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Regional Groundwater Modelling of Central Punjab

Sudhir Kumar, PK Majumdar and Kumkum Mishra
National Institute of Hydrology, Roorkee

Abstract : Groundwater resources in Punjab are subjected to rapid exploitation in the wake of increasing agriculture, urbanization and industrialization. It is, therefore, necessary to evaluate the existing trend of groundwater in time and space and its movement for proper management in future. In the present study, an attempt has been made to develop a groundwater model using *Visual MODFLOW* software to understand the reasons for declining water table in Central Punjab. Visual MODFLOW - a computer program simulates three-dimensional groundwater flows through a porous medium by using the finite-difference method. Groundwater flow model replicates the behavior of natural groundwater system by defining the essential features of the system in some controlled physical or mathematical manner. The groundwater flow model for the study area was formulated by using input hydrogeological data and appropriate boundary conditions. The computed hydraulic heads are calibrated by comparing with observed groundwater level data for years 1998 to 2002. In most of the areas, water table depletion appears mainly due to less rainfall, except in Jalandhar and Kapurthala districts. The water table in most of the area gets recouped once seasonal rainfall improves in the subsequent years. In addition, depleting water levels in the area is also influenced by the river water levels. Any change in the river flow influences the groundwater table scenarios accordingly. Regional water table is sensitive towards river water levels in Satluj, in particular reaches nearing to Harike. Depletion of well water levels in central Punjab region may also have relationship with the water logging conditions in districts like Mukhtsar in Punjab and even in some places in Ghaggar river basin.

The outcome of modeling shows that this model can be used for prediction purpose in the future by updating input boundary conditions and hydrologic stresses during the preceding year. The model can be further improved if more spatial and temporal input parameters are available and can be incorporated into the model for more realistic characterization of groundwater flow.

INTRODUCTION

Depletion of groundwater is a major concern in most parts of the country. As per recent information, water table dropped by more than 4 m during last 10 years in 249 districts in 18 states thereby threatening the India's food security. Punjab has unique distinction of achieving new heights in agricultural production each year. Consequently, it has been noticed that water table in some districts are falling rapidly in last few decades. A regional formulation of groundwater flow regime is required to understand the physics behind depleting groundwater table.

It has been discussed at various platforms that, the groundwater levels in central Punjab is depleting over the years due to high agricultural consumption and increase in domestic requirement. Groundwater draft in the present state of water table condition always has an impact on regional as well as local scale. Water table depletion could be of two types. Short duration depletions may be attributed to scanty rainfall or excessive draft for a particular period, which gets rejuvenated subsequently. In such conditions, water management may serve the purpose better rather than generating additional aquifer storage. Long-term water table depletion is mainly due to violating the safe yield criteria and artificial recharge practices may be useful, provided regional groundwater flow does not minimizes its impact on a local scale. This has been explored through numerical modeling approach.

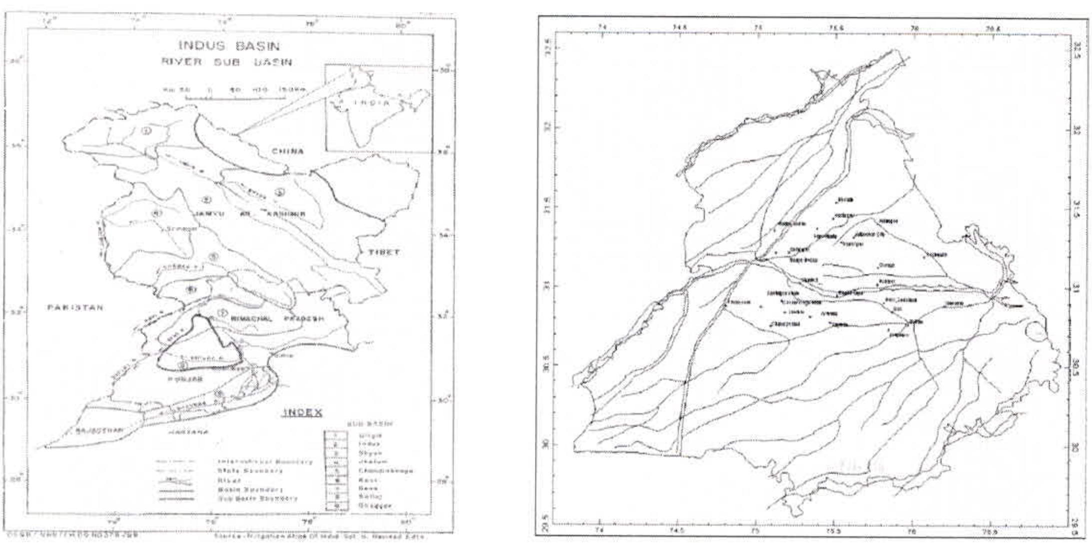
Groundwater flow modeling is an important tool frequently used to study the dynamic behavior of groundwater system. Groundwater flow models attempt to reproduce or simulate the operation of a real groundwater system using mathematical equations solved by a computer programme.

Recent trend in groundwater modeling is to use the user-friendly and robust software packages for develop groundwater management plans. A number of commercial groundwater software with GIS capabilities like Visual MODFLOW, GMS, GW Vista, etc are being widely used for this purpose. These models have been used to understand and manage various type of groundwater issues, such as basin water management (Sakthivadivel, 2001); modeling of aquifer system (Ravi et al, 2001; Stephen et at, 2003); simulation of the effect of subsurface barrier on groundwater flow (Elango and Senthil Kumar, 2006); groundwater management (Rejani et al, 2008; Kushwaha et al, 2008); groundwater flow modeling (Abbassgholipour and Aghay, 2008).

In this paper, an attempt has been made to analyze the reasons for depleting GW table in the region and to suggest possible remedial measures. Earlier analysis of the hydrological and geo-hydrological data of the region indicates that the GW system of the region very complex (NIH, 2004). It is felt that regional groundwater modeling study is required to be carried out to understand the complex regional water systems in order to manage those systems for optimal regional water resources management. Therefore, systematic procedure was needed to analyze complex regional water systems in order to understand depleting water table scenarios in central Punjab and suggesting efficient artificial recharge practices.

STUDY AREA

Study area lies in parts of Satluj and Beas catchments covering central Punjab (*Figure 1*). Administratively, study area is comprised of the districts of Hoshiarpur, Kapurthala, Jalandhar and Nawashahar and is bound by the hilly tracts along the Kandi belt on the northeastern side, river Beas on the western/ northern side and river Sutluj on the southern side. The river Beas is about 124 km on the western side of the study area whereas the length of river Sutluj binding the study area is about 152 km. The study area is approximately 13,000 km^2.



(a) Study Area in Indus Basin, (b) Drainage network and location of available lithologs

Fig. 1: Location Map of the Study Area

Catchments: The Satluj has its origin in regions of Mansarover Lake beyond the border of India while the Beas originates in the upper Himalayas near Rohtang Pass. The Beas and the Satluj practically form the Northern and Southern boundaries of Hoshiarpur district. The average rate of flows in the Satluj and the Beas together during the three months from April to June is approximately 1.4 times and from July to September is 4.7 times that in winter (six months October to march).

Rainfall, Temperature and Evaporation

Average annual rainfall ranges between 500 mm to more than 1200 mm. Highest rainfall occurs in the northern parts of Beas catchments. The annual isohyetal pattern indicates a NW- SE orientation exhibiting a high rainfall regime in the NW and gradual tapering of rainfall in the downstream catchments. Mean maximum temperature during the hot weather season (May) touches 41.2°C while during winter even the maximum temperature may be sub–zero at higher altitude stations located in Beas catchments. Monthly evaporation over Beas and Sutlej catchments is least in December of about 93mm. Highest evaporation is recorded in the month of May with the value of 430.9 mm whereas the mean annual evaporation is of the order of 2639.9 mm.

Majority of the land cover falls under agriculture command. Table 1 shows the land-use details of the land other than agriculture.

Hydro-geology: The alluvial deposits form good repositories of ground water. Sands, silts, gravel and boulders form potential aquifer zones. The depth to the water level varies from almost near surface to about 50 m below the land surface. Water level is deeper in the Kandi belt along the eastern fringe of Hoshiarpur and Ropar districts. The master ground water slope is towards southwest. Shallow tube wells yield 30-50 cum/hr and discharges of the order of 100-200 cum/hr are feasible from deep tube wells.

The groundwater gradient is steep in the NE foothill/Kandi region of Gurdaspur and Hoshiarpur district being of the order of 3.3 m / km. It is gentle in the rest of the sub basin and varies between 0.66 m/km to 2 m/km from place to place. District-wise groundwater balance has been computed by CGWB in different years. State level balance estimates are tabulated in Table 2.

Water Quality: The Mineralization of groundwater in northern districts of Punjab is comparatively low. EC values are high (> 4000 microhos / cm) in Western Southern part of Punjab varying between 4043 and 11017 micromhos per

Table 1: District-wise land use Pattern (km^2)

District	Geographical Area	Forests	Barren / unculturable land	Non Agriculture use
Kapurthala	1630	20	10	280
Jalandhar	2660	40	20	200
Nawan Shehar	1190	10	60	110
Hoshiarpur	3400	1090	10	110
Ludhiana	3680	100	-	490
Ropar	2160	520	110	170

Table 2: State level groundwater balance Estimates in ha-m (Source: CGWB)

District	Geographical Area	Forests	Barren / unculturable land	Non Agriculture use
Kapurthala	1630	20	10	280
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cm at 25^{0}C. Nitrate concentrations in ground water are more than the mandate limit of 45 mg / l in the entire district except Amritsar, Gurdaspur, Fatehgarh Sahib, Ropar, Kapurthala, Mansa. Nitrate concentration >100 mg/l in the ground water have also been observed in several districts. The Fluorides concentrations of the most areas were more than the desirable limits of 1.0 mg/l for drinking water. In the northern districts, it is comparatively low while in districts of Amritsar, Bhatinda, Faridabad, Ferozpur, Jalandhar, Moga, Muktsar and Sangrur, the fluorides values are high varying up to 6.4 mg/l.

DATA ANALYSIS

Variation in rainfall, groundwater levels and the river discharge during 1991 – 2001 is shown in Figure 2. The figure indicates that, in general, the pre-monsoon water table condition reaches to steady state irrespective of the post monsoon water table condition of the previous year. This gives an excellent opportunity to calibrate the conceptual model in steady state condition, i.e. steady state water table condition should arrive to identical scenarios, what so ever initial water table condition is input to the model.

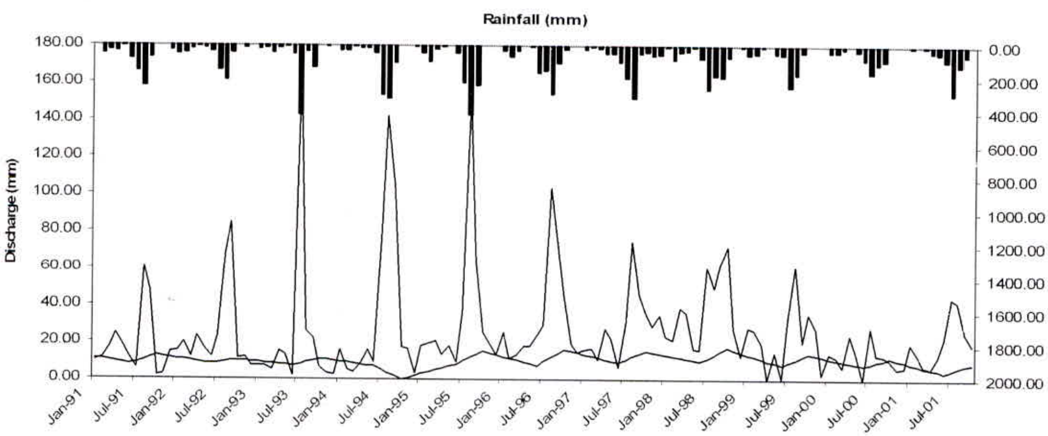


Fig. 2: Monthly Average Rainfall, Discharge at Harike and Average Depth to Groundwater Table in Central Punjab

As per CGWB observations, in June 1983 the water level in Beas sub basin lied between 1.5 m to 21.5 m b.g.l., and in Satluj same is 0.39 to 25.09 m b.g.l. In November 1983 water levels in Beas was between 0.8 and 22.8 m b.g.l and in satluj it is ranging from 0.8 to 33.7 m.b.g.l. Over all Beas sub basin noticed a rise in large part upto 1.7 m. in Satluj sub basin the water table shows a rise upto 4.8 m. In River Satluj, net change in water table from June 1978 to June 1983 showed a decline in water table in the entire area except the southwestern extremity, where there is a rise. The ground level trend analysis from 1974 to 1983 showed again decline trend in both the river basin.

The water table fluctuation, during the 1971 – 2001 period, in Jalandhar and Kapurthala Districts of Punjab are shown in Figure 3.

The figure indicates that the water table is showing a consistent water table declining trend during this period.

GROUNDWATER FLOW MODELING

Groundwater flow modeling is an important tool frequently used for three general purposes (Kresic, 1997):

- To predict expected changes in the system (aquifer) studied.
- To describe the system in order to analyze various assumptions about its nature and dynamics.
- To generate a hypothetical system that will be used to study principles of groundwater flow associated with various general or more specific problems.

The applicability of a groundwater model to a real situation depends on the accuracy of the input data and the parameters. This requires considerable study, like collection of hydrological data (rainfall, evapotranspiration, irrigation, drainage) and determination of the parameters mentioned before including pumping tests. As many parameters are quite variable in space, expert judgment is needed to arrive at representative values.

Groundwater flow models attempt to reproduce or simulate the operation of a real groundwater system using mathematical equations solved by a computer program. Groundwater flow models are used to calculate the rate and direction of movement of groundwater through aquifers (Owais et al, 2007). The outputs from model simulation are the hydraulic heads and groundwater flow rates which are in equilibrium with the specified hydrogeological conditions (i.e. hydrogeologic framework, hydrologic boundaries,

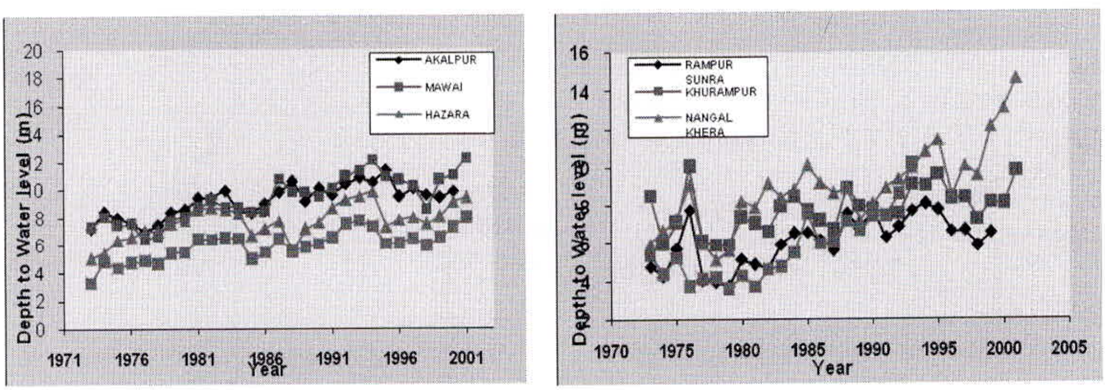


Fig. 3: Water Level variation in Jalandhar and Kapurthala districts (1971-2001)

initial and transient conditions, hydraulic properties and sources) defined for the modeled area. The governing flow equation for three-dimensional saturated flow in saturated porous media is:

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})-Q=S_s\frac{\partial h}{\partial t}$$

where,

Kxx, Kyy, Kzz =hydraulic conductivity along the x,y,z axes which are assumed to be parallel to the major axes of hydraulic conductivity;

h = piezometric head;

Q = volumetric flux per unit volume representing source/sink terms;

Ss = specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material.

Except for very simple systems, analytical solutions of this equation are rarely possible. Therefore, various numerical approached, such as, finite difference or finite element approaches are used to obtain approximate solution.

"A Modular Three Dimensional Finite-Difference Groundwater Flow Model" i.e. MODFLOW computer code, developed by McDonald and Harbaugh (1988), is the most common groundwater model being used world over. This model simulates groundwater flow using finite difference method. Through the process of model calibration and verification, the values of different hydrologic parameters are estimated to reduce any disparity between model simulation and field data and to improve the accuracy of the model.

Conceptual Model

Groundwater modeling begins with a conceptual understanding of the physical problem. It determines the dimensions of the numerical model, design of the grid and integrates the data and includes (a) the hydrogeological framework, (b) the physical framework, (c) a detailed description of the water budget, (d) the physical and hydraulic boundary conditions, (e) estimates of groundwater sources and sinks, and (f) information about regional flow paths (Anderson & Woessner, 1992).

Model Framework

The model boundaries are extended up to Sirhind canal in Satluj side, almost up to Ravi River in Beas side. Inactive cells are provided beyond Kandi Belt in Shivalik hillside. Regional level conceptual flow domain is conceived as per the model geometry developed by litholog analysis. Vertically 3 layers have been incorporated with top and bottom aquifers separated by aquitard in the middle.

Lithologs analysis has been carried out using ROCKWORKS. Co-relations are established and model geometry is generated for double aquifer system separated by an aquitard (Figure. 4)

Figure 4: Lithological Cross sections (a) Firozeshah – Ajithwala – Ludhiana – Samrala, and (b) Gopalpur – Phillaur – Adampur. For locations pl refer figure 1. Yellow colour indicates Aquifer and grey colour indicates Aquitard. Green colour is Top soil.

Grid: Horizontally model area is gridded into 150X150 cells having individual equal block dimensions of 1.0168kmX1.11706km (***Figure 5a***). Inactive cells are provided beyond Kandi Belt in Shivalik hillside.

Layers: The study area is generally composed mainly of sand and clay. As shown in Figure 4, two aquifers separated by an aquitard have been identified in the study area. Therefore, three layers system has been considered in the study area. Vertical discretisation of the model domain is shown in Figure 5(b). The top and bottom elevation of the layer has been taken between 264 m and 290 m above msl respectively.

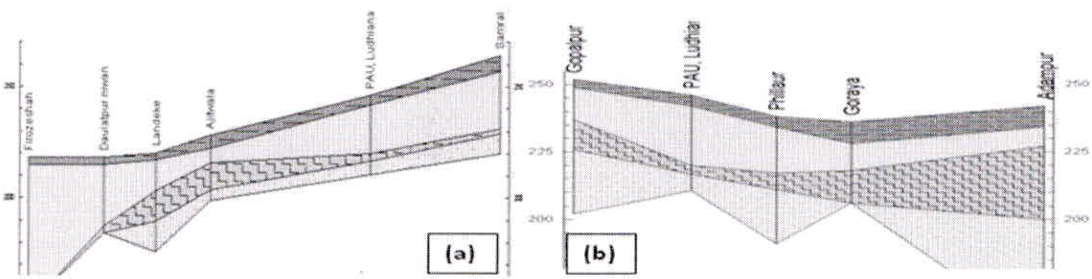


Fig. 4: Lithological Cross sections (a) Firozeshah – Ajithwala – Ludhiana – Samrala, and (b) Gopalpur – Phillaur – Adampur. For locations pl refer figure 1. Yellow colour indicates Aquifer and grey colour indicates Aquitard. Green colour is Top soil.

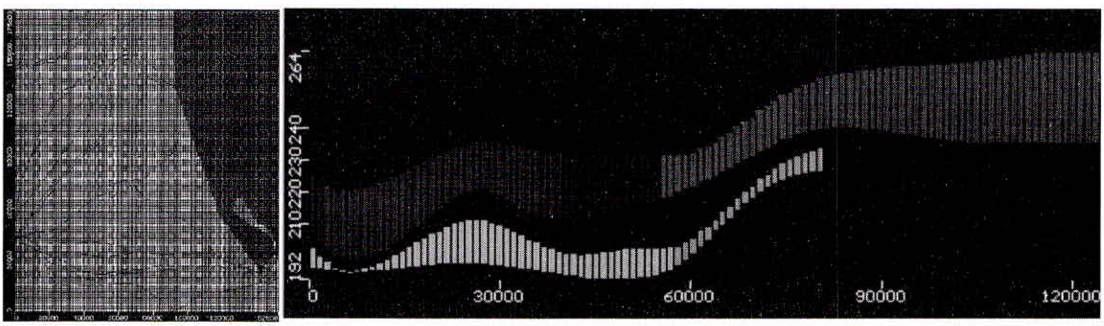


Fig. 5: Conceptual Model framework of the study area (a) discretisation in plan and (b) in layers.

Conceptual model geometry has been calibrated using MODFLOW for the year 1998 pre-monsoon water table condition. Subsequently it has been validated for rising and falling water table conditions, and the seasonal water balance is matched for both the scenarios.

Model Parameters

MODFLOW allows two basic parameters namely; Hydraulic Conductivity as flow parameter and Storage coefficient to allow storativity/specific yield effects in transient runs. More than 100 pumping test data analysis results are used to have spatial aquifer parameter effects in both the layers. Unconfined aquifer-pumping test data has been used for top layer, which has been considered under semi-confined condition and confined pumping test data results are incorporated in the bottom layer.

Boundary Conditions

Model boundaries were ascertained based on the physical and hydrological features present in and around the area of interest. Study area boundary conditions are Satluj, Beas and outcrop boundary due to Shivalik hills in three sides. Model boundary conditions are software-defined boundaries, minimum distance from study area boundary being safe enough to protect the model results from boundary effects. Sirhind and Bhist Doab canal network provides additional certainty in the mass balance but certainly less sensitive towards overall model results.

Top boundary condition for the model is recharge though rainfall and irrigation return flow, under unconfined to semi confined water table condition. Bottom face of the conceptual model is considered as impervious.

River water levels at 4 stations on Satluj River namely; Ropar, Phillaur, Yusufpur and D/s Harike and 3 stations on Beas River namely; Mirthal, Dhilwan and Mandi were used as river boundary conditions.

Natural Recharge

Source for natural recharge is considered from top and its spatial distribution is included as per the soil type distribution aerially. Three soil types are considered, they are; Sandy Loam, Loamy Sand and Silty Loam.

Groundwater Draft

Groundwater draft for domestic and irrigation requirements is considered here, neglecting the industrial requirements. Domestic requirement is estimated on census population data for each year of simulation. An average rate of 150 lpd/person is considered as domestic requirements. Block wise irrigation requirement for year 1995 was available from CGWB, which has been considered same for each year, looking at no appreciable change in the cropping pattern over the years.

Stress Periods

Total simulation period has been divided into number of stress periods depending upon the cropping seasons. Each year has been divided into two stress periods, Rabi (wheat November to April), Kharif (Paddy/Maize, June to October). Same stress periods have been repeated in each year of simulation. Ten daily time step has been considered for the transient simulation.

Model Calibration and Validation

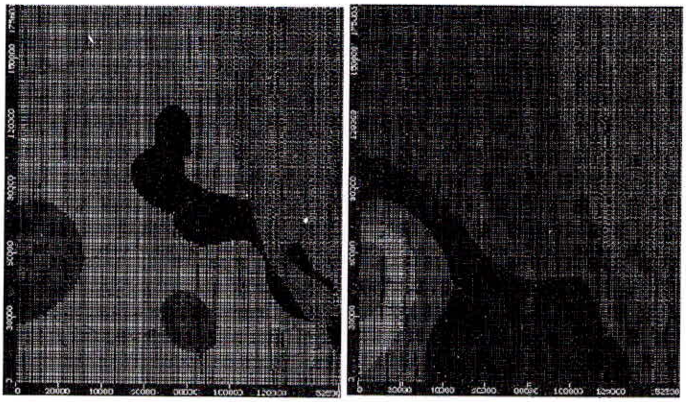
Conceptual model is calibrated by trial and error method using various realizations of hydraulic conductivity distribution generated through SURFER software. Pre and post monsoon water table contours have been generated for the pre and post monsoon seasons for the period 1991-2001. Most probable trends of water table contours have been generated for model calibration purposes. Top aquifer is under unconfined to semi-confined condition whereas bottom aquifer is under confined condition. Spatial aquifer parameter distribution is developed using lithologs and pumping test data available at point locations.

Calibration for the hydraulic conductivity value has been carried out under steady state condition as it has been observed that pre monsoon water table condition remain more or less same irrespective of previous season's post monsoon water table condition.

Various realizations of hydraulic conductivity zones have been tried without influencing the sample point hydraulic conductivity values. Specific yield / Storativity zones are also developed based upon surface cover information from litholog details and pumping test data for confined aquifer. Layer-wise hydraulic conductivity distribution is shown in Figure 6. Calibrated ground water table contours are plotted in Figure 7 for the top aquifer.

Calibrated model is validated for transient rising and falling water table conditions for a seasonal cycle starting with pre-monsoon initial water table condition for the year 1998 and simulating both post-monsoon and subsequent pre-monsoon water table scenario. Corresponding natural recharge and well draft components are also included here. Validated Storage Coefficient values and its spatial distribution in both the aquifers are shown in *Figure 8*.

Seasonal mass balance estimates are also matched with validated model mass balance results (Table 3). Mass balance result shows that, in general, water enters the domain from Beas riverside at the rate of 1506 cum/day and leaves from Satluj riverside at the rate of1610 cum/day.



(a) Top Aquifer (b) Bottom aquifer

Zone	Kx [m/s]	Ky [m/s]	Kz [m/s]
1	0.0001	0.0001	1E-5
2	1E-7	1E-7	1E-8
3	0.0001157	0.0001157	1.157E-5
4	0.0003471	0.0003471	3.471E-5
5	0.0005785	0.0005785	5.785E-5
6	0.0008099	0.0008099	8.099E-5
7	0.0008099	0.0008099	8.099E-5
8	0.0010413	0.00010413	1.0413E-5
9	0.0012727	0.0012727	0.00012727
10	6.9E-5	6.9E-5	6.9E-6
11	0.0001042	0.0001042	1.042E-5
12	0.0001736	0.0001736	1.736E-5
13	0.000243	0.000243	2.43E-5
14	0.000278	0.000278	2.78E-5

Fig. 6: Calibrated Hydraulic Conductivity Distribution

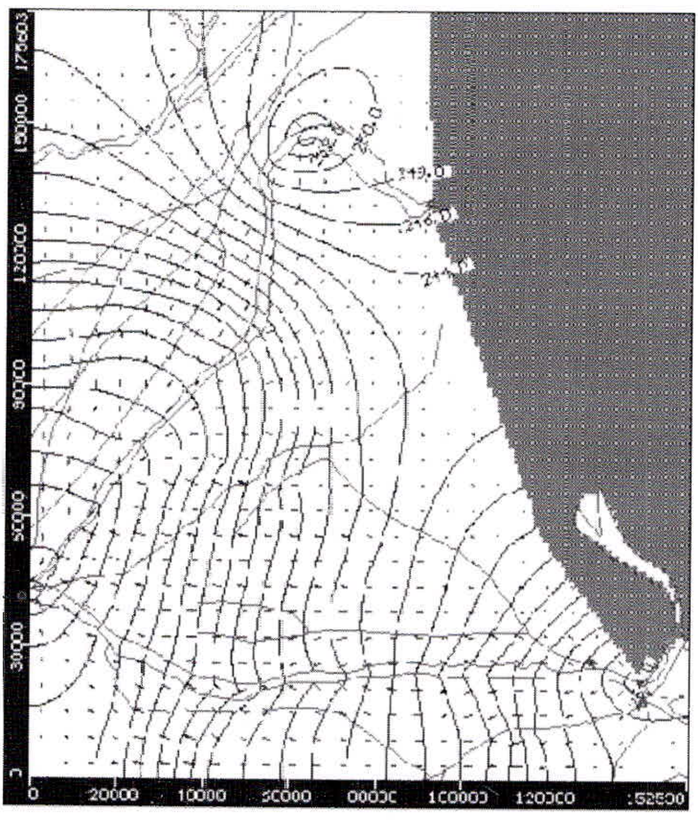
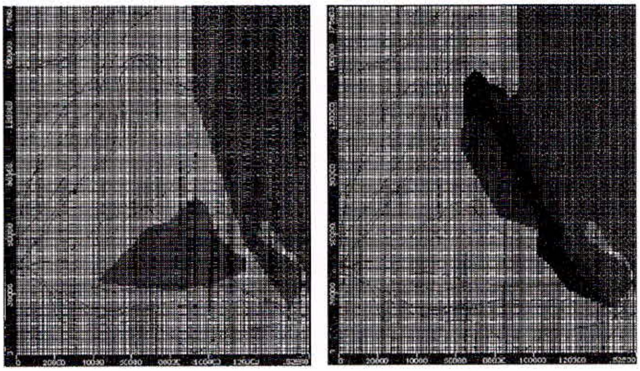


Fig. 7: Calibrated Semi-Confined Water Table in Central Punjab



Zone	Ss [m]	Sy []
1	0.001	0.15
2	0.005	0.15
3	0.015	0.12
4	0.025	0.12
5	0.035	0.12
6	0.035	0.12
7	0.0001	0.03

(a) Top Aquifer (b) Bottom aquifer

Fig. 8: Validated Model Storage Coefficient

It means that in natural conditions when there is no draft, base flow received by the domain is less than what is leaving the study area. Mass balance of the river stretches in steady state condition depict that it receives 54854 cum/day and leaves 54965 cum/day. It shows that, the rivers would not retain the water discharged by the domain to reach equilibrium condition.

Calibration, validation and simulation of shallow aquifer water table have been dealt here using the top aquifer, and bottom aquifer geometry has been included to extend the study to deeper aquifer in future.

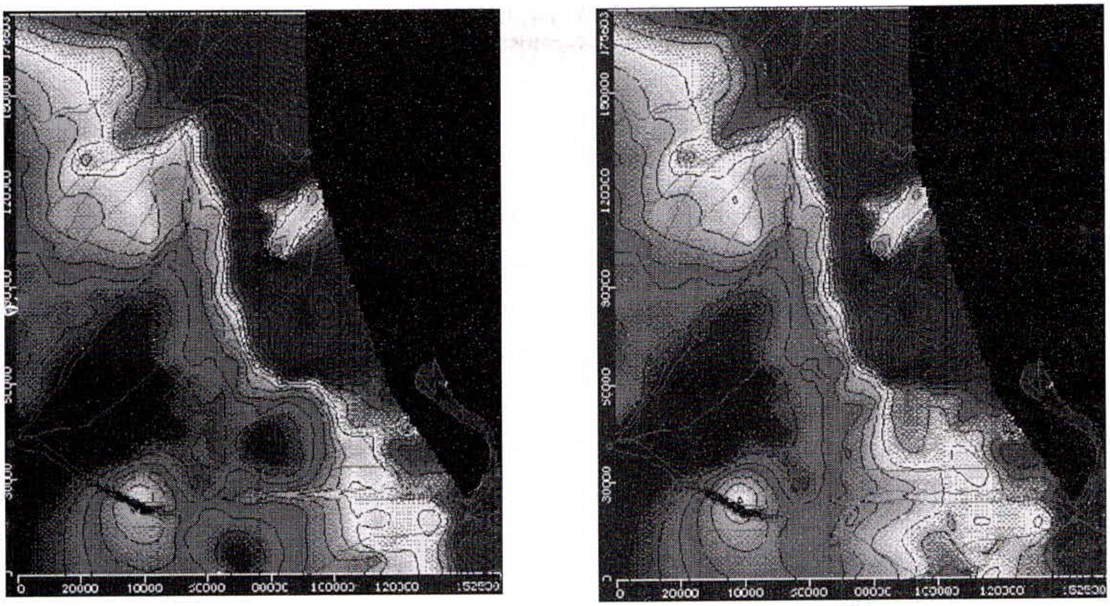
RESULTS AND DISCUSSION

Difference model and estimated mass balance results are in the range of 20 to 30% and is acceptable looking at the comparatively large grid size and both estimates being conceptual. Validated post monsoon water table contours of 1998 are shown in Figure 9 (a) and pre monsoon conditions of 1999 are depicted in Figure 9 (b). Monthly mass balance results for the 12 months are indicated in Table 4, which include both rising and falling water table periods.

Results of the analysis indicate that in rising water level period, outflow to rivers increases where as inflow from rivers decreases and recharge is mainly through rainfall and irrigation return flow. In the falling water table period it is just opposite. Two major inferences, which could be drawn out of this part of the analysis, are: 1) Artificial recharge with surface or subsurface measures would increase the outflow to river, and

Table 3: Mass Balance Comparison of the Validated Model with Assessed Mass Balance

Water Table Cycle	Model Mass Balance in terms of Depth in mm	Assessed Mass Balance in terms of Depth in mm
Rising Water Table	217	169
Falling Water Table	-48	-64



(a) (b)

Fig. 9: Validated Rising Water Table of Post monsoon 1998 (a) and Pre monsoon 1999 (b)

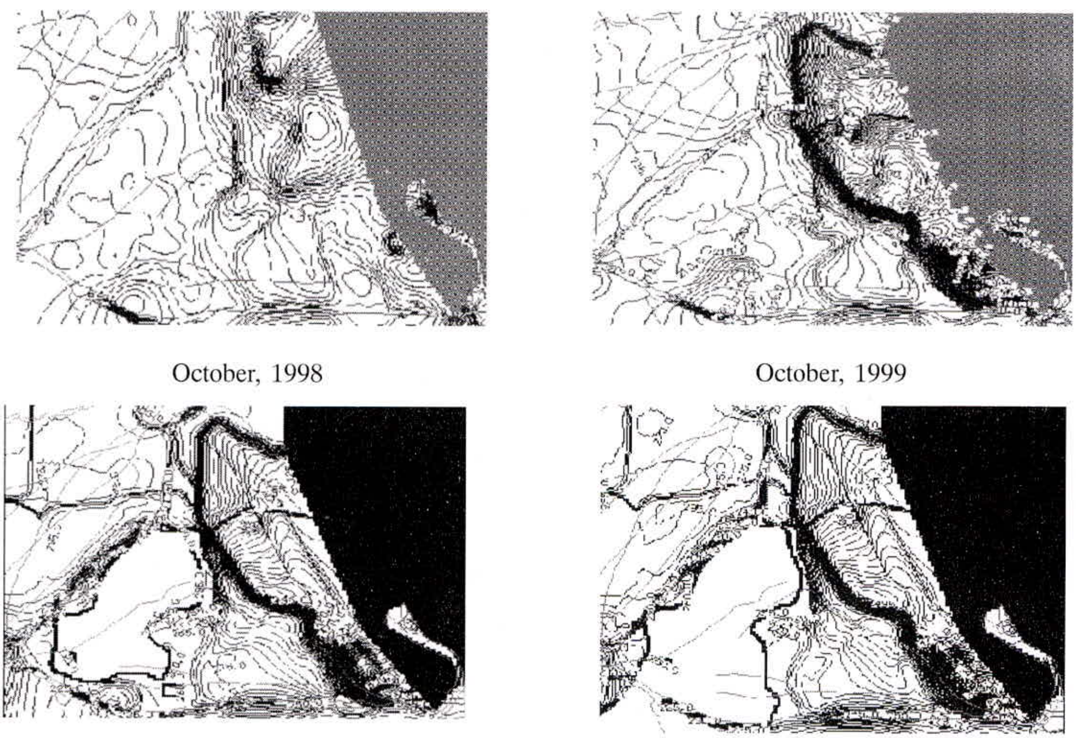
Table 4: Influences of Rivers in cum/day on Monthly Mass Balance

Month	Inflow from River	Outflow to River
June	1254590	1525290
July	145709	2093150
August	154232	2866050
September	2268	3649700
October	341059	1822610
November	486020	1354370
December	426920	1233370
January	487540	1205260
February	515240	1148440
March	470990	1118590
April	562480	1023110
May	634490	855460

2) In case of increase in draft, inflow from river stretches would increase. In general, Satluj river stretch and part of the Beas downstream Mandi plain gauging site act as Influent River and rests are Effluent River stretches.

Calibrated and validated model is applied for the simulation of 4 seasons namely; 1998-99, 1999-2000, 2000-2001 and 2001-2002. Simulated post monsoon water table conditions for these seasons are depicted in Figure 10. These simulations enable us to see the impact of river water levels on the groundwater table condition in the study area. River water levels at Yusufpur gauge site in Satluj River and Mandi gauge site in Beas River and corresponding monthly groundwater levels in selected locations in Jalandhar and Kapurthala district are tabulated in Table 5.

It shows that when river water level in Yusufpur guage site is high, corresponding groundwater levels in these districts are on a higher side. Same relation could be seen with Mandi gauge site in Beas River also. This shows that the water levels in Satluj River downstream of Phillaur and Beas River downstream of Mandi have positive impact on the groundwater levels in Central Punjab. Base flow in central Punjab region may be regenerating in to the river, mainly in this part of the river stretches, causing depletion in the groundwater levels.



October, 1998

October, 1999

October, 2000

October, 2001

Figure 10: Computed Water Level Trends in Central Punjab

Impact of Artificial Recharge

Any artificial recharge activity may have different kind of impacts on regional and local scale. On a local scale impact may be the improvement of the water levels in the neighboring wells, and on a regional scale, changes in groundwater flow system due to artificial recharge could be analyzed, which would finally suggest the availability of the recharged water at a specified time and space.

Central Punjab region includes agriculture command areas in large extent and is widely spread. Surface irrigation system applied for Wheat-Paddy combination is an indirect artificial recharge practice classified under surface flooding techniques.

Comparison of the water levels in Jullundhar, Kapurthala, Hoshiarpur, Nawashahar, Ropar and Ludhiana are shown in Table 6.

Water level contours for October with wheat-Maize combination are shown in Figure 11.

Table 6 does not show all together a deteriorating trend with Wheat-Paddy system, as compared to Wheat-Maize combination. Interesting to note here, that groundwater draft is nearly 60-80% more for wheat-paddy combination as compared to wheat-paddy combination. 232.7

Results of the local level models are in line with what is attempted with natural recharge. With increase in recharge rate base flow to rivers

Table 6: Comparison of the water level for Wheat-Paddy and Wheat-Maize

Location	Ground water Level in M							
	Wheat-Paddy				Wheat-Maize			
	June	Sept	Dec	Mar	June	Sept	Dec	Mar
Jullundhar	226.63	228.31	226.72	225.29	228.62	226.95	226.80	226.72
Kapurthala	217.87	219.97	218.96	218.37	217.94	218.15	218.15	218.25
Hoshiarpur	313.12	321.88	303.67	302.63	299.66	299.36	298.67	297.87
Nawashahar	248.03	250.61	249.80	249.08	248.14	255.92	248.54	248.70
Ropar	266.44	306.64	291.41	288.83	300.01	299.21	297.58	296.73
Ludhiana	227.22	229.01	227.53	225.21	227.51	227.62	227.57	227.64

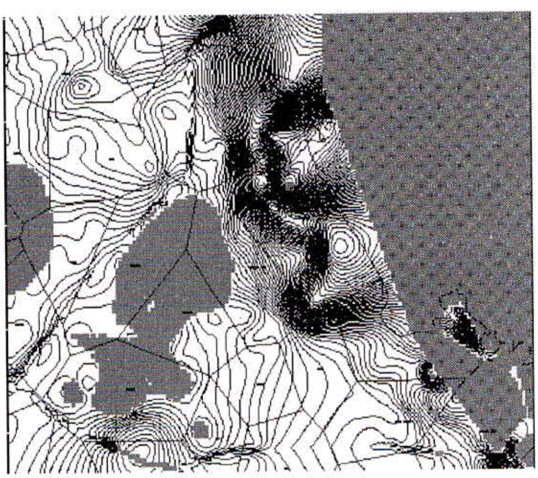


Fig. 11: Water Level Contours for the month of October with Wheat -Maize System

increases and the effect of the injected water could not be visualized with minimum grid sizes possible. Therefore any amount of water could be injected in to the aquifer but it will flow towards Satluj and Beas river with much more groundwater flow velocity, unless the water levels in rivers minimizes the existing hydraulic gradient.

CONCLUSIONS

From the regional scale groundwater modeling of the Saltuj-Beas doab of Central Punjab, it can be concluded that:

1. In most of the areas, pre monsoon water table condition reaches steady state irrespective of the post monsoon condition of the previous season. This shows that in non-monsoon months, groundwater flow in the regional aquifer approaches regime condition and is mainly governed by the river flows.
2. Long term as well as short term well water level trends show depleting condition in Jalandhar and Kapurthala districts. The decline may be attributed mainly to less rainfall recharge.
3. Model results show that the regional water table is sensitive towards river water levels in Satluj, in particular reaches nearing to Harike. However this conclusion needs to be substantiated by a modeling study in conjunction with Ghaggar river and basin subsurface water levels.
4. In the present scenario, base flow to the rivers increases by artificially recharging water. Recharge wells are found efficient but recharged water may have to be used immediately unless there is scope for minimizing hydraulic gradient of groundwater flow.

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