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Estimation of rainfall recharge in a coastal area through inverse groundwater modelling

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Abstract

Estimation of rainfall recharge is important for optimal development and efficient management of groundwater resource in coastal areas. Rainfall recharge, which is dependent on a number of hydrogeological and meteorological factors, is complex to study and analyze. Normally rainfall recharge is estimated as lumped component by using various empirical relationships between rainfall and soil type. Groundwater Estimation Committee (1984) has suggested a wide range (10-25%) of rainfall recharge for alluvial areas. Tyagi et al (1997) have estimated the recharge during monsoon season in the range of 13.4 –17.2%, 12.1-13.3% and 16.1-19.2% for Central Godavari, Mahanadi and Krishna deltas respectively by lumped groundwater balance approach.

The rainfall recharge, however, varies in space and time and as such, a distributed ground water modelling approach may provide better estimate of this input to the aquifers. Therefore, the inverse groundwater modelling technique was adopted in the present study to estimate the rainfall recharge and its spatial variation in the coastal aquifer of Central Godavari Delta, Andhra Pradesh (India). The area was discretized into 1x1 km grid and was grouped into various recharge zones according to the hydrogeomorphology of the delta. MODINV (MODular INVerse model) was used to estimate the distributed recharge in these zones during the monsoon season. On a distributed basis, the rainfall recharge coefficient in the lower, middle and upper reaches of the study delta is found to vary from 0.11 to 0.25. The recharge coefficient taken on lumped basis is obtained as 0.17.

INTRODUCTION

Groundwater development forms the bulk of irrigation development programmes in most of the states of India. Groundwater being a dynamic and replenishable resource, its potential is generally estimated from the component of annual recharge. Since rainfall is the principal natural source of groundwater recharge in the country, quantification of the rate of this natural recharge is a basic prerequisite for optimal development and efficient management of groundwater resource. It becomes particularly vital in a coastal aquifer where the draft in excess of this natural rate of recharge can induce the sea water intrusion into the fresh water aquifers. Rainfall recharge, which is a fraction of total rainfall, primarily depends upon a number of factors, e.g. soil moisture characteristics, topography, vegetal cover, soil moisture deficiency, thickness of top soil, depth to water table, intensity and duration of rainfall, and other meteorological factors. Quantification of rainfall recharge is, thus, one of the most difficult tasks in the evaluation of ground water resource. Estimates, by whatever method, are normally, and almost inevitably, subject to large error. Basically, the principal methods of recharge estimation can be grouped into two categories: (a) ‘from above’ – by analysis of water moving downwards through the unsaturated zone of soil, e.g. lysimeter measurements, tracers, soil moisture budget models and one dimensional soil water flow models, and (b) ‘from below’ - by inferring the recharge from water table changes, e.g. water level fluctuation method, ground water balance approach, inverse modelling (determination of the recharge necessary to maintain the groundwater levels).

The approach of inverse modelling was considered by Freeze (1983) to be the most straightforward way of estimating groundwater recharge. It is called an ‘Inverse Modelling’ because, contrary to the ‘Forward or Direct Modelling’ where recharge is known and hydraulic heads computed, here the recharge is computed from field measurements of hydraulic heads. Though, a few standard software like MODINV, MODFLOWP (parameter estimation), PMWIN etc. are available now a days for tackling the inverse problem, the recharge estimation by this method has not yet achieved the share of attention it deserves. In the present study, MODINV (MODular INVerse model) which is a software for parameter optimisation of MODFLOW has been used to estimate the recharge distribution in different zones of Central Godavari Delta.

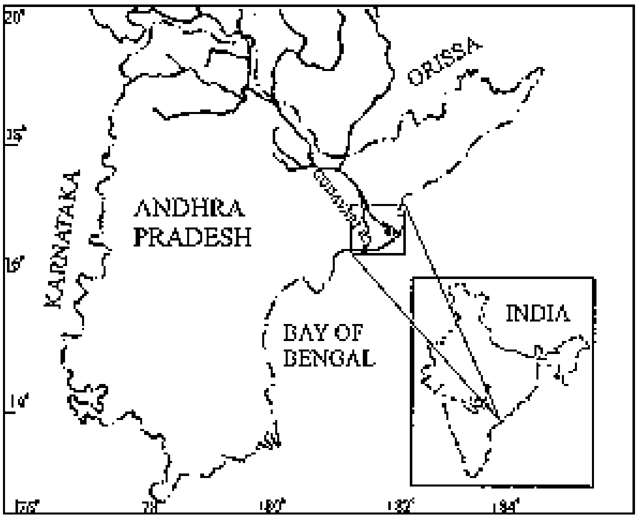


Figure 1. Index map of Central Godavari delta.

STUDY AREA

The study area comprising of about 825 km^2 lies in East Godavari District of Andhra Pradesh State, India. It forms a part of Central Godavari Delta with its hydrological boundaries as river Gowthami Godavari in the east, river Vasistha Godavari and its branch Vainateya in the west and the Bay of Bengal in the south. Geographically, the study area is located between 16°25’ to 16°55’ N latitude and 81°44’ to 82°15’ E longitude and is shown in Fig.1. Being the coastal region, the climate of the study area is comparatively equitable. The normal annual rainfall in the area is 1142 mm of which more than half is received during southwest monsoon (June to September) and a large portion of the rest occurs in October and November.

The study area consists of rich alluvial plain formed by river Godavari. Texturally, a major part of the study area consists of sandy loam and sandy clay loam. It has a gentle land slope towards the sea, with elevations varying from about 10 m at upper reaches to about 1 m near the coast, and so follows the ground water flow direction. The average depth of water table below ground level during pre-monsoon period varies from about 7 m in the upper reach to about 1.75 m near the coast. The average seasonal water table fluctuation (i.e. pre to post-monsoon) in these reaches is observed to vary from about 4 m to about 1 m respectively. The entire study area is under the command of the Godavari Central Canal system and is served by main canal, three branch canals, one distributary and a large number of irrigation channels. The canal system remains operational for 11 months with one month closure period during April-May. Besides, a good number of shallow tube-wells and filter points also exist in the study area.

There are mainly two cropping seasons namely *kharif* (June to November) and *rabi* (December to April). The study area is predominantly a rice growing area in both *kharif* and *rabi* seasons. Other important crops in the study area include coconut, sugarcane, banana, turmeric and vegetables. The crops like maize, *jowar*, *bajra* etc. are found in patches only. The entire area under paddy is irrigated by canal water. Other important crops like sugarcane, banana and vegetables are partly irrigated by tube-wells and partly by canal water. The gross cropped area is about 95000 ha of which about 75% is occupied by paddy, 15% by coconut trees and the remaining by other crops. The area under other deep-rooted trees is almost negligible, as there are no forests in the study area.

OVERVIEW OF MODINV

The MODINV suite of software comprises a number of programmes, built to enhance the usefulness of the popular USGS finite difference flow model, MODFLOW. The MODINV is a parameter optimisation programme for MODFLOW. Using this software, the specific values taken by any parameter that MODFLOW can read as a 2-dimensional data array (e.g., transmissivity, hydraulic conductivity, storage capacity, recharge, evapotranspiration) can be optimised such that model-generated heads are as well matched as possible with those observed in the field. Steady state and transient, single and multi-layer, confined and unconfined flow models can all be calibrated in this manner. Besides, providing optimised parameter values, MODINV indicates the reliability of these estimated aquifer parameters, given the observed head data those are used in calibration. Parameter values can be fixed, grouped or transformed to enhance optimisation stability and efficiency.

Fundamental to the operation of most inverse modelling algorithms is an ability to calculate model outputs using current estimates of model parameters. These model outputs are compared with actual measurements and the parameters are then adjusted to obtain a better comparison. MODINV uses MODFLOW as its forward processor. However as field-observed head data exist at only a discrete number of wells, the two-dimensional head arrays constituting MODFLOW's output are interpolated to yield MODFLOW-predicted heads at these observation wells. The interpolated head values are then compared with observed head data until the weighted squared sum of the differences between these two sets of heads is minimized.

MODEL CONCEPTUALISATION

Based upon the available information, a conceptual model was postulated to provide a framework that describes flow system geometry and the physical processes to be simulated by the numerical model. The geology of the area was interpreted from the exploration borehole information at Mandapeta. The study area is comprised of coastal alluvium. The alluvial deposits of the area are essentially contributed by Godavari River. The subsurface geology existing at Mandapeta and approximate depth of units are given in Table 1. The thickness and lateral continuity of individual layer as given in Table 1 does not vary much throughout the flow domain in the study area. The study area consists of mainly two aquifers for groundwater development – the unconfined or phreatic aquifer and the confined aquifer. Hydrogeological investigations carried out in the study area reveal that a large number of shallow tubewells and filter points, mainly used for irrigation purpose, have been sunk into the phreatic aquifer. This aquifer is recharged mainly through the direct infiltration of rainwater, besides some recharge taking place due to irrigation return flow. Therefore, instead of incorporating two aquifers, only one unconfined aquifer system is conceptualised in the present model. The clay bed below this aquifer would act as the bottom boundary for the conceptual model.

Table 1. Lithology at Mandapeta.

Depth range (m)		Description	Depth range (m)		Description
From	To		From	To	
0.0	1.5	Top Soil	49.5	55.5	Sand, fine to medium
1.5	18.0	Sand, fine to medium	55.5	61.5	Sand, fine
18.0	19.5	Sand, Coarse to very coarse	61.5	67.5	Sand, fine to medium
19.5	31.0	Clay	67.5	73.5	Sand, medium
31.0	39.0	medium to very coarse Sand	Below	73.5	coarse to very coarse Sand
39.0	49.5	Sand, medium to coarse			

The spatial domain is discretized into 75x85 grids, each grid having a dimension of 1 km x 1 km. The aquifer is represented by a single model layer having a uniform thickness of 18 m. The active cells over the spatial domain are shown in Fig.2. Two branches of Godavari river running on two sides of the study area are bounded by inactive cells. The Bay of Bengal on the third side of the study area is considered a constant head boundary with head as 0 m.

The natural rivers on two sides of the study delta, and canals running through the area are expected to interact with the aquifer system depending upon their stages and the water table levels in the aquifer. Therefore, these natural rivers and canals are represented in the model through the river package in MODFLOW. The existing 3950 shallow tubewells and filter points, well spread over the study area, are incorporated in the model through 396 numbers of pumping wells in the model (the limit on maximum no. of wells in MODINV being 400). The EVT package in the model accommodates the evapotranspiration process. The EVT surface elevation is taken as the elevation of the land surface. The study area has large number of coconut trees, which draw water directly from the ground water reservoir. Therefore, EVT extinction depth is taken as 3 m. The rainfall and the irrigation return flow are the two major sources of groundwater recharge in the study area and are considered in the conceptual model. The spatial variability in recharge rates is incorporated in the model by defining eight recharge zones considering the factors such as rainfall, unsaturated thickness, and location with respect to rivers and canals (Fig.3). The soils in the zone of water table fluctuation are assumed homogeneous and isotropic. As seen from the well log data, mainly fine to medium sand is encountered in this aquifer. The hydraulic conductivity and specific yield for this soil medium generally vary from 6 to 15 m/day and 9 to 18% respectively. The representative values of these parameters have been optimised through calibration.

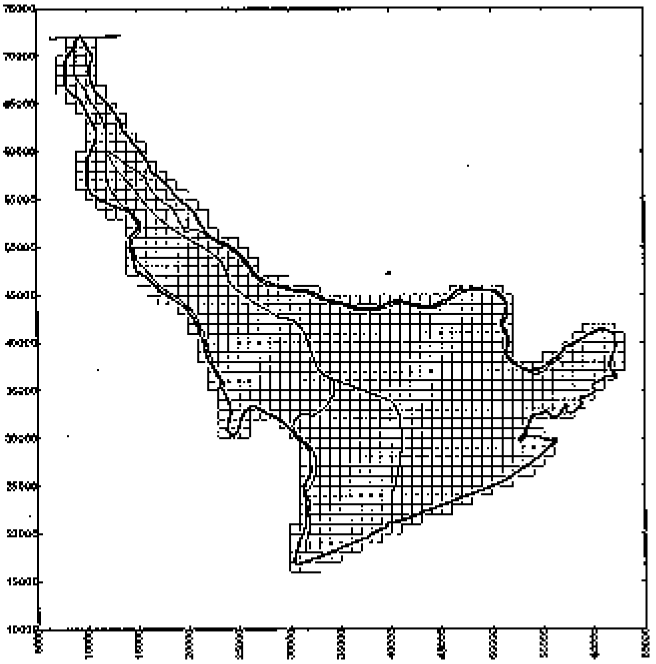


Figure 2. Active cells in model.

MODEL CALIBRATION

Parameter estimation of a groundwater model is essentially synonymous with model calibration, which is synonymous with solving the inverse problem. The MODINV, as used in the present study, employs the automated calibration technique to optimize the parameter values by comparing the simulated heads with the observed ones. The input data and the initial estimates of parameter values were transferred to the model through PREMOD and PREINV, which are the preprocessors for MODFLOW and MODINV respectively. The model was calibrated for transient conditions of the monthly water levels of non-monsoon period of 1985 by taking 4 stress periods (Feb. to May 1985), each representing 30 days, with initial conditions taken as of January. The reason behind the selection of non-monsoon period for calibration purpose is that the recharge during this period takes place mainly from irrigation return flow (which can be estimated from irrigation water quantities), and little or no recharge from rainfall.

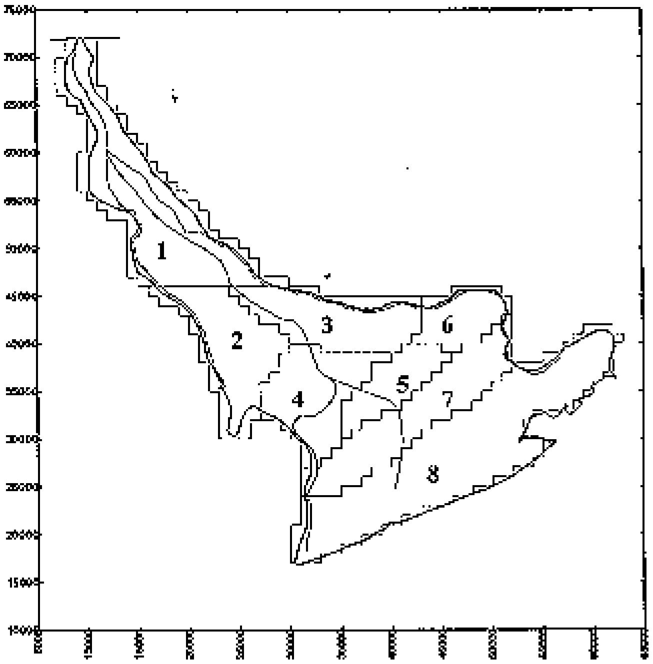


Figure 3. Recharge zones in model.

The mean areal rainfall over the study area from Feb. to May 85 was 15 mm and is therefore neglected for recharge purpose. Based on the Groundwater Estimation Committee (1984) norms, the recharge volume due to return flow, derived both from canal and well irrigation, over the calibration period of Feb. to May 85 is estimated as 107 MCM (Tyagi et. al., 1992). A uniform rate of recharge, computed from this lumped recharge estimate, was assigned to each of the recharge zones as an initial estimate. These recharge rates, however, have been defined in the model as parameters for estimation. This would allow the recharge rates to be optimized for each stress period and for each zone depending upon the flow conditions in the respective zones. The model was initially calibrated for the steady state conditions taken as the average of 10 years February water levels. This was followed by second calibration for the transient conditions.

Numerous model runs were carried out and the calibration was achieved. The objective function, which is the sum of the weighted squared head difference between observed and model heads, was obtained as low as 0.233. The calibrated values of hydraulic conductivity and specific yield were obtained as 10.3 m/day and 10% respectively. The scatter plots of observed and simulated heads for all four stress periods are given in Fig.4 (a to d). It can be observed that the points in all the scatter plots fall almost along a straight line. The correlation coefficients between observed and simulated heads are obtained as high as 0.999, 0.992, 0.994, and 0.989 for stress periods 1 to 4 respectively. The total simulated recharge volume over 4 stress periods was obtained as 109.80 MCM which is also very close to the return flow recharge estimate of 107 MCM (estimated earlier), showing a difference of 2.8 MCM (2.6%) only. With the above performance, it was presumed that calibration was in an acceptable stage and the calibrated model could be used for estimation of recharge in monsoon season.

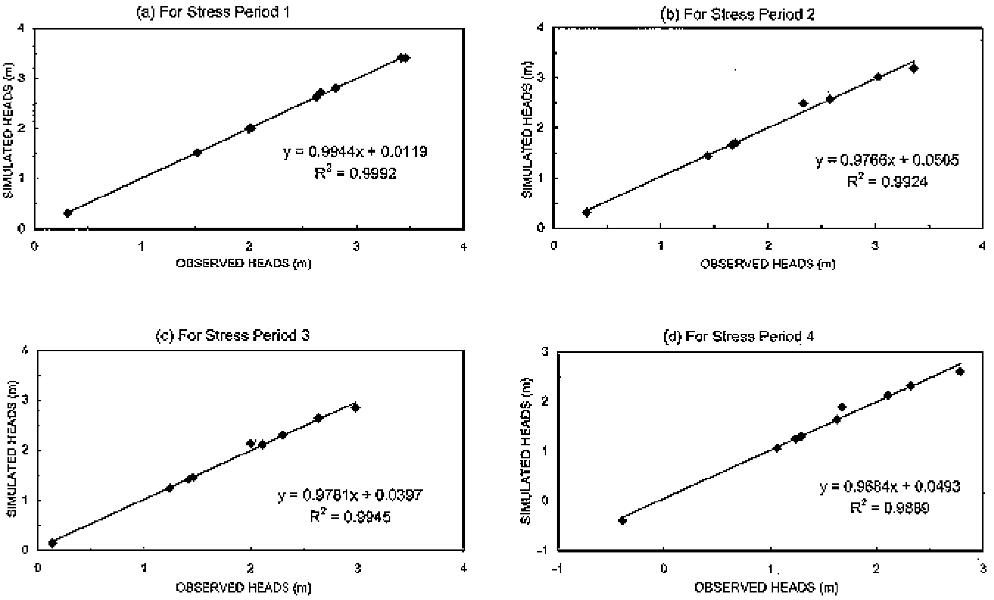
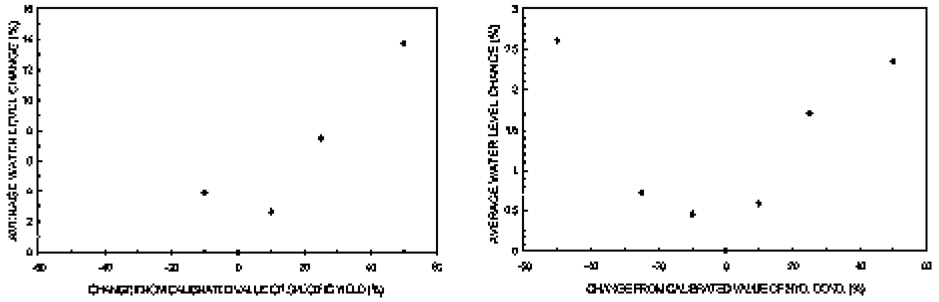


Figure 4. Plots between observed and simulated heads for calibration period.

Sensitivity Analysis

The sensitivity analysis is performed for specific yield and hydraulic conductivity by changing one parameter value at a time. The calibrated value of each parameter was systematically changed within the previously established plausible range. The resulting change in average water level from the calibrated solution with respect to specific yield and hydraulic conductivity for stress period 4 are plotted in Fig. 5.



(a) (b)

Figure 5. change in water level (a) with specific yield and (b) with hydraulic conductivity.

RESULTS AND DISCUSSIONS

Estimation of Recharge

Rainfall recharge to the aquifer is estimated during monsoon season since the major portion of annual rainfall takes place during this period. The calibrated model was run under transient conditions with five stress periods (30 days each) i.e. July to Nov.85, to optimize the recharge rates for the corresponding observed heads. Only river stages and evapotranspiration values were controlled in the input data and all other parameters were kept as per the calibrated model. The objective function for optimization process during this period was obtained as 0.1715. The observed and the corresponding simulated heads are presented in Table 2. The contour maps of observed and simulated heads for four stress periods are given in Fig.6. It can be observed that the observed and simulated heads are quite comparable and hence acceptable.

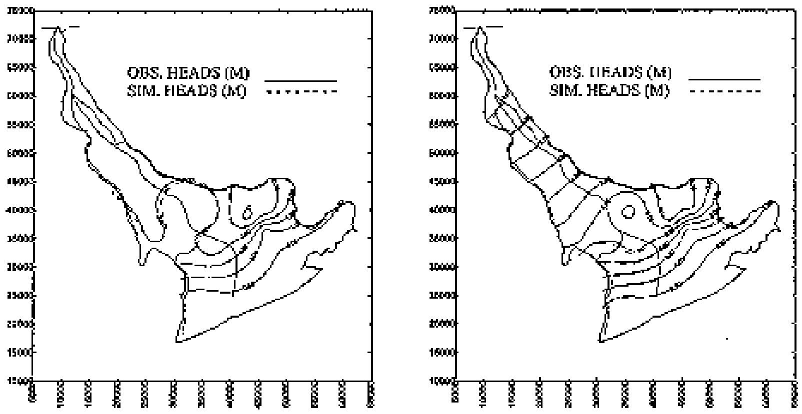
Table 2. Observed and Simulated Heads (m) for Monsoon Period.

Stress Period (month)		Well Nos.								
		1	2	3	4	5	6	7	8	9
1 (July,85)	Obs.	-0.40	2.30	0.90	2.78	3.11	1.47	1.89	2.06	2.09
	Sim.	-0.40	2.32	0.89	2.76	3.15	1.51	1.90	2.07	2.07
2 (Aug.,85)	Obs.	-0.07	2.69	1.36	3.48	3.72	2.33	2.54	3.16	6.09
	Sim.	-0.06	2.80	1.35	3.51	3.61	2.33	2.55	3.15	6.13
3 (Sep.,85)	Obs.	0.46	2.64	1.52	2.88	3.56	2.53	2.50	3.11	5.53
	Sim.	0.48	2.74	1.52	2.96	3.53	2.55	2.52	3.13	5.57
4 (Oct.,85)	Obs.	0.62	3.03	2.51	3.08	4.09	2.74	3.06	3.73	6.49
	Sim.	0.64	3.21	2.52	3.14	3.98	2.76	3.07	3.76	6.54
5 (Nov.,85)	Obs.	0.46	2.43	2.1	2.68	3.54	3.11	2.78	3.41	6.44
	Sim.	0.45	2.58	2.05	2.69	3.35	3.12	2.78	3.40	6.50

Table 3. Simulated Recharge in Central Godavari Delta for Monsoon Season.

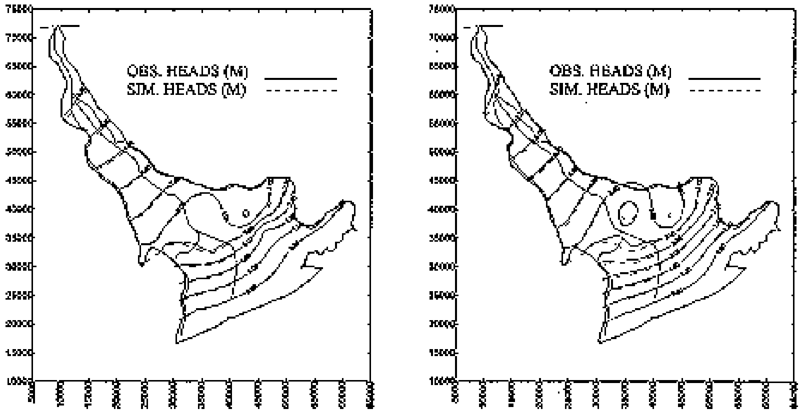
Stress periods (Months)	Total recharge in different recharge zones (m)								Total Re-charge (MCM)
	1	2	3	4	5	6	7	8	
(July, 85)	0.045	0.059	0.058	0.112	0.133	0.210	0.035	0.042	53.7
(Aug.,85)	0.309	0.151	0.108	0.086	0.095	0.128	0.078	0.061	113.2
(Sept.,85)	0.004	0.040	0.070	0.040	0.078	0.010	0.077	0.116	49.5
(Oct.,85)	0.085	0.111	0.062	0.095	0.111	0.058	0.163	0.065	74.6
(Nov.,85)	0.027	0.009	0.096	0.018	0.012	0.018	0.022	0.038	26.6
Total									317.6

(1) Total simulated recharge in all the Stress periods = 317.6 MCM
(2) Estimated irrigation return flow from June to Oct.85 = 180.0 MCM
(3) Recharge due to rainfall = 17.6–180 = 137.6 MCM
(4) Mean areal rainfall over the basin = 971 mm = 801.1 MCM
(5) Rainfall – Recharge Coefficient (Lumped basis) = 37.6/801.1= **0.172**



FOR STRESS PERIOD 1

FOR STRESS PERIOD 2



FOR STRESS PERIOD 3

FOR STRESS PERIOD 4

Figure 6. Contours of observed and simulated heads during monsoon period.

Analysis of Rainfall Recharge

The optimized recharge rates for each of the recharge zones and the total recharge volume during each stress period are presented in Table 3. Total recharge of 317.6 MCM is comprised of recharges occurring from two sources viz., recharge from rainfall, and recharge from return flow. Since the study aims at establishing the recharge from rainfall alone, it is accomplished by subtracting the recharge due to return flow from the total simulated recharge. The recharge due to irrigation return flow over 5 months, estimated using Groundwater Estimation Committee norms, has been calculated as 180 MCM (Tyagi et. al 1992). Therefore, the recharge from rainfall is obtained as 137.6 MCM. Based on the mean areal rainfall during the period, the rainfall-recharge coefficient (recharge due to rainfall/rainfall) is also calculated for the study area. The lumped recharge coefficient calculated as 0.17 is found well within the prescribed range for the alluvial soils (0.1 - 0.25).

Table 4. Distribution of Rainfall-Recharge Coefficient in Different Recharge Zones.

Recharge zones (1)	Simulated recharge over five stress periods (m) (2)	Recharge due to return flow over five stress periods (m) (3)	Depth of rainfall recharge (m) (4)=(2)-3)	Mean areal rainfall during five stress periods (mm) (5)	Rainfall-recharge coefficient (6)=(4)*1000/(5)
1	0.469	0.218	0.251	1005.5	0.250
2	0.369	0.218	0.151	1042.9	0.145
3	0.394	0.218	0.176	999.3	0.176
4	0.351	0.218	0.133	916.0	0.145
5	0.429	0.218	0.211	958.7	0.220
6	0.424	0.218	0.205	998.0	0.206
7	0.375	0.218	0.157	947.2	0.165
8	0.322	0.218	0.104	942.0	0.110

Spatial Distribution of Rainfall Recharge

The above analysis gives a lumped estimate of rainfall-recharge coefficient over the study area, but actually, the recharge rates may vary in different parts of the area. Therefore, the distribution of rainfall-recharge coefficient in different recharge zones has been computed and is presented in Table 4. The total depth of simulated recharge in each zone is calculated by adding the rates of recharge of all the stress periods in that zone. As the entire study area is covered by a well distributed canal and distribution network system, it is assumed that the recharge due to return flow is uniformly distributed over the study area of 825 km^2. With this assumption, the recharge due to rainfall in each zone is calculated and the rainfall-recharge coefficient established for each of the zones.

The rainfall-recharge coefficient is found to vary from 0.11 to 0.25 in different recharge zones. A careful look on the location of the recharge zones (see Fig.3) gives a definite trend of spatial variation of recharge coefficient across the delta. Based upon the coefficient values, all the recharge zones are regrouped into following three reaches:

1	Upper reach	Zone 1
2.	Middle reach	Zone 2,3,4,5,6 and 7
3.	Lower reach	Zone 8

The lower reach comprising an area of 225 km^2 (27%) along the coast has a lowest recharge coefficient of 0.11. The highest recharge coefficient of 0.25 is obtained in upper reach, which accounts for an area of 176 km^2 (21%). While the recharge coefficient in most part of the middle reach (335 km^2; 41%) varies in the range of 0.145 to 0.176, an area of about 89 km^2 (11%) in this zone is found to have a higher coefficient which ranges between 0.206 to 0.220. This higher value might be the effect of some local phenomenon, which needs to be investigated in the field.

One of the possible reasons for variation in recharge coefficient from 0.11 to 0.25 might be the effect of water table depth in these zones. As stated elsewhere in the paper, the average depth of water table below ground level during pre-monsoon period varies from about 1.75 m in the lower reach to about 7 m in Upper reach. The average seasonal water table fluctuations (i.e. pre to post monsoon) in these zones are observed to vary from about 1 m to about 4 m respectively. This indicates that the aquifer in the lower reach can get fully recharged with smaller amount of rainfall as compared to that in the upper reach. Once the water table in the lower reach rises to its highest position (i.e. close to the ground surface), the rainfall in excess of aquifer recharge capacity goes as runoff and thereby reduces the recharge-coefficient in this reach.

CONCLUSIONS

MODINV was used to estimate the rainfall recharge during monsoon season in the Central Godavari Delta of Andhra Pradesh. Based on the results of the study, it is concluded that the inverse groundwater modelling technique is a viable distributed approach for estimating the rainfall recharge. The distributed values of rainfall-recharge coefficient in the lower, middle and upper reaches of study delta were found to vary from 0.11 to 0.25 during monsoon period of 1985. On lumped basis, the recharge coefficient was found to be 0.17.

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