Groundwater Recharge Process and Groundwater Flow Models in Granitic Terrain & Alluvium : Emerging R&D Problems

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The groundwater recharge has been routinely estimated as a residual of various components of soil moisture budget viz., Surface runoff, Evaporation from soil, Transpiration from Plants, Interception loss, Soil moisture store and Precipitation. The measurement accuracy of various parameters results in errors in the estimates. For example surface runoff is estimated using SCS runoff curve number model involves lumping of land use, soil type and antecedent moisture conditions. Soil evaporation is also dependent on leaf area index and antecedent moisture conditions. Transpiration estimates depend on crop coefficient is a gross approximation. Errors encountered during the estimation of above parameters would show influence on recharge computation. Long term data sets more than 10 years have been used to compute recharge through the application of soil moisture deficit models on a daily basis. The computed recharge has been applied in the groundwater flow model in monthly time steps to account for changes in well hydrograph under transient simulation. Two typical watersheds in granitic terrain viz., Dulapally watershed near Hyderabad and Parkal watershed in Warangal district has been simulated in the groundwater flow model. The calibration well hydrographs in the groundwater flow model with observed ones indicate efficacy of the soil moisture deficit models for better understanding of the dynamic recharge process. The long term calibration of well hydrographs has accounted the high rainfall and drought conditions during the simulation period. The long term average groundwater recharge in Parkal watershed in Warangal district has worked out as 160 mm/yr whereas average groundwater recharge in Dulapally watershed near Hyderabad has been 125 mm/yr.

Recent times due to over exploitation of alluvial aquifers in northern India the thickness of vadose zone has been increasing year after year. To understand the impact of increased thickness of unsaturated zone on reduction of groundwater recharge potential, Soil Water Infiltration Movement (SWIM) model has been applied for two scenarios of sandy loam soils. The SWIM model results in the Punjab Agriculture University Campus, Ludhiana indicate that the reasons behind deep water table in the canal irrigated areas may be attributable to large thickness of vadose zone which may be holding the irrigation return flows as available moisture in that zone above the water table, but not contributing actually to the water table. The study warrants imperative need for reduction of overexploitation of groundwater resources in the area. As overexploitation of groundwater has been resulting in reduction of recharge potential of applied irrigation return flows as well as monsoon rainfall reaching water table aquifers in various parts of Punjab.

Recharge Process Model

Water balance method of estimation of groundwater recharge utilizes the balance among various components of the water balance equation

$$RE = P + Ir - (Int + Rof + AE + ATR + WC)$$

where P = Rainfall
Ir = Irrigation
Int = Interception loss
Rof = Surface runoff
AE = Actual evaporation from soil surface
ATR = Actual transpiration
WC = Soil moisture storage and
RE = Groundwater recharge

Daily rainfall data has been used to estimate surface runoff whereas pan evaporation measurements have been utilized to estimate actual soil evaporation and transpiration from vegetation.

Interception Loss

Interception loss has been assumed as 0.5 mm per rainfall event on a rainy day preceded by a dry day. If precipitation for the rainy day is less than or equal to 0.5 mm interception loss is equal to precipitation. Also for a rainy day followed by previous rainy day Interception loss has been assumed to be zero.

Surface Runoff

The surface runoff from the rainfall has been estimated through use of soil conservation service (SCS) runoff Curve Number Model

$$Rof = (P – 0.2S)^2 / (P + 0.8 S)$$

Where
S = Potential maximum surface retention
The retention volume is given as
$S = 25400 / CN - 254$

Where, CN is the runoff Curve Number, a parameter dependent on soil type, landuse and antecedent moisture condition. Considering land use pattern a representative weighted average curve number for the entire watershed has been estimated as 60, 78 and 90 under CNI, CNII and CN III conditions respectively. Generally soils are assumed to be in the Antecedent Moisture Condition I (AMC I) prior to monsoon and after initial monsoon rains the antecedent moisture condition may change to AMC II or AMC III depending on the rainfall pattern during the monsoon period till early October and corresponding CN from above will be considered for runoff computation.

Actual Soil Evaporation

Loss of water by evaporation from the soil surface is a major component of annual water balance of semi-arid tropics. Actual evaporation from soil surface nearly equals potential evaporation when soil surface is saturated with water. Maximum depth of soil where soil evaporation will occur depends on texture of the soil and it is very difficult to measure in the field. Daily actual soil evaporation AE has been estimated as a function of daily pan evaporation value Ep, the number of days t, following rain of sufficient amount to recharge 20 cm thickness of soil zone from surface and fraction B of incoming solar radiation reaching the soil surface (Russel, 1989). The following equation is used to compute the daily actual soil evaporation from the daily rainfall data and pan evaporation data

$$AE = B.\ Ep / t$$

Under uncropped conditions of barren land B = 1.0, but under cropped conditions, it is a time dependent function of crop growth that can be measured directly or estimated from the leaf area index (LAI). Also it was found at ICRISAT Campus, Hyderabad that the actual evaporation from soil may not be greater than half of the pan evaporation after applying corrections to pan coefficient (Pathak et al, 1989).

Actual Transpiration

To compute ET crop, a three stage procedure has been proposed by Food and Agriculture Organization (FAO, 1977). The effect of crop characteristics on crop water requirements is given by the crop coefficient (Kc) which represents the relationship between reference (ETo) and crop transpiration (ET crop)

$$ETcrop = Kc.\ ETo$$

values of Kc are dependent on the crop, its stage of growth, growing season and weather conditions. To convert pan evaporation (Epan) into reference crop transpiration (ETo), empirically derived coefficient (Kp) is given which takes into account climate and pan environment. Reference crop transpiration (ETo) can be obtained from

$$ETo = Kp\ .\ Epan$$

where, Epan = Pan evaporation in mm / day and represents the mean daily value of the period considered
Kp = Pan Coefficient

Considering average daily pan evaporation at Parkal village in Warangal District on yearly basis and the rainfall pattern during monsoon season, the pan coefficient Kp; has been selected as 0.8 for moderate wind and medium humidity conditions.

Soil Moisture

Some surface runoff will be generated after a sufficient rainfall event and the remaining rainfall tries to saturate the soil zone up to field capacity and surplus water if any leaves soil zone as recharge to the underlying groundwater table. The moisture which has remained in the soil zone as available soil moisture will be lost either as soil evaporation or transpiration by vegetation. A two layer soil zone has been assumed in the water balance model. In the top layer, which has a thickness of 20 cm from ground surface both soil evaporation and transpiration could occur whereas in the second layer underneath the first layer up to 45 cm from surface only transpiration by plants could take place as long as soil moisture is available. The average available moisture holding capacity of Alfisols in the region ranges from 45 -75 mm / 45 cm of soil zone (Randhawa and Singh, 1988). A representative average thickness of 45 cm of soil zone has been assumed to be possessing an average water holding capacity of 60 mm. The component of groundwater recharge could ultimately be obtained from the water balance computation. Various components of the recharge process model, viz., surface runoff, actual soil evaporation, actual transpiration, soil moisture status, and groundwater recharge have been computed following a daily soil moisture accounting procedure.

Results of Recharge Process Model of Parkal Watershed

The annual groundwater recharge and other components of the water balance model during 1976-1990 has been shown in Table 1. Groundwater recharge in the watershed mostly takes place during July to September (Table 2). Average annual rainfall, the estimated annual surface water runoff and annual groundwater recharge from the water balance model in the watershed are 1090 mm, 305 mm and 164 mm respectively. Under normal rainfall conditions groundwater recharge and surface runoff with respect to annual rainfall works out to be 15% and 28% respectively during the study period. The percentage of groundwater recharge in the Parkal watershed is comparable with the groundwater recharge rates of 14.5% of annual rainfall of Dulapally watershed near Hyderabad (Narasimha Reddy et al, 1991). The recharge estimates of Vedavathi river basin in parts of Karnataka and Andhra Pradesh on a similar granitic terrain are reported to be varying between 13-20 percent of annual rainfall (Sukhija and Rao, 1983).

Table 1 Annual water balance components in Parkal Watershed (in mm)

Year	Rainfall	Inter-ception Loss	Surface Runoff	Soil evapo-ration	Transpi-ration	Recharge
1976	1061.4	15.4	352.7	144.2	314.9	234.2
1977	724.6	15.4	57.4	205.8	434.3	11.5
1978	1394.0	18.6	373.5	252.4	540.6	209.2
1979	784.8	15.3	189.2	133.6	341.3	98.7
1980	710.0	15.4	82.8	144.5	381.3	92.6
1981	1144.2	19.8	281.5	191.1	452.3	199.7
1982	1052.0	15.0	205.3	197.6	455.9	177.9
1983	1386.4	14.0	505.7	138.5	359.5	357.5
1984	946.3	14.5	240.6	182.1	426.2	94.3
1985	719.2	14.0	142.2	145.8	359.6	57.7
1986	1087.0	12.5	411.7	137.9	419.5	91.5
1987	873.7	13.4	199.2	212.0	414.6	36.9
1988	1501.4	12.0	549.6	214.4	443.9	281.4
1989	1346.6	7.8	527.5	144.4	394.5	272.4
1990	1628.1	12.5	465.8	262.5	645.3	241.9
AVG.	1090.6	14.4	305.6	180.4	425.6	163.8

Table 2 Monthly Groundwater Recharge during 1981-1990 (in mm)

S No.	Year	June	July	August	September	October
1	1981	16	57	96	20	11
2	1982	-	72	106	-	-
3	1983	3	44	125	108	76
4	1984	-	37	23	26	9
5	1985	-	3	54	-	-
6	1986	-	13	-	-	-
7	1987	-	37	-	-	-
8	1988	-	152	55	75	-
9	1989	1	239	32	-	-
10	1990	92	32	72	-	22

Parakal Watershed, Warangal District

Parkal watershed, in crystalline rocks of granitic terrain, covering about 12.35 sq. km. is situated in Warangal district, Andhra Pradesh State and falls under Semi-arid Tropics. Rainfall mostly occurs during South- West monsoon from June to September and the mean annual rainfall is 1090 mm. Groundwater divide coincides with the topographic boundary, thus forming a closed groundwater regime. Some outflow leaves the watershed across 2.61 km section of the Paidpally Tank in the North. The streams are ephemeral with intermittent flash flows after good rains and the surface runoff is being harvested in three tanks. Sandy Loam and Loamy sandy clays occur in the watershed with thickness ranging from 0.3 to 1.0 m. Paddy is the only irrigated wet crop grown in the ayacut of tanks. Maize and green grams (cereals) are the major rainfed crops grown during monsoon season. Second crop is mostly grown in the ayacut of tanks and is also supplemented with groundwater pumping.

The watershed is underlain by crystalline rocks of Archean age comprising of grey and pink granites and traversed by quartz and pegmatite. Weathering of rocks has been observed down to a depth of 8 m below ground surface. Fractures at depths below the weathered zone have been identified during drilling. Groundwater occurs under water table conditions in the weathered and fractured parts of the hard rocks. Groundwater levels in dug wells and bore wells generally start rising during last week of June till first week of October. There are twenty observation wells monitored regularly since 1980. The depth to water level during post-monsoon (October) varies between 0.5 - 7.0 m (bgl) whereas it stands at 2.5 - 9.0 m (bgl) during pre-monsoon. Recharge to the groundwater regime mainly takes place from monsoon rainfall.

Groundwater Flow Modeling

The governing equations for groundwater flow is

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right]-W=S_s\frac{\partial h}{\partial t}$$

$$V_i=-\frac{K_{ii}}{\theta}\frac{\partial h}{\partial x_i}$$

The watershed is divided rectangular cells and within any cell, the groundwater head and all material properties are assumed to be the same. Flows between cells can then be computed using Darcy's law and defining the gradient as difference in heads between neighboring nodes. With these assumptions a system of equations can be constructed with one equation for each cell centre. Once the equations are set up, they may be solved using any one of many available matrix inversion sub routines.

The 3-D Modular Finite Difference Groundwater Flow Package MODFLOW (McDonald and Harbaugh, 1988) was selected for the simulation. It is based on the horizontal and vertical discretization of model domain and solves groundwater flow equation for each cell of the model. MODFLOW allows simulation of leakage between adjacent hydrogeological units and it can reproduce flow paths in all three spatial directions. MODFLOW is a finite-difference ground-water model to simulate two-dimensional aerial or cross sectional and quasi or fully three dimensional, transient flows in anisotropic, heterogeneous, layered aquifer systems. The model is based on a block-centered finite-difference approach, using variable grid spacing in x, y, and z-direction. Layers may be simulated as (semi-) confined, unconfined, or convertible between the two conditions. The model can also handle layers that pinch out (representing aquifers, aquitards, or layers within an aquifer). The model allows for analysis of external influences such as constant and time-varying aerial recharge, groundwater pumping, evapotranspiration, and stream flows. Furthermore, MODFLOW has a full implementation of boundary conditions, both constant and varying in time.

Solver for Visual MODFLOW (WHS)

The solver uses a bi-conjugate Gradient stabilized (Bi-CGSTAB) acceleration routine implemented with stone one incomplete decomposition for preconditioning of the groundwater flow partial differential equations. The solution of large set of partial differential equations is obtained iteratively through an approximate solution. Because the matrix equation for groundwater flow is initially "ill-conditioned", effective pre- conditioning of these matrices is necessary for an efficient solution. Two "levels" of factorization are available with the WHS solver. While convergence of the solver requires less iteration with a factorization level of 1, the memory required running the solver increases. The work per solver iteration increases with the level 1, factorization such that total solution time may not be less than the solution time using the level 0 factorization.

The solver works on a two- tier approach to a solution at one time step. Outer iterations are used to vary the factorized parameter matrix in an approach towards the solution. An outer iteration is carried out wherein hydro-geologic parameters of the flow system are updated (i.e., transmissivity, saturated thickness, storability) in the factorized set of matrices. Different levels of factorization allow these matrices to be initialized differently to increase the efficiency of solution and model stability. Inner iterations are used iteratively; solve matrices created in the outer iteration. Maximum number of outer (non-linear) iterations are fixed at 50. Maximum numbers of inner iterations are 500. After an outer iteration is completed, the solver checks for maximum change in the solution at every cell. If the maximum change in computed solution is below the set convergence tolerance then the solution converges and the solver stops, otherwise a new outer iteration is started. Solution accuracy of 0.01 m of head change in the simulated domain is used. While the head change criterion is used to judge the over all solver convergence, the residual criterion is used to judge the convergence of the inner iterations of the solver. If the change in successive inner iterations is less than the tolerance of .001 m then the solver will proceed with the next outer iteration. Dampening factor for outer iterations allows the user to reduce the head change calculated during successive outer iterations and a dampening factor of 1 was used. This parameter can be used to make a non-convergent solution process more stable such that a solution will be computed. This will be done by decreasing the damping factor to a value between 0 and 1 (rarely < .6). This parameter is similar to "acceleration parameters" used in other solvers. Relative residual criterion is another method of checking for convergence of the inner iterations. It compares the residual from the most recent inner iteration to the residual from the initial inner iteration. Once the most recent inner iteration residual is below the initial inner iteration residual times the relative residual criterion, the current outer iteration is completed, and a new outer iteration will be started (Guiger and Franz, 1996).

Conceptual Model

A numerical groundwater flow model is the mathematical representation of an aquifer in a computer using the basic laws of physics that govern groundwater flow; we instruct the computer to consider physical boundaries of the aquifer, recharge, pumping, and interaction with rivers, or other phenomenon to model behavior of the aquifer overtime. These models will then be used to make predictions of how water levels might change in the future in response to changes in pumping and climate. The conceptual model represents the best idea of how the real system works. Developing a good conceptual model requires compiling detailed information on geology, water quality, and recharge, interaction with water bodies including rivers, water levels, hydraulic parameters, and groundwater pumping. The model architecture refers to which computer program to use and the dimensions of the layers and cells that makes up a model. Calibrating and verifying involve showing that the model can reproduce water levels measured in the past. A good calibration and verification gives confidence that the model produces reasonable predictions of water levels in the future. The dimensionality of the model (one or two or 3D) should be selected during the formulation of the conceptual model. For one and two-dimensional models, the grid should be aligned with the flow system so that there is no unaccounted flux into or out of the line or plane of the grid. For example, if a two-dimensional areal model is applied, then there should be no significant vertical components of flow and any vertical leakage or flux must be accounted

Data Requirement for Groundwater Flow Model

a. Surface data
   i. Topography
   ii. Surface water levels
   iii. Amount of recharge
   iv. Pumping rates
   v. Contaminant sources (for Mass Transport Model)

b. Subsurface data
   i. Soil / aquifer properties and stratigraphy
   ii. Density, dispersivity, fraction organic content
   iii. Water Chemistry
   iv. Groundwater elevations

The conceptual model consists of a set of assumptions that reduce the real problem and the real domain to simplified versions that are acceptable in view of objectives of the modeling.

Assumptions should relate to such items as

- Geometry of boundaries of the investigated aquifer domain.
- Kind of material comprising the aquifer (with reference to its homogeneity, isotropy etc.)
- Mode of flow in the aquifer (3D or 2D horizontal)
- The groundwater flow regime (laminar or non-laminar)
- Relevant state variables and the area, or volume over which averages of such variables are considered
- Sources and sinks of water and of relevant pollutants, within the domain and on its boundaries (with reference to the approximation as point sinks and sources, or disturbed ones) and
- Conditions on boundaries of considered domain, that express the way the latter interacts with its surrounding

Groundwater Flow Model of Parkal Watershed

The computer code visual MODFLOW computes a system of groundwater flow equations using integrated finite difference method by implicit discretization of time steps. The cell size used in the Parkal watershed aquifer model is varying from 200 m to 400 m (Fig. 1). A well distributed 13 representative observation wells have been selected for construction of well hydrographs from June 1981 to May 1991. The water level configuration of June 1981 has been assumed to be under equilibrium condition and therefore, has been considered as initial water level configuration for aquifer modeling. The groundwater levels between observation wells have been interpolated taking care of surface topography, stream-bed elevations and water level in the surface water bodies and the same has been simulated as known water levels in the model accordingly.

Aquifer parameters viz., transmissivity and storage coefficient were estimated by conducting pumping tests on four dug wells in the area. Transmissivity is varying from 14 to 42 m^2/day and the average specific yield is 0.054. Considering the saturated zone thickness, the permeability has been assigned to the corresponding cells and at the remaining cells, the K values have been assigned block-wise considering geomorphologic and subsurface geological features. The boundaries have been realized by terminating the cells with no flow boundary condition by assigning zero permeability values in the model. Typical pumping schedule for pumping centre has been shown in Figure 2.

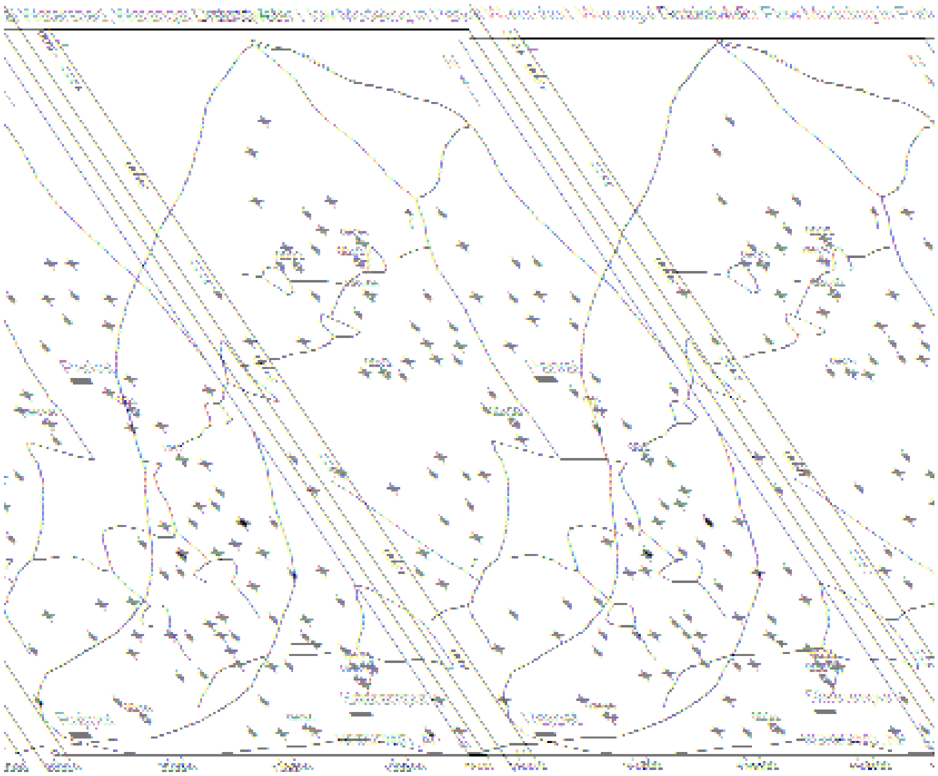
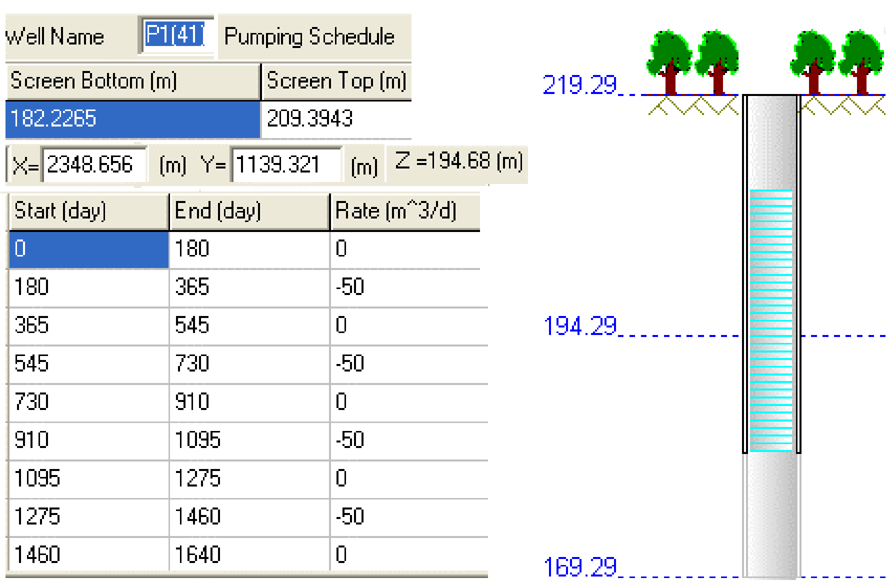


Fig. 1 Observation Wells & Pumping Centers in Parkal watershed, Warangal Disrrict, A.P.



Start (day)	End (day)	Rate (m^3/d)
0	180	0
180	365	-50
365	545	0
545	730	-50
730	910	0
910	1095	-50
1095	1275	0
1275	1460	-50
1460	1640	0

Fig. 2 Typical Pumping schedule of Pumping Centers

Recharge to the groundwater regime due to monsoon rainfall forms the main input to the aquifer system. Seepage from surface water bodies and irrigation return seepage from paddy fields also contributes as input stresses to the flow regime. The outflow occurs mainly through groundwater withdrawal from open wells and bore wells during non-monsoon season mainly for irrigation and intermittent base flow towards streams during monsoon season. The base flow joins the surface water outflow and leaves the watershed through the Paidipally tank.

Steady State Calibration

Groundwater withdrawal has been estimated based on well inventory and average running hours of pumping, the cropping pattern and thus a unit draft of 0. 67 ham / annum has been assigned to each cell based on density of wells falling in a particular cell. Average groundwater recharge of 164 mm/yr, which is estimated from the water balance model has been uniformly distributed as input at all the cells, except at those meshes falling on the stream courses and surface water bodies. The seepage from surface water bodies through beds of tanks at a rate of 46 cm /year has been assumed and the same has been distributed appropriately over 9 months period in a year in the model. The computed groundwater levels of the steady state calibrated model are found matching with the observed water levels within 1.0 m (Fig. 3 & Fig. 4). It was noticed during the processes of model calibration that variation of permeability produced negligible changes in the computed water levels and mainly the input and output stresses determined groundwater level configuration.

The groundwater balance of Parkal watershed for steady state condition is summarized in Table 3. An average annual input of 2.18 mcm (million cubic meters) consists of recharge due to rainfall, seepage from surface water bodies and Irrigation return flow from paddy fields under tank ayacut areas. The output stresses include groundwater pumpage from open wells and bore wells to the tune of 1.67 mcm, a base flow towards streams of 0.27 mcm and a subsurface outflow through the Paidipally tank of 0.24 mcm.

Table 3 Average Annual input and output stresses for steady state (June, 1981)
mcm (million cubic meters)

RUN	INPUT Recharge due to rainfall Seepage from tanks and Irrigation return flow	Ground water Draft	OUTPUT Base flow to streams and outflow
1	2.18	1.80	0.38
2	2.18	1.61	0.57
3	2.18	1.67	0.51

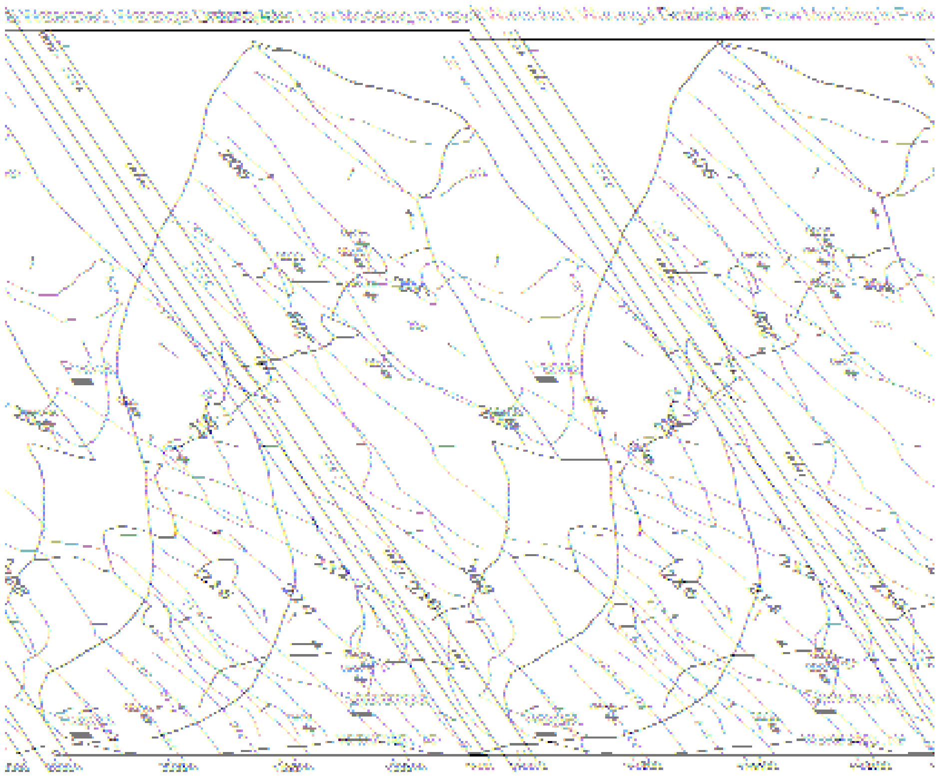


Fig. 3 Computed groundwater levels in m(amsl) during June 1981

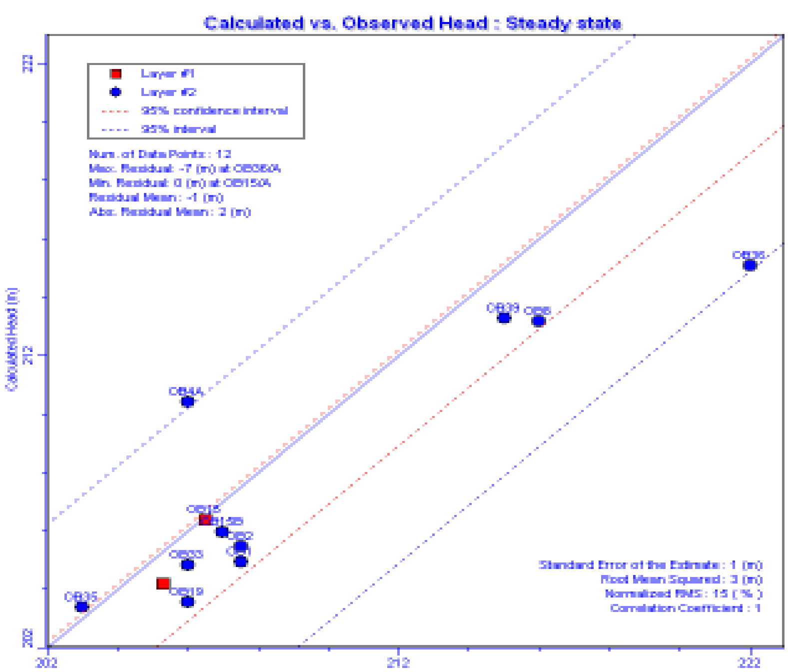
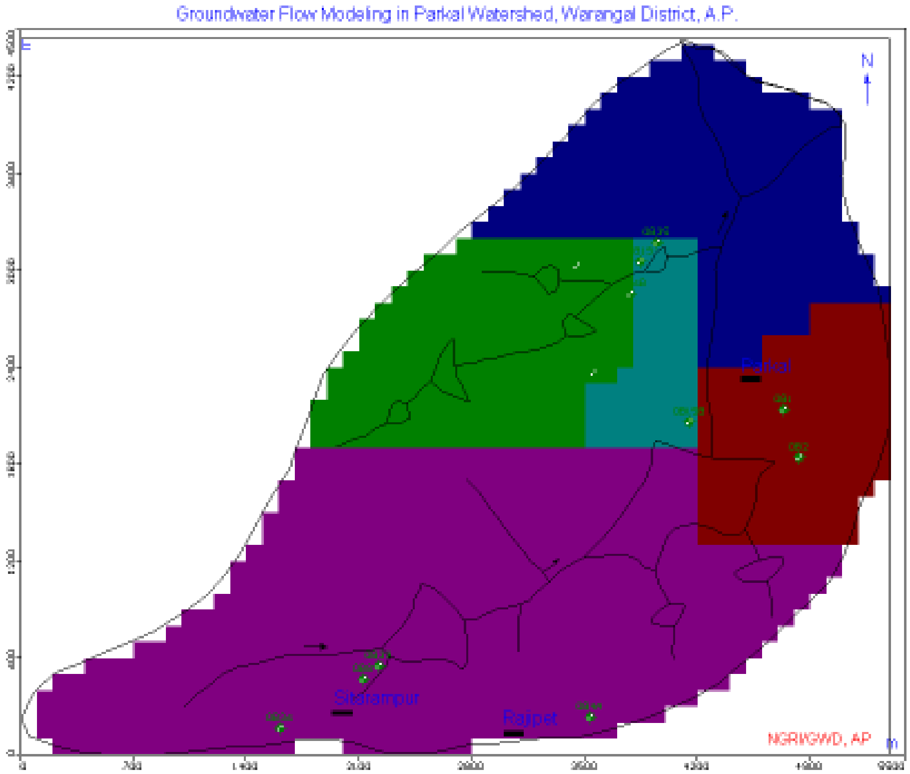


Fig. 4 Computed vs. Observed Groundwater levels – Steady State calibration   June 1981



Storage

Zone		Ss [1/m]	Sy []	Eff. Por. []	Tot. Por. []
1			0.2	0.15	0.3
2		0.0011	0.054	0.15	0.15
3		0.0009	0.047	0.15	0.15
4		0.0006	0.033	0.15	0.15
5		0.0009	0.047	0.15	0.15
6		0.0011	0.054	0.15	0.15

Fig. 5 Specific storage used for Transient model calibration

Transient State Calibration

The average specific yield determined through pump tests have been converted to specific storage considering the thickness of aquifer and the same has been assigned at all the cells (Fig. 5). Dynamic variation of groundwater pumping at pumping centres as well as the groundwater recharge estimated earlier has been fed to the aquifer model in monthly time steps during transient condition (ref. Table 2). The groundwater flow model has been calibrated for 10 year period from June 1981 to May 1991 through comparison of computed vs observed well hydrographs. The time- variant draft of 1.5 mcm/annum was maintained till 1986-87 and later on a draft of 1.6 mcm/ annum, which is about 6 % higher has been simulated in the model. Some relative reduction of annual groundwater withdrawal has been effected during above normal rainfall years using monthly rainfall information and availability of surface water in the tanks.

Yearly input and output stresses for transient simulation are shown in Table 4. Groundwater withdrawal has been redistributed at some cells and specific storage has been localized and assigned to cells to obtain a close match between computed and observed well hydrographs particularly at well no. 16B, 33 and 1. At this stage the computed and observed well hydrographs are found to be not matching during 1986 and 1987 at most of the observation wells. This may be attributable to some excess groundwater recharge occurring during August 1986, which could not be simulated in the model due to lack of understanding on preferred pathways flow, which occurring after two years of drought. Thus additional groundwater recharge has been given to the model during August 1986 to match computed well hydrographs closely with the observed ones during 1986. The comparison of computed and observed well hydrographs at the observation wells is shown in Figures. 6a, b and c.

Table 4 Annual input and output stresses for transient condition mcm (million cubic meters)

		Input	Output		
Sl.	Year	Recharge due to rainfall & Irrigation Return flow	Ground Water Draft	Base-flow to Streams & Outflow	Change in Storage
1.	1981-82	2.50	1.50	1.00	0.00
2.	1982-83	2.39	1.54	0.86	-0.01
3.	1983-84	4.31	1.51	1.60	+1.20
4.	1984-85	1.40	1.45	0.86	-0.91
5.	1985-86	1.00	1.58	0.30	-0.88
6.	1986-87	1.30	1.57	0.13	-0.40
7.	1987-88	1.20	1.55	0.00	-0.35
8.	1988-89	3.50	1.60	0.81	+.1.06
9.	1989-90	4.80	1.60	1.42	+1.78
10.	1990-91	1.70	1.50	1.15	-0.95

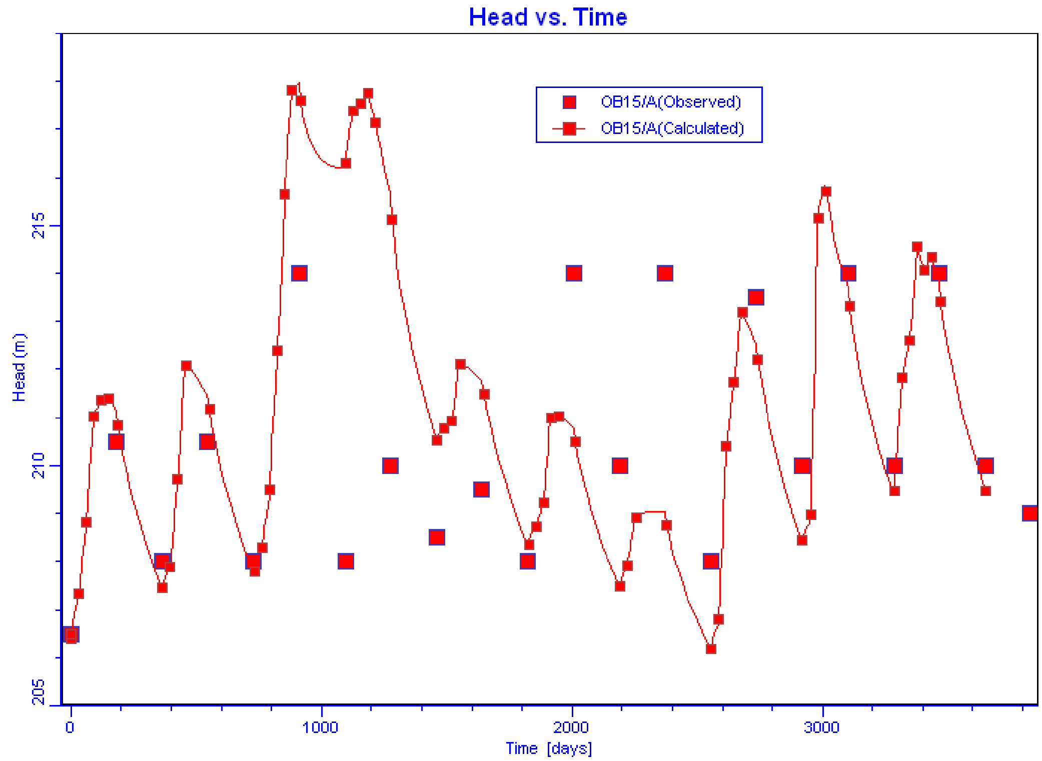


Fig. 6a Comparison of computed vs. observed Well hydrograph at OB15

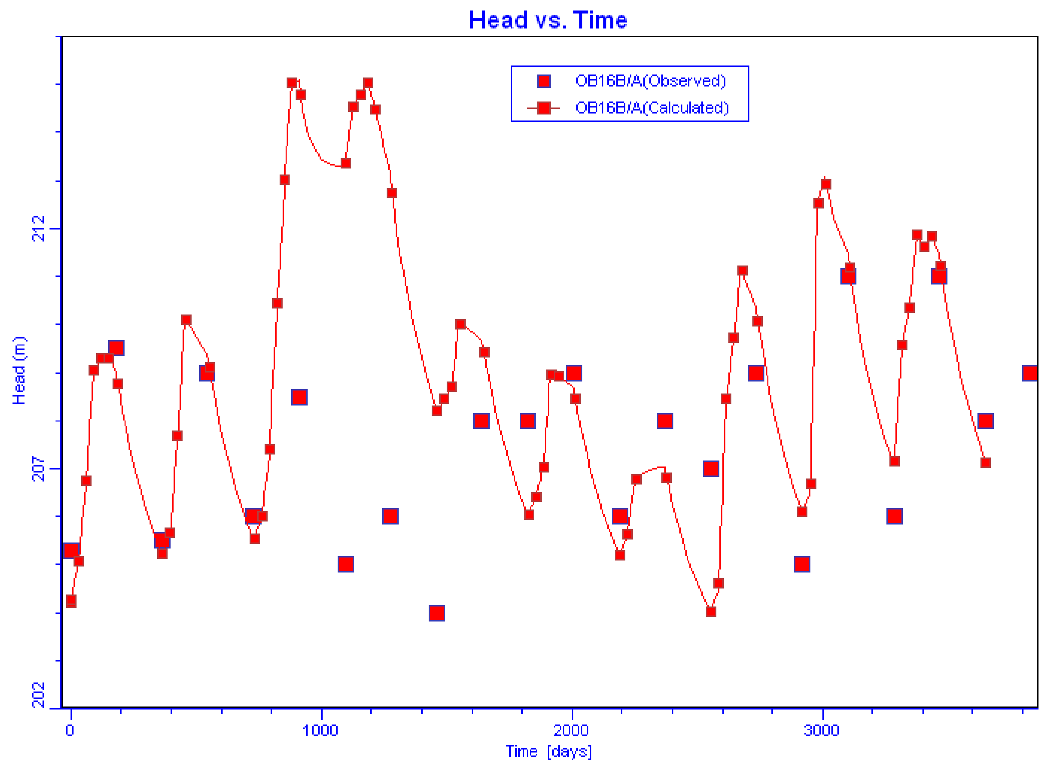


Fig. 6b Comparison of computed vs. observed Well hydrograph at OB168

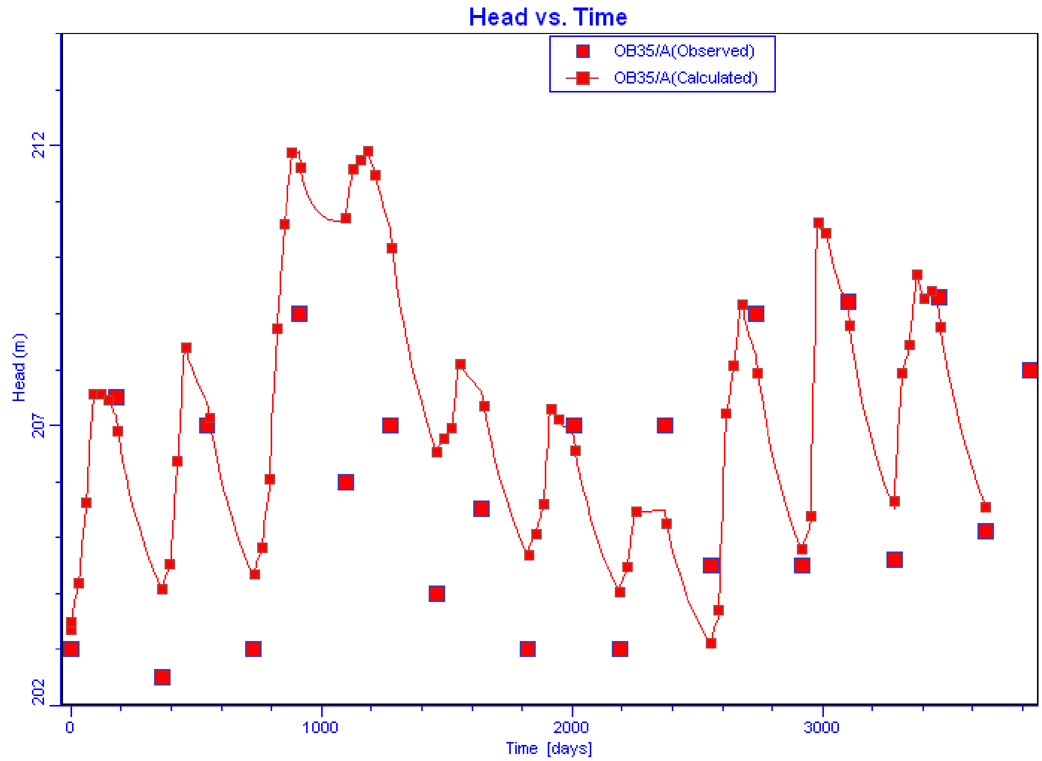


Fig. 6c Comparison of computed vs. observed Well hydrograph at OB35

Groundwater Recharge Model of Dulapally Watershed, Ranga Reddy District, A.P.

Dullapally watershed, in a hard rock granitic terrain covering 44 sq. km is situated about 20 km north of Hyderabad city occupying a part of the uppermost part of the Musi river catchment in semi-arid tropics region. The average annual rainfall is 867 mm during January 1974 to May 1990. The watershed topographic boundary coincides with the groundwater divide and thus forming a closed watershed with a narrow stream outlet in the South. Both surface and groundwater leaves as outflow through the stream. Numerous small streams in the watershed build up trellis drainage pattern. Gentle slope is predominant about 80% of the watershed with average slope between 0.02 to 2.64%. Surface water stored in seven tanks in the area is mostly used for irrigation of second crop. All the streams are ephemeral with intermittent flash flows after good rains. In some years there is no base flow, for example during most part of the rainy season of 1975 the groundwater level remained below streambed.

Thickness of red soil varies from 0.2 to 0.6 m. An average water holding capacity for Alfisol of 60 mm/45 cm thickness in Dulapally watershed has been considered in the water balance study. Further the soil zone has been divided into two layers consisting of top layer of 20 cm thickness and the rest as the second layer. Water loss from the soil zone is mainly due to evaporation from soil, transpiration from native vegetation and subsurface outflow. Paddy is the only irrigated wet crop grown and maize occupies major part as rain fed crop and vegetables are also grown. Grape gardens were spread in patches around Kompally village and between Mysammaguda and Pochampally villages during 1974-90. Tanks are partly filled during the end of June and continue to build up till the end of October.

Hydrogeology

Dulapally watershed is mainly underlain by biotite gneiss and pink Gneissic granite of Achaean age and is traversed by two major dykes striking East - West direction. A pegmatite vein is striking North South direction. The weathered fractured aquifer system consists of 2 – 5 m thickness of upper stratum and 4 – 8 m thickness of middle section in weathered zone underlain by 10-15 m thick fractured zone. Groundwater flows horizontally in the fractured zone. Storage coefficient may range between 1 and 2 percent. The effective porosity of the aquifer formation is rather low, but gravity flow of water through fractures is faster compared to the overlying weathered material where the downward leakage is slow. The lithologs of bore wells drilled by the groundwater department indicate three distinct lithologic units viz., soil zone, weathered zone and fractured zone underlain by basement rock. Soil zone thickness is varying from 0.5 - 1.5 m from uplands to the valley portions. Weathered zone thickness is 17 m in Dulapally village and is varying between 10 m to 20 m in the northern parts in the watershed. Weathered zone thickness is extended up to 30 m around Kompally, Pochampally and Mysammaguda villages. The fractured zone starts at 14 m depth and is occurring as two or three zones at different depths at 20, 25 and 28 m. The fractured zone in some areas is extending up to 33 m depth.

Groundwater Conditions

Groundwater occurs in water table condition in weathered fractured aquifer system in pink granite gneiss complex. There are about 50 observation wells in the watershed monitored regularly for water levels, which include domestic wells, irrigation wells and bore wells. Water levels generally stand maximum during first week of October and depth to water level vary between 3. 0 - 8.2 m bgl whereas during pre-monsoon it varies 5.5 - 11.55 m bgl. As the watershed is a closed one recharge to groundwater mainly takes place from rainfall. Surface runoff in streams is harvested in tanks and some runoff leaves the watershed through a small stream outlet near Dulapally village. Regional groundwater table contours indicate that the groundwater flow is predominantly towards stream channels with a general groundwater gradient from North to South, which also closely follows topography. Groundwater table elevations are minimum around Dulapally village and are maximum around Mysammaguda, Pochampally and Kompally villages. No flow enters or leaves the watershed through the watershed boundaries, except small outflows through the stream outlet near Dulapally village.

Water Balance Model of Dulapally Watershed

Daily rainfall and open pan evaporation have been measured since 1974 at Dulapally hydro-meteorological station maintained by Groundwater Department. Irrigation component could be negligible since rainfed crops are grown more than 80% of the area. The rainfall data has been used to estimate the surface runoff using SCS Runoff Curve Number (CN) model and water availability in the soil zone whereas the pan evaporation measurements have been utilized to evaluate the actual evapotranspiration. The weighted average composite runoff curve number under three antecedent Moisture conditions I, II & III are 64, 81 and 91 respectively in the watershed. Recharge to groundwater table in the watershed has been estimated from the water balance model, the annual average groundwater recharge and annual groundwater recharge have been shown in Table 5 and Table 6 respectively. The monthly various computed from the Water balance model are shown in Table 7.

Table 5 Annual water balance of the soil zone (in mm) in Dulapally watershed

Year 1974 - 1989	Average
Rainfall	867.8
Interception loss	16.5
Surface runoff	181.4
Evapotranspiration	545
Soil evaporation	157.8
Transpiration	387.2
Groundwater Recharge	124.7
Soil moisture	9.9

The groundwater recharge occurs from the end of July onwards till October. The monthly groundwater recharge varies from 3 -128 mm during 1977-1989. Groundwater recharge of 128 mm has been estimated due to 266 mm of rainfall during November 1987, which is a rare phenomenon. The surface runoff has been estimated by weighted average runoff curve number using SCS method. The average annual quantities of rainfall, estimated surface runoff and recharge of the watershed are 867 mm, 181 mm and 124 mm respectively under normal agro-climatic conditions. The percentage of groundwater recharge and surface runoff works out to be 14.4 and 20.9 of average annual rainfall respectively.

Table 6. Annual groundwater recharge (in mm) in Dulapally Watershed (1974 – 1989)

Year	Recharge in "mm"
1974	51.3
1975	248.7
1976	101.6
1977	37.2
1978	111.1
1979	34.6
1980	61.7
1981	152
1982	23.3
1983	296.7
1984	65.1
1985	20.3
1986	93.3
1987	247.4
1988	290.6
1989	159.9

Average annual recharge is 124.7mm

Table 7. Variations of Monthly groundwater recharge (in mm) during 1977-1989

S. No	Year	Jun	Jul	Aug	Sep	Oct	Nov
1	1977			12	25		
2	1978	37	33	16	25		
3	1979			34			
4	1980	2		60			
5	1981		23	65	51	13	
6	1982		8			16	
7	1983		26	77	107	86	
8	1984		1	43	2	19	
9	1985		7	9		5	
10	1986	12		51			
11	1987	11	74	34			128
12	1988		84	120	63	23	
13	1989		104	19	24	13	

Groundwater Flow Model Using MODFLOW

The Dulapally watershed groundwater flow model has been simulated using MODFLOW software (Fig. 7). The entire data has been taken from the past records for dynamic simulation (from 1977 to 1989). Firstly, the watershed boundaries has been delineated, and it is digitized using SURFER software. The simulated model domain is spread over 9000 m x 7000 m has been discretized into rectangular cells with dimension of 100 m x 100 m. The aquifer geometry and permeability distribution have been taken from pumping test data and lithologs. River and constant head boundaries have applied as the boundary conditions for the simulation for streams and at outflow nodes respectively. A no flow boundary condition has been assigned along watershed boundary. Input and output stresses include groundwater recharge and groundwater withdrawal from pumping wells. Finally the groundwater model has been run for steady state and transient conditions, and is calibrated for the historical data. Out of 50 observation wells monitored for water levels only 8 observation wells where reduced elevations are available could be utilized for construction of well hydrographs from June 1977 to May 1990. The water level configuration of June 1977 has been assumed to be in equilibrium condition and the same has been considered as starting condition of the aquifer model.

Aquifer parameters such as transmissivity and specific yield values were estimated by conducting pumping tests on 9 wells in different parts of the basin and are varying from 19 to 125 m^2/day and S values are varying from 0.0084 to 0.016. The permeability value has been assigned considering geomorphologic features and subsurface geology viz.. Weathered granite, semi Weathered granite, fractured granite and shallow basement. The model boundaries have been realized by terminating the grid with no flow boundary condition.

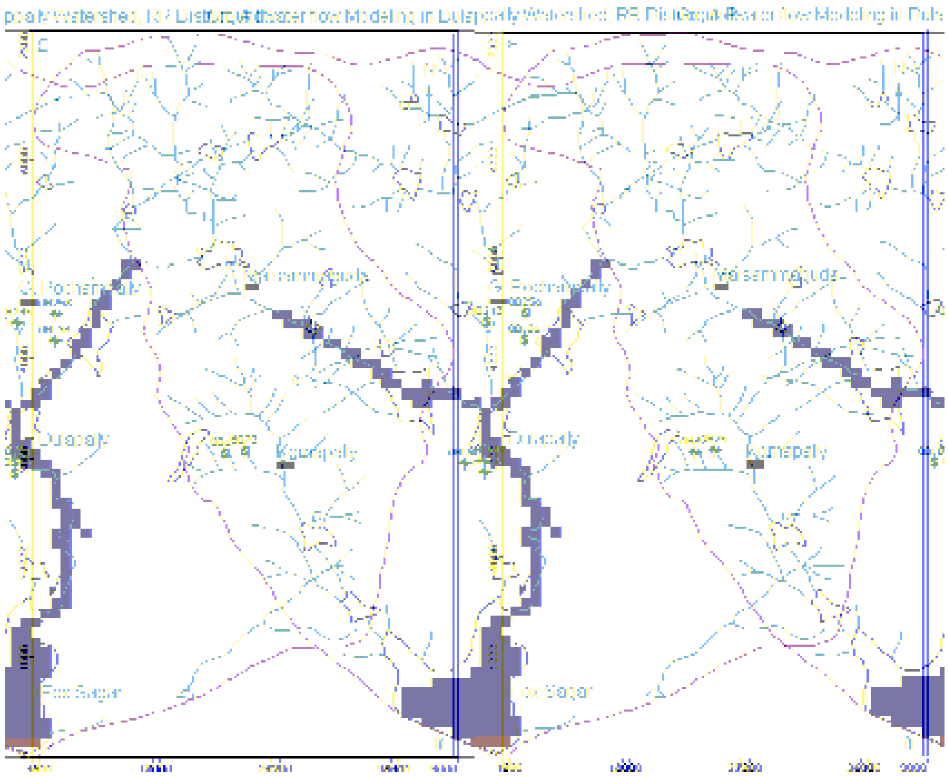


Fig. 7 Boundary Conditions of Dulapally Watershed Groundwater Flow Model

Input and Output Stresses

Input to the weathered fractured aquifer system is groundwater recharge due to monsoon rainfall and seepage from surface water bodies. However, a small outflow leaves the watershed at the Southern end through stream. The output stress from the groundwater regime is mainly through groundwater withdrawal from open wells and bore wells and intermittent base flow to streams during monsoon season whenever the groundwater level rises above the stream bed. The base flow adds to the surface runoff and escapes through the steam outlet in the south near Dulapally village. The groundwater withdrawal for irrigation mostly takes place during non – monsoon period from October to May. However, domestic consumption of groundwater continues throughout the year. The groundwater draft has been assigned to individual cells based on density of wells falling in each cell and is depicted in Fig.6. The annual groundwater recharge 124 mm has been uniformly fed at all the mesh nodes in the aquifer.

Steady State Condition

The computed water level configuration is about 40 - 60 m higher than the measured water levels. Later the stream network has been simulated through river package to compute groundwater level configuration under steady state condition (June 1977). The following modifications have been resorted to during calibration stage and the computed water levels show a predominant groundwater flow towards the Fox Sagar (Fig. 8).

- Permeability in the uplands has been marginally modified to allow more lateral flow towards the stream channels

- Groundwater draft around Kompally village has been redistributed over a larger area to obtain a better fitting of computed groundwater levels at the observation wells Nos. 67 and 75
- A minor redistribution of groundwater draft around Pochampally tank has been resorted to obtain a close fit of measured water levels at observation wells Nos.245 and 256

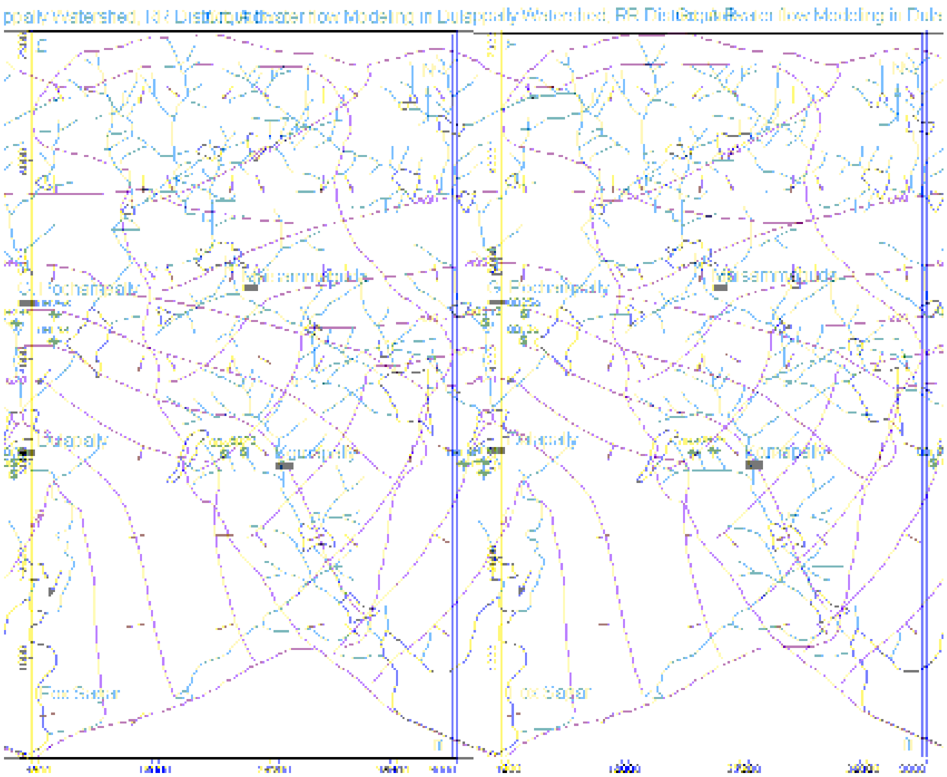
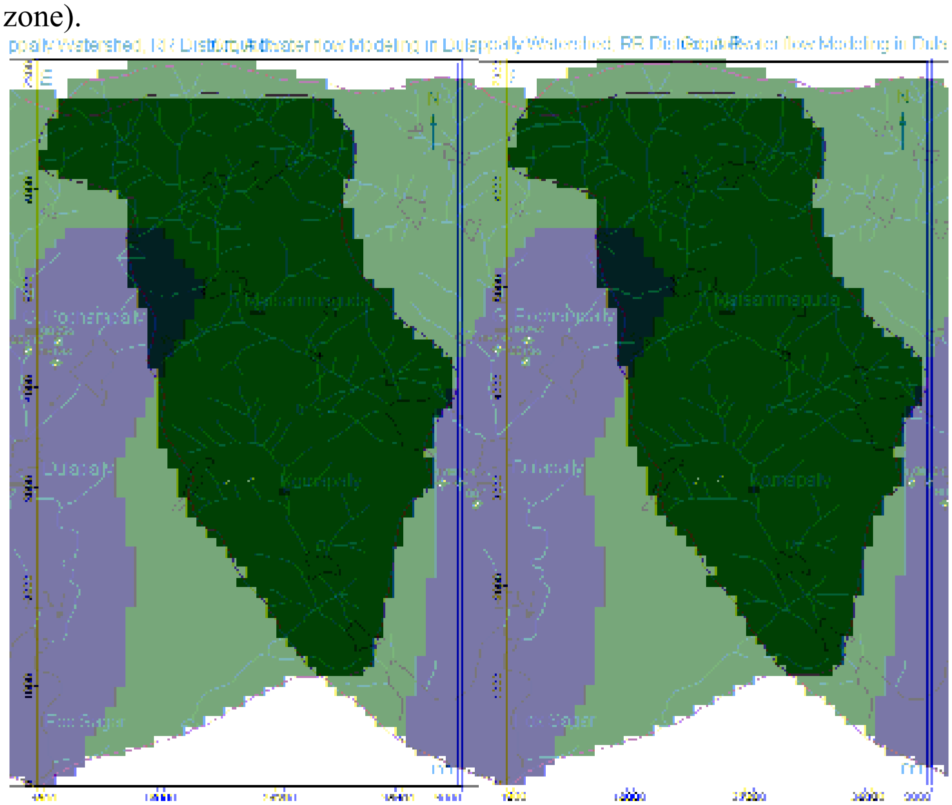


Fig. 8 Computed Groundwater Level in m(amsl) & Velocity Vectors - June 1977

Validation of Recharge Estimate (Transient Condition)

- Storativity values estimated through the pumping test have been assigned at all the cells (Fig. 9). Temporal variation of monthly recharge computed from the recharge process model has been given in monthly time steps during transient condition (ref. Table 3). The ground water flow model has been calibrated from June 1977 to May 1990 during transient condition through comparison of well hydrographs at 8 observation wells.
- Well hydrographs of all the observation wells have been found matching under normal rainfall years except during drought years of 1978, 1984, 1985 and 1986. Comparison of computed vs. observed well hydrographs of observation wells nos. 75, 67, 186, 245, 256 were shown in Figures 12, 13,14,15,16 respectively.
- Comparison of well hydrographs of Observation wells 75 and 67 shows that the computed and observed groundwater levels during pre-monsoon of 1980 to 1983 and post-monsoon o f 1981, 1982, 1985 match within +/-1.0 (Figs. 10a, b and c).
- In general groundwater level fluctuations in all the observation wells followed the observed ones indicating a realistic simulation of storativity values and recharge parameter in the groundwater flow model.

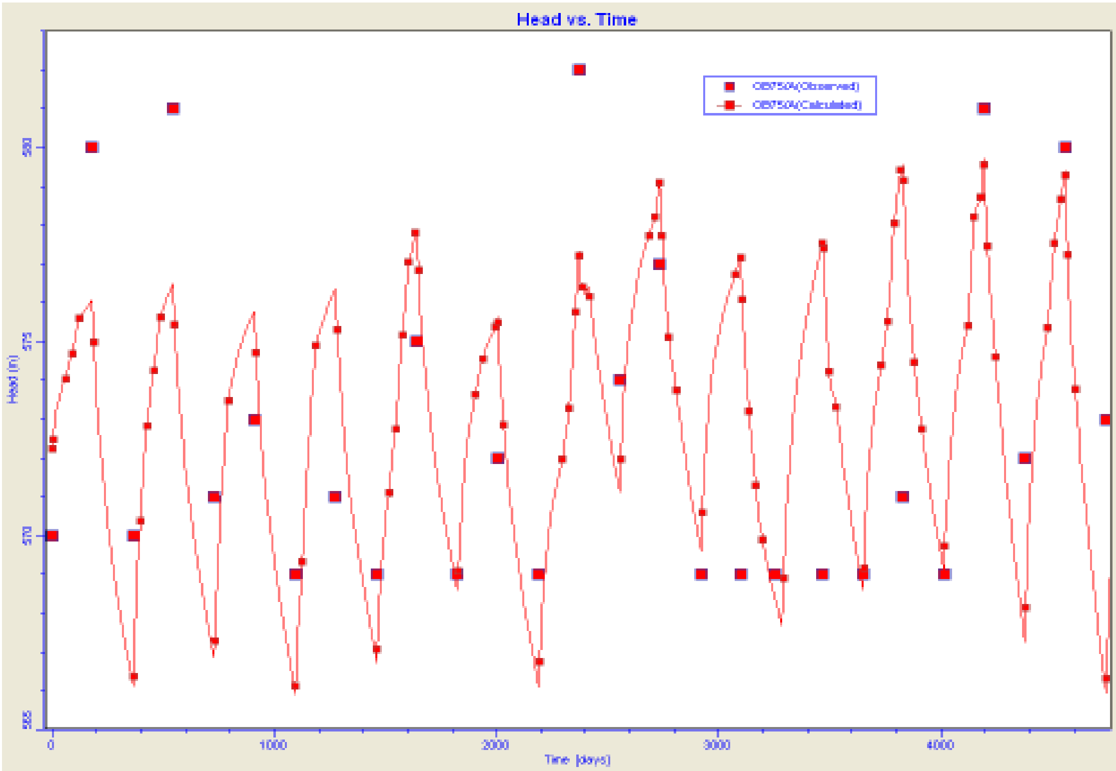
Thus the groundwater flow model simulation confirms and validated accuracy of the temporal variations in recharge estimates obtained from the recharge process model (Water balance model of soil zone).



Storage

Zone		Ss [1/m]	Sy []	Eff. Por. []	Tot. Por. []
1		1E-5	0.2	0.15	0.3
2		0.0009	0.012	0.15	0.15
3		0.0012	0.013	0.15	0.15

Fig. 9 Specific Storage used for Transient Simulation



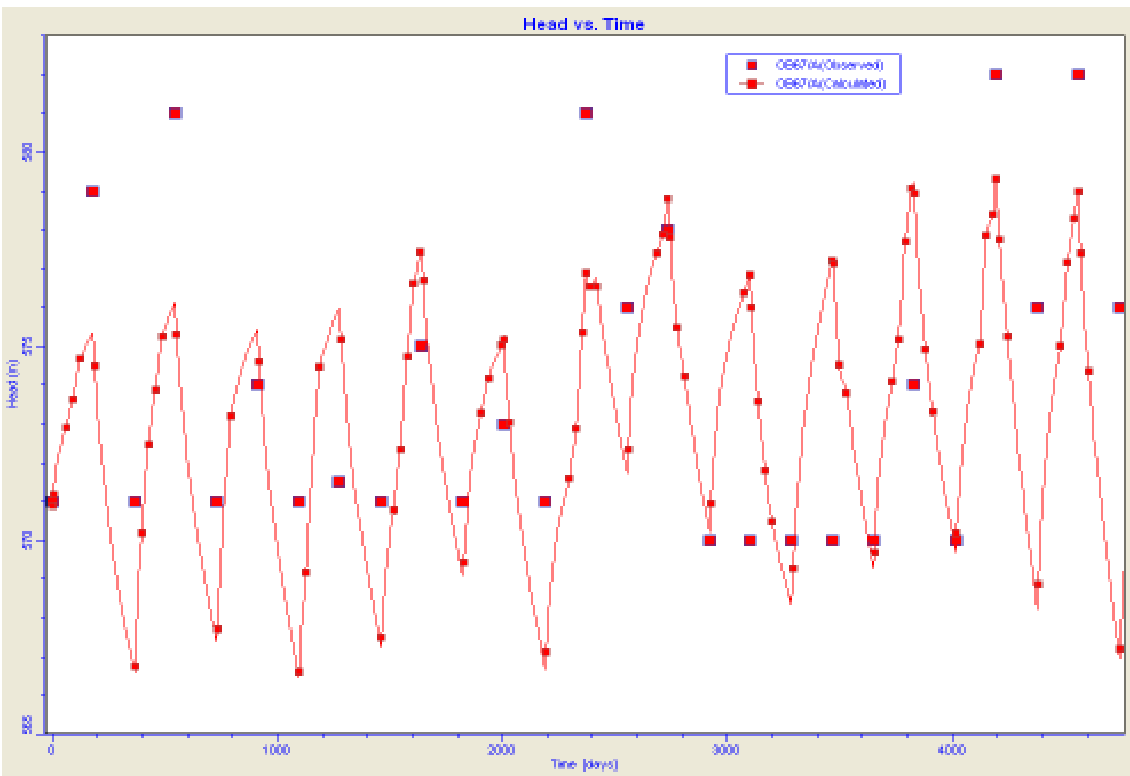


Fig.10a&b Computed vs.Observed Well hydrographs at OB75&67during June1977-1991

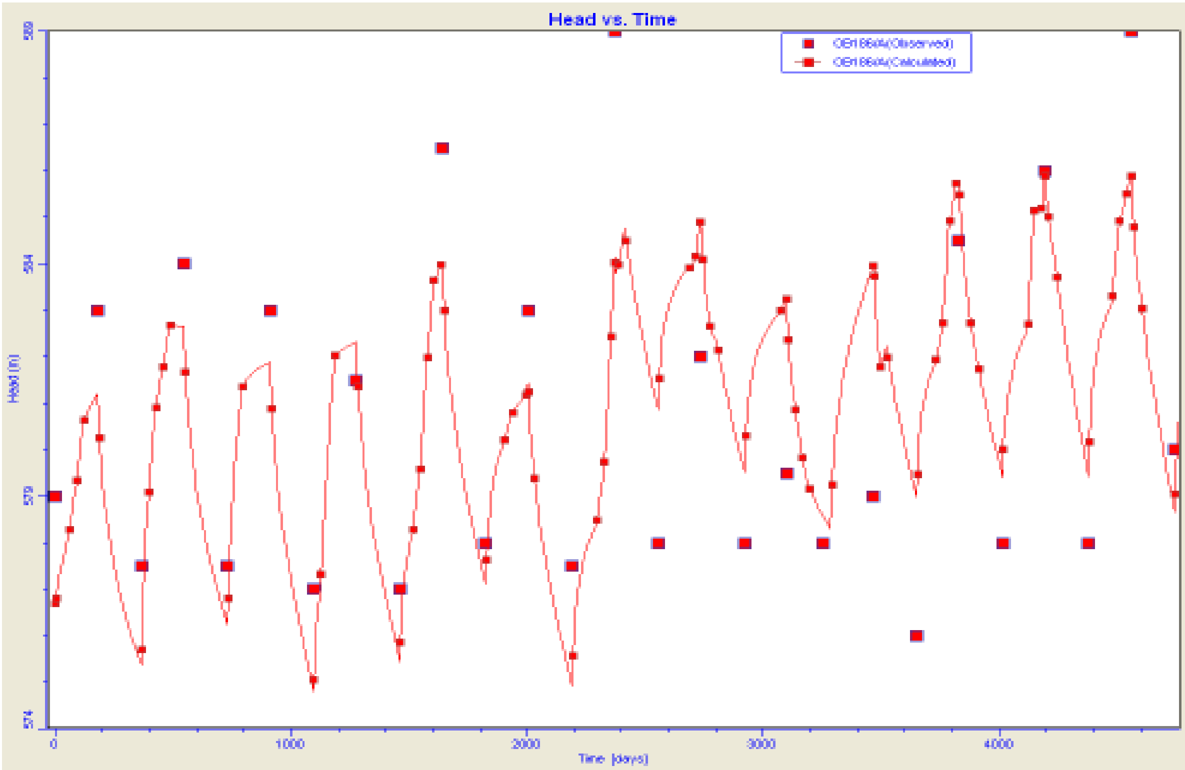


Fig. 10c Computed vs. observed Well hydrographs of OB186 during June 1977 – 1991

Soil Water Infiltration and Movement (SWIM)

Soil Water Infiltration Model (SWIM) has been applied for computation of groundwater recharge from irrigated paddy field in PAU Campus. Total precipitation and applied irrigation has been about 2460 mm. The model out put gives about actual evaporation of 1798 mm with runoff of 82 mm. The unavailable water in soil zone is 569 mm with available water at the end of simulation of 499 mm and the groundwater recharge worked out to be 441 mm for 3 m sandy loam profile (Fig. 11). The natural recharge estimated by tracer measurements made in Punjab state is about 55 mm. The actual irrigation return flow works out to be 396 mm, which is about 1 mm/day. The groundwater recharge at the end of one year has been worked out as 149 mm for 6 m sandy loam profile.

Total precipitation and applied irrigation water has been considered to be about 2460 mm. The model output gives about actual evaporation of 1798 mm with runoff of 81 mm. The unavailable water in soil zone is 1139 mm with available water at the end of simulation of 1150 mm. Groundwater recharge computed from SWIM Model at the end of one year has been worked out as 149 mm for 6m depth profiles. The actual irrigation return flow in this case will be 94 mm/yr, which is hardly 0.2 mm/day. It seems that the amount of recharge could be even less when deep water table is encountered due to over exploitation of groundwater in the area resulting in large thickness of vadose zone, which a common situation in Punjab.

The SWIM model results in the Punjab Agriculture University Campus, Ludhiana indicate that the reasons behind deep water table in the canal irrigated areas may be attributable to large thickness of vadose zone which may be holding the irrigation return flows as available moisture in that zone above the water table, but not contributing actually to the water table.

Further refinements to the above study are recommended with actual monitoring of soil moisture profile through neutron probe. The study warrants imperative need for reduction of overexploitation of groundwater resources in the area. As overexploitation of groundwater has been resulting in reduction of recharge potential of applied irrigation return flows as well as monsoon rainfall reaching water table aquifers in various parts of Punjab. It is recommended to measure moisture variation with depth using neutron moisture probe to ascertain the above findings which may provide a better understanding of recharge process in overexploited alluvial aquifers.

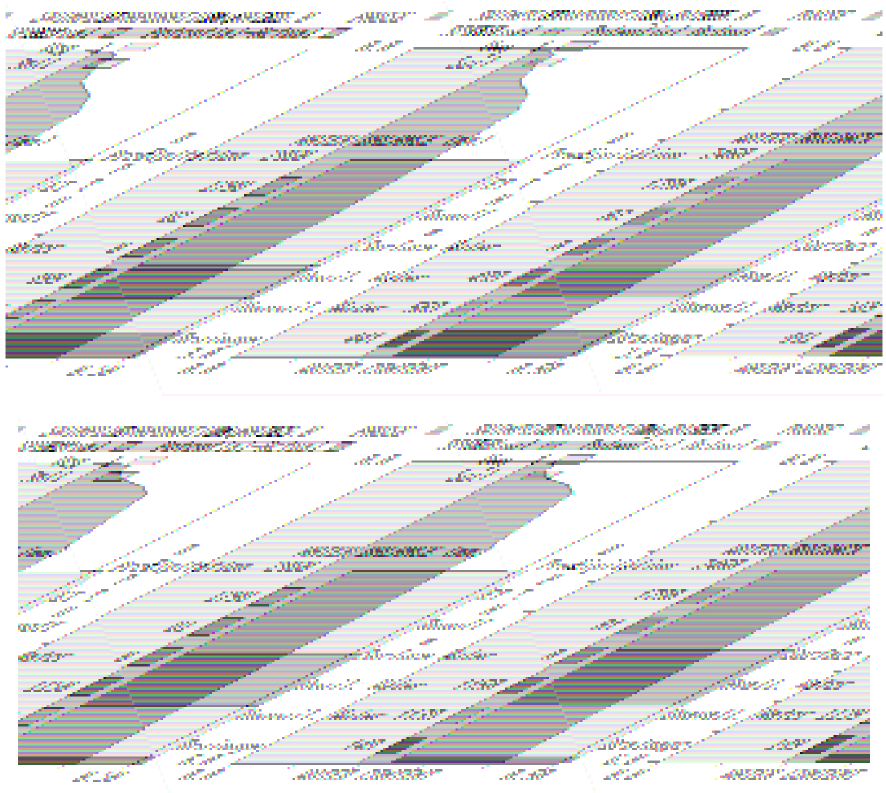


Fig. 11 Comparison of annual Groundwater Recharge in shallow and deep Alluvium Conditions in Muktsar District & PAU Campus, Ludhiana Respectively -- 2004

Conclusions

- Recharge estimates essentially serve as starting values for assigning as input due to rainfall to the aquifer system and moreover on small size watersheds the spatial variations of recharge could be negligible.
- Comparison of computed vs. observed well hydrographs in the groundwater model provides for close matching of hydrographs and the importance of dynamic recharge processes occurring in the granitic terrain.
- Sensitivity study of the flow model indicates that variation of conductivity and recharge individually by +/- 10% will not effect considerably the computed groundwater levels at the observation wells.
- The groundwater flow model of aquifer system has attempted to confirm and validate the aquifer parameters estimated from pumping tests as well as quantitatively synthesize the recharge process through simulation of the dynamic behavior of the aquifer system by

comparing well hydrographs of computed and observed water levels at the observation wells in the watershed.

- SWIM Model predictions indicate that irrigation return flows are unable to replenish the deep groundwater as expected since most of the moisture is being exhausted for replenishing the increasing thickness of vadose zone due to over exploitation of groundwater.

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