) is the base flow and \( D \) is the draft. Assuming the base flow to be small compared to the other components, \( S_y \) can be calculated from this equation. The range of these values varied between 0.003 and 0.03.

**Net groundwater flow:** Net groundwater flow \( (Q_f) \) is calculated from the transmissivity by the equation

\[ Q_f = \frac{1}{A} \left(T \times \left(\frac{\Delta h}{L}\right) \times W \times 365\right) + Q_g \]  

(4)

where \( T \) is the transmissivity, \( \Delta h/L \) is the hydraulic gradient between consecutive zones, \( W \) is the width of the boundary between the zones, and \( A \) the area of the recharge zone. The transmissivities are based on the estimates in Table 1. The average net flow calculated with this method is very low, ranging between 10 and 13 mm/year.

**Recharge:** Recharge is calculated from the equation

\[ Q_r = Q_f + S_y \Delta z \]  

(5)

The annual recharge factor can then be obtained using Eq.(2). Average value is found to be around 5% for both zones and matches well with the recharge factor estimated from the inverse modeling.

**Recharge Modeling**

An estimation of daily recharge has been made on the two observation wells in the recharge zone (OW8 and OW9). Runoff is calculated using the curve number method. Soil water budget is calculated daily, taking into account rainfall, runoff and PET. Recharge factor calculated from this method are consistent with those obtained with the water balance approach and regional modeling. Simulation of water table level is achieved considering a single store linear reservoir for groundwater, and the specific yield was used from the water balance method. Results of simulations show a reasonable fit between observed and measured trends for water table level in OW8 (Figure 7a) and OW9 (Figure 7b). Calculated groundwater discharge is also very close to that calculated in the above modeling approaches, around 10 mm/year.

**Analysis of Groundwater Chemistry**

A large number of groundwater samples in the Gundal have been collected in the last few years by DMG, for chemical characterization in terms of TDS and hardness. Figure 4 presented the spatial distribution of TDS (expressed in mg/l). It shows that a broad range of TDS values are found in Gundal. Figure 8 shows that in the North-South transect along the main river course, a good correlation exists between TDS and depth to the water table. However, the relation between depth and TDS is not linear considering the whole data set. Figure 9 shows that by considering separately the data in the discharge zone (C) and the high pumping zone near Gundulpet (A), the remaining data set (B) exhibits a linear correlation. The high values of TDS in Gundulpet area (A) associated with over pumping zone result in sharp decline in water levels and consequent re-circulation of pumped water through return flow, which extracts soluble salts over
The examination of relationship between calcium and bicarbonate concentrations in the wells during 1988-89 indicates two interesting opposite patterns. Though the measured calcium and bicarbonate concentrations in wells are few in number, the general trends indicate that they capture the significant hydrogeological characteristics of the basin. While bicarbonate increases in one case (Figure 10a), the other (Figure 10b) shows decrease with increase in calcium content. Further it is noted that bicarbonate is strongly correlated with TDS in both the cases. The only way for the later possibility (Figure 10b) is the conversion of calcium into calcium carbonate and formation of soluble bicarbonates of monovalent cations.
The negative correlation between calcium and bicarbonate may indicate interesting possibility due to subsurface inflow/recharge. While this recharge can decrease calcium and bicarbonate concentrations, the decrease in the bicarbonate content will be lower than indicated by the calcium content. This can be used to infer the subsurface inflows/recharge into the region.

**Assumption of Zero Flux Boundary in the Recharge Zone**

Figure 5(a) shows that slope of water level decline during the periods 1973-1975 and 1979-1983 in the three wells (OW9 and OW8 located in the recharge zone, and OW7 located in the excessive pumping zone away from the recharge zone) is approximately same, which indicates that the behaviour of the groundwater system is uniform in these zones and the dynamics are in equilibrium with recharge and pumping. However, during the period 1983-1991, the slope of water level decline in the wells (OW8 and OW9) is considerably less, while in the well (OW9) for the same period is similar to the earlier years. The slope of water table decline in these wells further reduces during 1992-1999 when OW9 also shows reduction in the slope similar to the other two wells. The values of these slopes and corresponding average annual rainfall during these periods are shown in Table 3. Based on the yearly slope during 1973-75 and 1979-1983, which is referenced with the rainfall during these periods, the slopes of water table declines are estimated in the three wells for the other two periods of 1983-1991 and 1992-1999 applying correction for rainfall using a linear relationship. The estimated values of the slopes for the three wells are shown in Table 3. It is interesting to note that the estimated slopes for OW9 and OW8 are much higher than the observed, which show a decreasing trend with years. This indicates that the water levels of OW9 and OW8 are supported from subsurface inflows from the neighbouring sub-basins. This is more evident for OW8, which shows more deviation between observed and estimated slopes. In the case of OW7, the observed slope is much higher in the period 1983-1991 than the estimated, indicating the effect of increased pumping. However, the observed slope during 1992-1999 decreases drastically in comparison with the estimate, indicating the effect of increased inflows from the recharge zones supported by the inter-basin transfer during this period. Figure 11 schematizes the consequences of the hypothesis with regard to the boundary condition to be used in the recharge zone. If the assumption of zero flux boundary in the recharge zone is valid (Figure 11a), the excessive pumping in the Gundulpet area should have led to depletion of water levels in the recharge zones, which is not the case observed. On the other hand, if the scenario shown in Figure 11b is valid, the water levels in the recharge zones will be sustained at the present level due to the inflows from the adjacent Nugu river basin. This might result in decline of water levels in the region of Bandipur national park in the Nugu river basin, which is associated with the recharge boundary of Gundal basin.

This aspect is further buttressed by analyzing the temporal variation of hardness in the wells close to the recharge boundary of the sub-basin, which indicates a decreasing trend (Cases 1 and 2 of Figure 12). It is further noted for these wells that the relationship between calcium and bicarbonate is as described by Figure 10b. This supports the conclusion drawn above with regard to the contribution of groundwater flow from the neighbouring Nugu basin into the higher groundwater depleting regions located on the west side of the Gundal river. The well (Case 3 of Figure 12) exhibits the same characteristic after a delay since it is located farther away from the basin boundary.

**Conclusions**

Modeling of groundwater quality and recharge is found to be important for the Gundal sub-basin, which is located in a semi-arid portion of the Kabini river basin. The runoff in the Gundal river has declined over years due to increased pumping from groundwater irrigation. Also the

<table>
<thead>
<tr>
<th>Period</th>
<th>Annual rainfall (mm)</th>
<th>Observed yearly slope of water level decline (m/yr)</th>
<th>Estimated yearly slope of water level decline (m/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>OW9</td>
<td>OW8</td>
</tr>
<tr>
<td>1973-75</td>
<td>762</td>
<td>−2.33</td>
<td>−3.06</td>
</tr>
<tr>
<td>1979-83</td>
<td>713</td>
<td>−2.06</td>
<td>−2.08</td>
</tr>
<tr>
<td>1983-91</td>
<td>593</td>
<td>−0.90</td>
<td>−0.60</td>
</tr>
<tr>
<td>1992-99</td>
<td>793</td>
<td>−0.51</td>
<td>−0.24</td>
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</tbody>
</table>
watershed comprises surface water irrigation from Kabini canal system along with various land-use types. Some parts of the watershed form the forest area of the Bandipur National Park near Mysore and there is an interest to evaluate the impact on the forested area also. The following are some of the conclusions drawn from this study.

1. The application of regional groundwater model for the semi-arid Gundal watershed in the Kabini river basin suggests that there is a potential for application of such a method for assessing the groundwater balances with the available “hard” data of wellwater levels measured periodically in a year along with “soft” data of remote sensing by using GIS tools.

2. It is demonstrated that the groundwater model coupled with parameter estimation module with a suitable parameter zonation structure based on the thematic layers of lithology, structure, geomorphology, soil, land-use and land cover obtained using remote sensing and topographic maps and other ancillary data is very useful in generating the water level responses in various years with low and high rainfall.

3. The different modeling approaches used gave consistent set of specific yield, transmissivity and rainfall recharge factor with the assumption of zero flow condition specified along the basin boundary. However, it was observed that values of some of these parameters are lower than what is usually known to occur in this geo-climatic context. If the assumption of zero flux boundary in the recharge zone is relaxed, there is a possibility of a different set of these parameters especially in the recharge zone.

4. The results of groundwater modeling, further supported through the groundwater chemistry analyses, show the impact of pumping resulting in regional groundwater flows influencing the hydrogeological regime in the recharge zone. The study also indicates that water levels in the excessive groundwater depletion zones in the Gundulpet are sustained at the present level due to the inflows from the adjacent Nugu river basin. This might result in decline of water levels in the region of Bandipur national park, which is associated with the recharge boundary of Gundal basin. Further studies will be needed to investigate and quantify these effects more clearly for a better management of water resources in this very sensitive region.

References


Hill, M.C. (1992). A computer program (MODFLOWP) for estimating parameters of a transient, three-dimensional,


