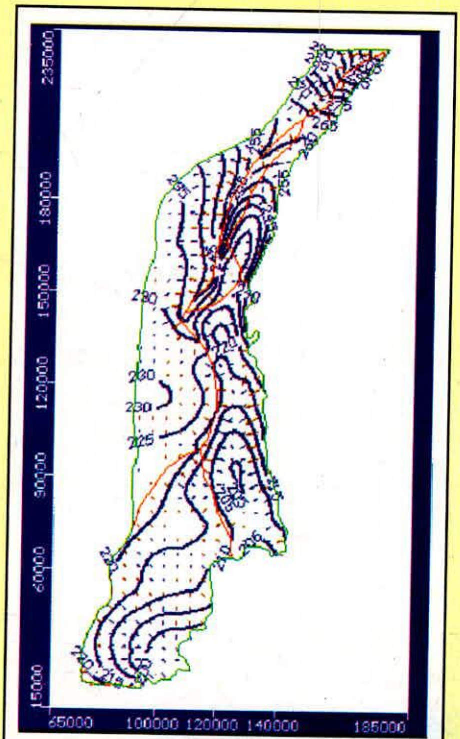
PROJECT REPORT

SYSTEM SIMULATION STUDY FOR DEVELOPMENT OF OPTIMAL ALLOCATION PLAN FOR GROUND AND SURFACE WATER IN PARTS OF WESTERN YAMUNA CANAL COMMAND AREA IN THE STATE OF HARYANA



A JOINT STUDY BY

NATIONAL INSTITUTE OF HYDROLOGY
&
CENTRAL GROUND WATER BOARD

2005-07

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PREFACE

Surface water and groundwater are two important constituents of the hydrological cycle governing the water resources system in any physical environment. Isolated development and utilisation of surface and groundwater resources has resulted in adverse effects in many parts of the country. Decline in groundwater levels and water logging are two major consequences and both are not desirable as those degrade the sub-surface environment.

With the introduction of canal irrigation and launching of five-year plans starting from the first five year plan in 1950-51, the objective was to achieve the increased irrigated area in the country. While achieving the above goal, the integrated and conjunctive use of surface and groundwater was not given the attention and consideration it deserved. Hence, in course of time, the twin problem of water logging and soil salinity started coming up. Realising these problems the National Water Policy (1987) also stressed on the integrated and coordinated development of surface and groundwater and their conjunctive use which should be envisaged right from the project planning stage and should form an essential part of the project. While this is possible in the case of new projects, in case of projects which have already been executed and are in operation for a long time and where the damage has already occurred, only prevention and alleviation programme can be taken up, so that further damages could be arrested.

Recognising the crucial importance of the conjunctive use of surface and groundwater in general and in the irrigation command in particular, a study entitled 'System simulation study for development of optimal allocation plan for ground and surface water in parts of the Western Yamuna Canal command area in the state of Haryana' was taken up jointly by the National Institute of Hydrology (NIH) and the Central Ground Water Board (CGWB). The Western Yamuna Canal (WYC), the oldest canal in the State of Haryana, takes off from the Yamuna River at the Hathnikund barrage and supplies water for irrigation, drinking and industrial use in the state of Haryana. The WYC command area is part of the well known Indo-Gangetic alluvial area and is rich in groundwater potential. This area has witnessed phenomenal increase in the development of *groundwater over the years by private and state government agencies. The area experiences the problem of declining water table in some parts and rising water table in other parts.*

This report has been prepared by Dr. Vijay Kumar, Scientist 'E1' and Dr M K Goel, Scientist 'E1' of NIH and Sh. K J Anandhakumar, Scientist 'B' and Sh. P Das, Asst. Hydrogeologist of CGWB. I hope that the conclusions brought out in this report will be useful for the development and management of surface and groundwater resources in the western Yamuna canal command.

20.12.07

(K D Sharma)
Director

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ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The Western Yamuna Canal (WYC) takes off from the Yamuna River at the Hathnikund barrage and supplies water for irrigation, drinking and industrial use in the state of Haryana. Its command covers parts of the Upper Yamuna Basin and the inland alluvial basin in Haryana and is rich in groundwater potential. This area has witnessed phenomenal increase in the development of groundwater over the years by private and state government agencies. The area experiences the problem of declining water table in some parts and rising water table in other parts. Long-term behaviour of water table (May1985 – May 2004) reveals that in central, north and all along river Yamuna, water level has gone down by 10 to 16 m. In the south and south-western part, water level has risen by 5 to 10 m. Due to intense irrigation, water table in certain area has become much shallow creating waterlogging conditions. As such, the area faces the problem of over-development of groundwater and the water demand is very high as compared to water supply. Out of 49 blocks which fall in the command area, groundwater in 27 blocks is already in the over-developed category.

The objective of the present study was to develop a mathematical model to simulate the hydrogeological conditions and groundwater flow system in part of command area and to create different allocation plan of surface water and groundwater to find a solution to alleviate the problem of rising and declining groundwater levels.

An area of 7508 sq. km out of the total 13543 sq km area of Western Yamuna Canal command was selected for modelling. The model area includes 32 blocks (some full and some partial) of Yamuna Nagar, Karnal, Panipat, Sonipat, Rohtak, Jhajjar, Kurukshetra and Jind districts.The area receives on an average 506 MCM of surface water in a year through WYC system. About 41% of this water is received in monsoon and remaining 59% in non-monsoon period. An amount of 1370 MCM of water is available from rainfall but is not being used presently and goes off as runoff.

The dynamic groundwater resources of the model area are of the order of 2104 MCM. Sixty six percent of this resource is available in monsoon and remaining 34% in non-monsoon period. Private and Govt agencies have extracted

1159 MCM of groundwater in monsoon and 1603 MCM in non-monsoon period of 2002, with a total extraction of 2762 MCM. Out of 32 blocks, 6 blocks have groundwater development of more than 150% with a maximum of 190%, 19 blocks have groundwater development between 100-150% and remaining 7 blocks between 50-100%. The minimum groundwater development (56%) is in Matenhali block of Jhajjar block. Based on the stage of groundwater development and long term groundwater level trend, 15 blocks fall under over-exploited category, 11 blocks under critical category, one under semi-critical and remaining 5 under safe category.

The total water demand in the year 2002 for various sectors namely, domestic, livestock, industries and irrigation have been computed to be 5623 MCM. Out of this, 5328 MCM (95%) is for agriculture sector.

An area of 15 sq. km around Israna, Gohana, Rohtak, Kharkoda and Bahadurgarh blocks was found to be waterlogged and 71 sq km was found to be prone to waterlogging in pre-monsoon 2004. During three years from 2002 to 2004, the waterlogged area increased from 3.75 sq. km to 15 sq. km in pre-monsoon season and from 28.5 to 84 sq. km in post monsoon season. During the same period, the area prone to waterlogging increased from 52.5 sq. km to 71.1 sq. km in pre-monsoon and from 81.6 sq. km to 198.7 sq. km in post monsoon season.

A mathematical model has been set-up to simulate the hydrogeological conditions and groundwater flow in the model area. The 3-D Modular Finite Difference Groundwater Flow Package MODFLOW with Visual MODFLOW as an interface is used for model development. Conceptualization of the area was done based on the hydrogeological, bore hole lithology, fence diagram and water level fluctuation in wells as reported in Upper Yamuna Basin reports of CGWB. The area is modeled as a three layer system with layer 1 representing upper phreatic aquifer, layer 2 representing confining layer and layer 3 representing confined/semi-confined aquifer. The area was discritized into 1km×1km grids. The eastern and south-western side of the model area was represented by river boundary, western side as no flow boundary and north and southern sides as flux boundaries. Major canals and drains were also simulated as river in the model to account for their recharge/discharge to groundwater system. The various inputs like hydrogeological parameters, areal recharge and groundwater abstraction was assigned to the model based on the data available in Upper Yamuna Basin reports and groundwater estimation report of Haryana state.

A total of 29 observation wells (20 in aquifer I and 9 in aquifer II) were used for model calibration. The model was run for three years (June 2002 to May 2005) consisting of 37 stress periods with first stress period under steady state condition. Very good calibration is achieved for aquifer I (layer 1). But due to very limited data availability, mainly recharge and discharge, the calibration results achieved for 3rd layer (aquifer II) are not as good as those of layer I.

Various scenarios were created to find a solution to the problem of declining and rising groundwater levels in the study area. The calibrated model was run for next ten years (2005-2015) to test the created scenarios. The scenarios tested included allowing the present groundwater pumping conditions to continue; reducing groundwater withdrawal by 10%, 20% and 30%; reducing recharge and increasing withdrawal from the blocks facing waterlogging problem; water withdrawal from the IInd aquifer in lieu of Ist aquifer; and combination of these scenarios.

As per the modelling results, continuing with the present groundwater pumping conditions for next ten years will result in further deterioration of groundwater conditions in the study area. A reduction in groundwater pumping by about 20% of the present amount will arrest the falling water table in the area facing groundwater decline. Similarly, an increase in pumping by about 20% from the blocks facing problem of waterlogging/ rising groundwater levels will reverse the trend of rising groundwater level in these blocks. Water withdrawal from the second aquifer in place of the first aquifer is not likely to alleviate the problem of declining/rising groundwater levels of first aquifer. Stopping the surface water irrigation and increased pumping by 20% from blocks facing waterlogging/rising groundwater levels (Israna, Gohana, Kharkhoda, Rohtak, Sampla, Jhajjar, Beri, Salahwas, Bahadurgarh, Kalanaur, Matanhali) and reducing pumping by 20% from all other blocks will arrest the falling groundwater levels in blocks facing such problem and will lower the groundwater level in blocks that are waterlogged/prone to waterlogging. This strategy is thus recommended for application in the field.

1.0 INTRODUCTION

The Western Yamuna Canal (WYC) is the oldest canal in the State of Haryana. It supplies water for irrigation, drinking and industrial use through its network of branches, distributaries, minors, water-courses and direct outlets. The WYC command area is part of the well known Indo-Gangetic alluvial area and is rich in groundwater potential. This area has witnessed phenomenal increase in the development of groundwater over the years by private and state government agencies (CGWB, 2000). To augment deficient surface water availability, schemes for large scale development of groundwater in the command have been planned and executed. In order to augment canal supplies and prevent water logging in adjacent tract, a large number of augmentation wells were constructed along WYC. Further in order to prevent seepage losses from WYC and to further augment its supply, a lined augmentation canal, taking off from Yamuna Nagar and out falling in WYC at Munak (69 kms in length), was constructed in 1971. Heavy duty wells constructed along this canal used to direct about 14-15 cumecs of ground water to surface water canal system. In addition, there were similar augmentation wells constructed along Delhi Parallel Branch and the Narwana Branch Canal link.

To study this kind of development of groundwater, Central Ground Water Board carried out "Groundwater Studies in Upper Yamuna Basin" as a project from 1973 to 1977. The Upper Yamuna Basin covers parts of the states of Himachal Pradesh, Haryana, U.P. (including Uttarakhand) and NCT Delhi. The detailed studies included collection and analysis of hydro-geological, hydro-meteorological, hydrological and geophysical data, sitting and drilling of piezometers, construction of test wells, conducting pumping tests, chemical analysis of water, measurements of rain fall and groundwater balance with a view to evaluate availability of groundwater resource and its management in view of large scale development of groundwater through tube wells by the state of Haryana (Bhatnagar et al., 1982a; 1982b; 1982c; 1982d; 1982e; 1983; 1985, and CGWB, 1977; 1984; 1985; 2000 and Romani et al., 1979). This study formed the main base for understanding and conceptualizing the area for development of the simulation model.

Conjunctive use studies for the whole of WYC command area, covering an area of 13543 s q k m, was taken up by Central Ground Water Board, North

Western Region, Chandigarh, during Annual Action Plan (AAP) 2003-04 and 2004-05. As a follow up of this study, it is proposed to develop a mathematical model to simulate the hydrogeological conditions and groundwater flow for a part of the study area. This study is being carried out as a collaborative study between National Institute of Hydrology and Central Ground Water Board.

This report presents the results of quantitative assessment of surface water and groundwater resources; status of waterlogging in the area; mathematical modelling to simulate groundwater flow system in the area; and analysis of various scenarios to reach at optimal allocation plan for surface water and groundwater resources to alleviate the problem of rising/declining groundwater levels in the study area.

2.0 WESTERN YAMUNA CANAL COMMAND AREA

WYC Command covers part of Upper Yamuna Basin (UYB) and inland alluvial basin, located between the north latitudes 28°20' & 30°28' and east longitudes 75°48' & 77°35' in the state of Haryana covering eastern, central and southern parts of the state (Fig. 1). The total geographical area of the WYC Command is 13,543 Sq. km. About 45 Sq. km area of Chhachrauli block of Yamuna Nagar district lie within the Kandi Zone i.e. the piedmont deposits forming 2 –3 km wide fringe zone along the outer margin of Siwaliks. WYC takes off from the Yamuna river at Hathni kund Barrage (3 km upstream of Tajewala, (Plate-1) the old head works). At Hathni kund the water from Yamuna is diverted in to two canal systems, namely Eastern Yamuna Canal, serving the parts of U.P. and Western Yamuna Canal, (Plate-2) serving Haryana. The water from WYC is also diverted to NCT Delhi for water supply. A lined augmentation canal (Plate 3) was constructed from Yamuna Nagar to Munak to prevent seepage from unlined WYC.

The command area is identified in blocks falling fully in the districts of Karnal, Panipat, Sonipat, Rohtak and Jhajjar and partly in the districts of Hissar, Bhiwani, Jind, Yamuna Nagar, Gurgaon and Rewari. A total of 49 blocks fall in the WYC command area. The area is predominantly an agricultural tract, with more than 70% area under cultivation. The major crops grown in the area are wheat, paddy, gram, pulses, oil seeds, bajra and sugar cane.

2.1 Climate and Physiography

The climate of the WYC command area is mainly categorized by the extreme dryness of the air except during monsoon months, intensely hot summer and cold winter. The average annual rainfall of the WYC Command area is 608 mm. The south west monsoon rainfall sets in last week of June and withdraws at the end of September and contributes 82% of the average annual rainfall. July and August are the wettest months. During 33 years (1971 to 2003), only two areas, viz. Yamuna Nagar and Sonipat were free from drought while the other areas were affected by drought. January is the coldest month and June is the hottest months of the year. The air is generally dry during greater part of the year.

The WYC command area has a flat and monotonous topography with a regional slope from north-east to south-west direction. The surface elevation varies from 210 to 320 m amsl. Yamuna river is the natural drainage in the command and is a perennial river. It takes a course of around 223 km from Hathni Kund barrage to the border of Delhi. Along its course, it behaves as an influent stream at places mostly in the northern part of the command area and effluent at other places, mainly in southern part The flood plains have high potential for ground water development, as they are underlain by thick aquifers which are hydraulically connected to the river Yamuna.

WYC command area is one of the flood prone areas of the Haryana state. Many artificial drains (Plate 4) have been constructed in the area as flood control measure and also to drain the excess rainfall to the main river Yamuna. Many 'canal escapes', to provide alternate waterway to pass the canal water in emergencies to protect the structures and canal system, also exist in the command area.

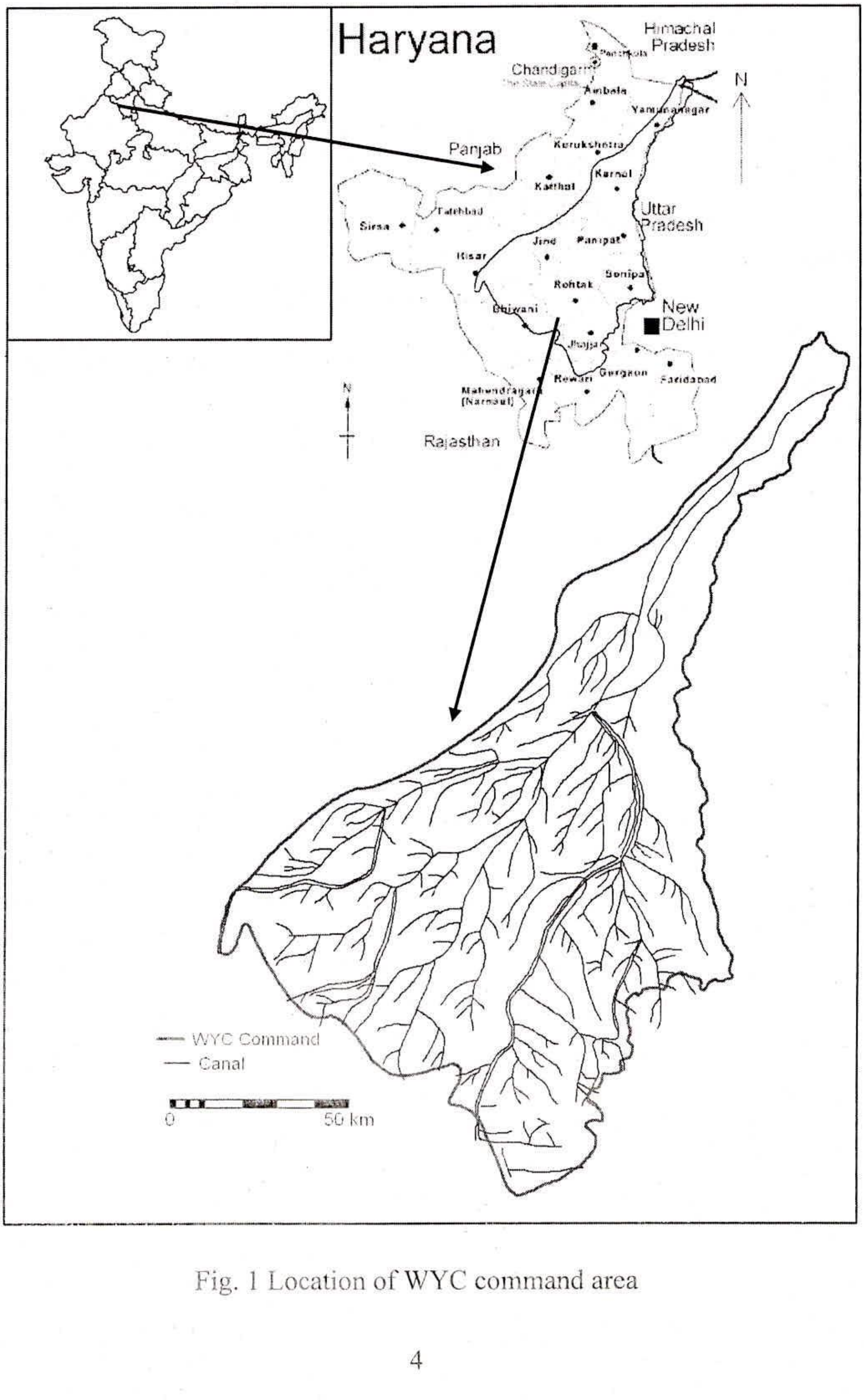


Fig. 1 Location of WYC command area

Plate 1. Tajewala Head Works

Plate 2. Hathni Kund Barrage

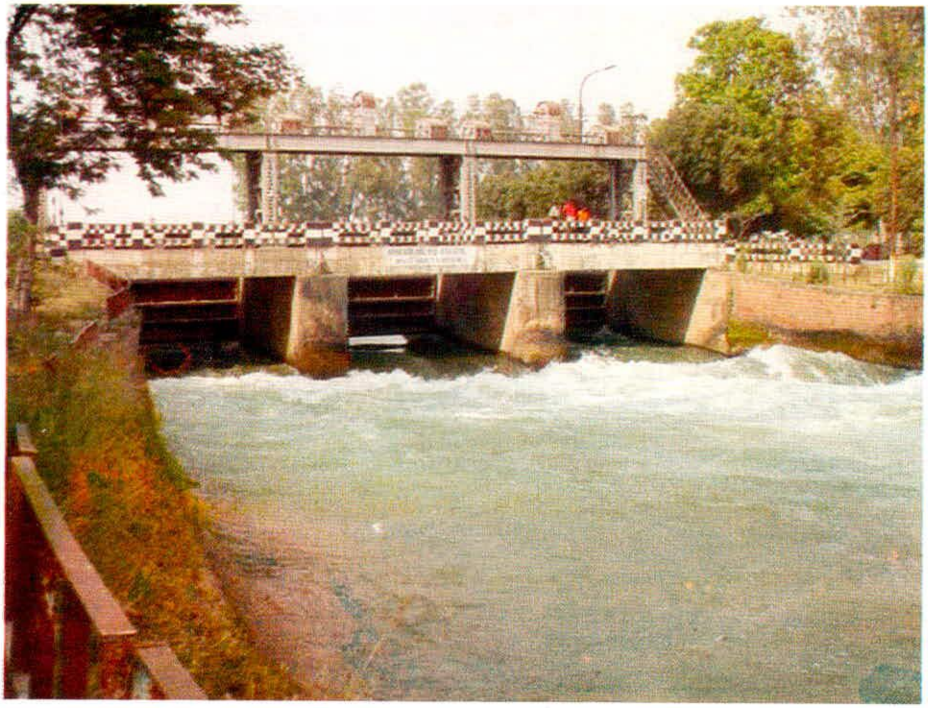


Plate 3. Augmentation Canal Head Works At Yamuna Nagar

Plate 4. Indri Drain Near Munak

2.2 Soil Characteristics

In general, the soils of the command area are classified as sandy, sandy loam, loam to clayey loam of the Indo-Gangetic alluvium. The soils of major part of command area are sandy loam to loam. The soils in Chhachhrauli and Jagadhri block of Yamuna Nagar district are shallow and loamy sand to fine sandy loam. In part of Panipat, Sonipat, Jind, Rohtak, and Jhajjar districts considerable salinisation and alkalinisation of the soil has occurred due to rise in water table.

2.3 Hydrogeology

The plain tract of WYC command lying south of the Siwalik zone forms a part of Indo-Gangetic alluvial plains of recent origin. The thickness of the alluvial deposit is small along the fringe of peninsular mass but progressively increases towards northwards and is maximum in the fore deep area lying immediately south of the Himalayan zone. The alluvial plains are underlain by loose unconsolidated river borne sediments and form very good repository of ground water. The aquifer system lying closest to the land surface holds water in unconfined condition. At deeper levels, particularly below regionally or sub-regionally extensive poorly permeable layers, the ground water occurs in semi-confined to confined conditions. It is expected that with increasing depth, the alluvium could get more and more consolidated because of the increasing over burden and hence have reduced porosity and permeability. The unconfined aquifer, which is quite potential, generally bears an effluent relation with the surface drainage.

2.4 Sub-surface Geology and Hydrogeological Units

Exploratory drilling in UYB covering parts of Ambala, Yamuna Nagar, Kurukshetra, Karnal, Panipat and Sonipat districts has revealed existence of three aquifer systems down to 450m depth (Fig. 2), briefly described hereunder (CGWB, 1977, Bhatnagar et al., 1982a).

Aquifer Group-I: This extends from the ground surface downwards to different depths to a maximum of 167m bgl and occurs all over the sub-basin. This is composed of relatively coarser sediments and at places is subdivided into two subgroups by occurrence of sub-regional clay. It is underlain by a clayey horizon, 10 to 15m thick, which appears to be more to less regionally extensive except in

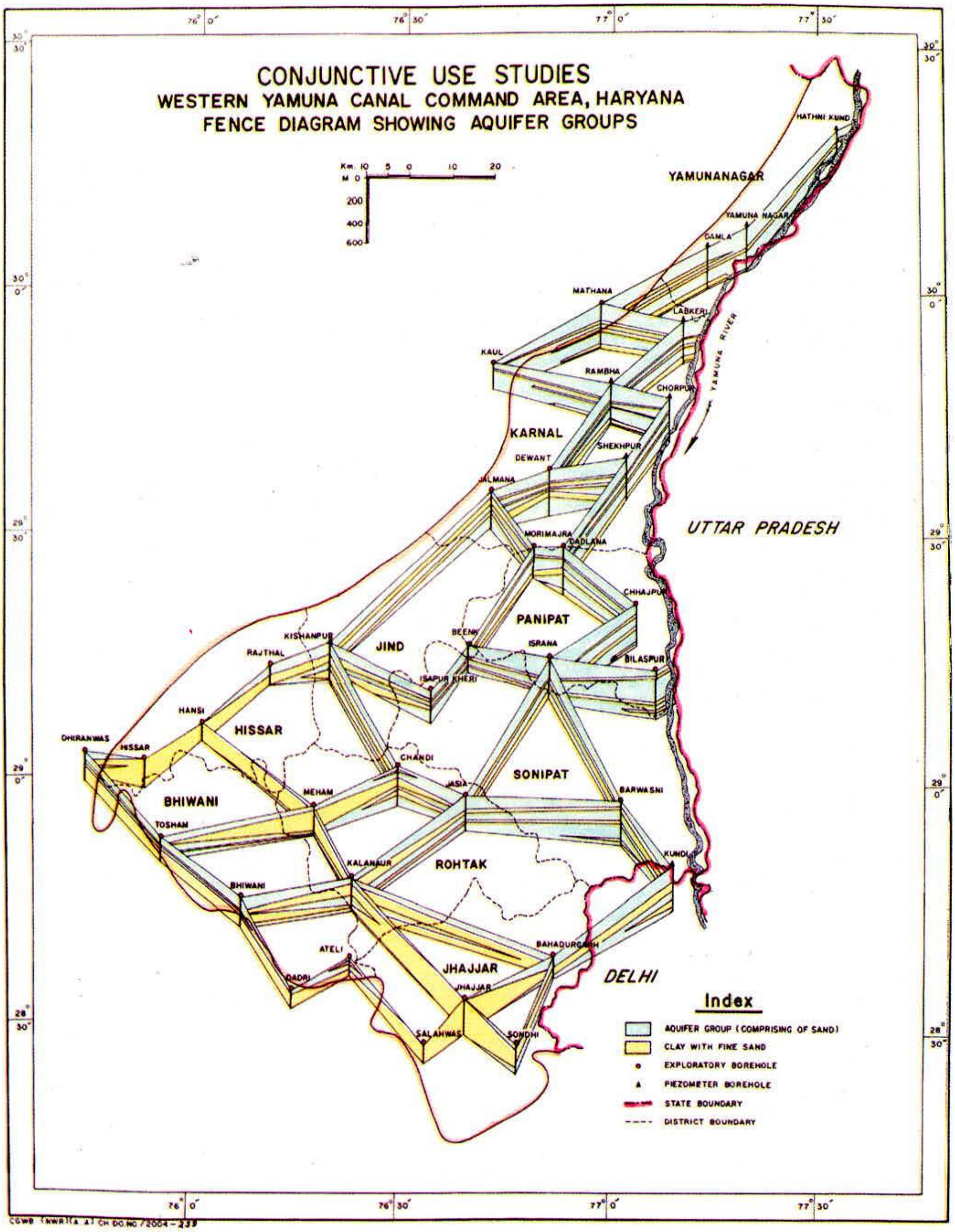


Fig. 2 Fence diagram of WYC command area

the foothill region. The group is unconfined and semi-confined. The aquifer parameters of this group are given below (Bhatnagar et al., 1982c).

Table-1 Aquifer parameters of Group-I Aquifer

Parameter	Range	Average Values
Transmissivity (m^2/day)	800 – 5210	2200
Lateral Hydraulic Conductivity 'K' (m/day)	8.75 – 47.1	24
Specific Yield (Sy) (%)	2.1 – 24	12

Aquifer Group-II: This group consists of numerous sand and clay lenses occurring at variable depth ranging from 65m to 283m.bgl. The sediments of this group are less coarse and are occasionally mixed with kankar. The ground water occurs under confined to semi-confined conditions. This aquifer is underlain by another clayey horizon which is considerably thick at places and appears to be regionally extensive. The aquifer parameters of this group are as below (Bhatnagar et al., 1982c).

Table-2 Aquifer parameters of Group –II Aquifer

Parameter	Range	Average Values
Transmissivity (m^2/day)	350 – 1050	700
Lateral Hydraulic Conductivity 'K' (m/day)	4 – 11	7.2
Storativity	5.6×10^{-4} to 1.7×10^{-3}	1.0×10^{-3}
Vertical conductivity of the upper confining clay layer 'K' (m/day)	5.35×10^{-4} to 2.7×10^{-3}	1.9×10^{-3}

Aquifer Group-III: This group comprises of thin sand layers alternating with thicker clay layers occurring at variable depths ranging from 197 to 346 m bgl. The granular material of this group is generally finer in texture. Kankar occurs in the southern parts of the area. In this aquifer group, the ground water normally occurs under confined condition. The parameters are given below.

Table-3 Aquifer parameters of Group –III Aquifer

Parameter	Range	Average Values
Transmissivity (m^2/day)	345 – 830	525
Lateral Hydraulic Conductivity 'K' (m/day)	3.5 – 10.7	7.1
Storativity	6.6×10^{-4} to 2.4×10^{-4}	4.5×10^{-4}

2.5 Behaviour of Groundwater

The discussion given below is based on the UYP reports and follow up study undertaken in 1978. The elevation of water table in the command varies from 300 m amsl in northern part to 200 m amsl in south western and southern part. The phreatic surface is a subdued replica of surface topography. Prominent groundwater ridge was found along WYC. The master slope of water table is from north to south with lateral slopes away from the ground water ridges. There is a prominent ground water trough roughly along river Yamuna, but this departs westwards in areas between Panipat to Delhi. A general down-valley shift of contours in post monsoon period in response to recharge has been observed. The depth to water level varies from less than 2 m to more than 20 m bgl. The water levels are deeper (20 – 25 m) in eastern and northern parts of the area. In southern and western parts of the area water levels are shallow even less than the 2 m.

The area faces both the problems of declining water level in central, northern and all along the river Yamuna covering approximately 8060 sq km. and rising water level covering an area of approximately 5480 sq km. Long-term behaviour of water table (May1985 – May 2004) reveals that in central, north and all along river Yamuna in an area of 8060 sq km, water level has gone down by 10 to 16 m. In the south and south-western part in an area of 5480 sq km, water level has risen by 5 to 10 m. The long-term water table behavior also reveals that the area under water level between 0-2m, 2-3m and 10-20m has increased substantially whereas area under water level in the range of 3-10m has decreased substantially. However, the water level in between 3-10 m is the most suitable depth to water level for various users. The water level trend depicts that the water level in majority of the area covering north, north central, eastern, south eastern and south western part of the area is falling at a rate of 0.3 cm/yr to 58.30 cm/yr.

The area in south central, south western and patches in east and north shows rising trend in the range of 0.2 cm/yr to a maximum of 64 cm/yr (Bhatia et al., 2005). Due to intense irrigation, water table in certain area of Rohtak, Jhajjar, Hissar, Sonipat and Panipat districts has become much shallow creating water logging conditions (Plate 5).

It was noted in the UYB study that both aquifer I and II receive recharge in Bhabhar tract and areas along the major canals and discharge the same to Yamuna drainage. The study of daily hydrographs of river levels along with those of ground water levels in the river tract for one year indicated a general sympathetic behaviour and a good hydraulic connectivity of the river with ground water storage along the banks. It was concluded from the study that influent – effluent relation of river with the areas in immediate vicinity of the two banks changes with places and times and may not always coincide with the regional relation of ground water body with the river, on either bank. Study of piezometric levels (twice a day during monsoon of 1975) at 8 sites where piezometric nets were constructed indicated that there is general simultaneous rise and fall in water levels of piezometers installed in aquifer I, II and III.

Over all, the ground water quality is good/fresh except in the southern and southwestern part of WYC area.

2.6 Groundwater Resources

The ground water resource was estimated by the CGWB, NWR, Chandigarh based on the GEC (1997) methodology (CGWB, 2005). The net annual ground water availability (of phreatic aquifer) for WYC command area worked out to be 3091.768 MCM/yr. The existing gross ground water draft for irrigation is 3227.1045 MCM and the existing gross ground water draft for all users is 3301.6595 MCM.

It has been observed that out of 49 blocks falling in WYC Command area, 19 blocks fall in safe category, 1 block in semi-critical, 2 in critical and 27 in over-exploited category. The majority of blocks under safe category fall in the districts of Bhiwani, Hissar, Rohtak, Jhajjar, Sonipat and Jind where ground water quality is brackish. In these blocks canal water is preferred than ground water for domestic and irrigation purposes. However, there is still sufficient scope to develop ground water in these blocks.

The development of ground water is directly related to availability of fresh ground water which can be readily utilized for various uses. The low development of ground water in some blocks is due to presence of marginal to saline ground water and dense network of canals. In Chhachhrauli block development of ground water is low as it falls in Kandi area where water level is deep and construction of well is expensive.

2.7 The Present Scenario

The tube wells drilled along the augmentation canals have dried up due to failure and non-maintenance (Plate- 6). So, the shallow water level problem in this area does not exist any more. The lined augmentation canal is being used as conduit of canal water as loss due to seepage will be less than the unlined canal.

The farmers have slowly changed the cropping pattern and have started using high return crops like paddy and sugarcane, which are high water consuming. This has resulted in decline in the water level. The development of industries in this area with the time and increase in population has resulted in the increase in the demand of water for industrial and domestic use. All these have resulted in groundwater depletion in general in all the aquifers. The long term fluctuation of the water level shows a general fall of 10-16 m in the last 20 yrs. The fall is generally observed in the central, north and all along the river Yamuna. However the water level also shows a rise in some areas, especially in the south western part.

Plate 5. Waterlogged Area Near Kharkoda Village

Plate 6. Defunct Augmentation Tubewell Along The Augmentation Canal

2.8 Groundwater Problems in the Area

At present the groundwater problems in the area which are to be studied in detail are:

- Over-development of groundwater has led to groundwater resource depletion in many blocks of the study area.
- Inequitable distribution of canal water coupled with the poor surface drainage and subsurface movement of groundwater has led to waterlogging in some areas and groundwater salinity problems at other places.
- Disposal of brackish water, unutilizable for irrigation, to make way for fresh water recharge in some areas.
- Water demand-supply gap. Demand is around 5623 MCM and the total availability is around 2610 MCM with a gap of around 3013 MCM.

3.0 OBJECTIVES OF THE PRESENT STUDY

The CGWB took up studies on conjunctive use of surface and groundwater resources in WYC command area. In continuation to this study, it is proposed to develop a mathematical model to simulate hydrogeological conditions and ground water flow system in parts of the WYC Command area and develop optimal allocation plan for water resources. The main objectives are:

a. Quantitative assessment of surface and ground water in space and time.

b. To identify critical areas of water logging within the canal command area.

c. To recommend the suitable areas for ground water irrigation development.

d. To develop a mathematical model to simulate hydrogeological condition and groundwater flow system.

e. To develop optimal allocation plan for surface and groundwater.

4.0 MODEL AREA

To attain the above objectives, a part of WYC command area was selected as model area after detailed discussions, keeping in mind the data availability and objectives of the study. Discussions were held with the CGWB scientists who are working or have worked in the study area. After several rounds of discussion it was decided to include the WYC and augmentation canal though these were initially to be kept as boundaries of the area. Accordingly an area of around 7500 Sq km (Fig. 3) was selected after consulting depth to water level maps, long term groundwater level fluctuation maps, topographical maps and literature. The selected area faces the twin problem of depleting groundwater level in some part and rising groundwater levels in other area. The selected area includes 32 blocks (Fig. 4), 13 fully and 19 partially, out of total 49 blocks of WYC command area. The selected area includes part of Yamuna Nagar, Karnal, Panipat, Sonipat, Rohtak, Jhajjar, Kurukshetra and Jind districts. Table 4 gives list of blocks and their area included in model area.

Fig. 5 shows the soil map of the model area. Most of the model area falls under loamy soil. Clayey soil is found in parts of Jagadhri and Radaur blocks. Some sandy soil patches exist in parts of Rohtak and Jhajjar districts. Fig. 6 shows the digital elevation model of the model area. The ground elevation in the model area varies from 210m to 320m. The main drains draining the model area are shown in Fig. 7.

Table-4 List of blocks and their area included in model area

District	Block	Block Area (Sq km)	Area in Model	
			Sq km	% of Block area
Yamuna Nagar	Chhachhrauli	516.4	288.50	55.87
	Bilaspur	268.0	11.35	4.24
	Jagadhri	384.2	287.10	74.73
	Radaur	293.3	205.00	69.89
Sub-total			**791.95**	
Kurukshetra	Ladwa	177.9	108.90	61.21
	Thanesar	405.7	81.66	20.13
Sub-total			**190.56**	
Karnal	Indri	247.6	247.60	100.00
	Nilokheri	505.4	413.00	81.72
	Karnal	378.9	378.90	100.00
	Nissang	390.4	310.70	79.59
	Assandh	432.7	133.50	30.85
	Gharaunda	365.7	365.70	100.00
Sub-total			**1849.40**	
Panipat	Panipat	181.7	181.70	100.00
	Bapoli	187.5	187.50	100.00
	Madlauda	336.1	321.10	95.54
	Israna	358.9	323.40	90.11
	Samalkha	268.3	268.30	100.00
Sub-total			**1282.00**	
Jind	Safidon	190.3	45.43	23.87
Sub-total			**45.43**	
Sonipat	Ganaur	314.4	314.40	100.00
	Gohana	345.5	287.80	83.30
	Sonipat	396.4	396.40	100.00
	Kharkhoda	295.5	295.50	100.00
	Rai	286.4	286.40	100.00
	Mundlana	294.6	129.10	43.82
Sub-total			**1709.60**	
Rohtak	Rohtak	311.6	118.90	38.16
	Sampla	263.6	263.60	100.00
	Kalanaur	433.9	9.07	2.09
Sub-total			**391.57**	
Jhajjar	Jhajjar	497.1	497.10	100.00
	Bahadurgarh	311.9	311.90	100.00
	Beri	413.9	194.00	46.87
	Matanhali	465.6	43.60	9.36
	Salahwas	490.6	201.00	40.97
Sub-total			**1247.60**	
TOTAL			**7508.11**	

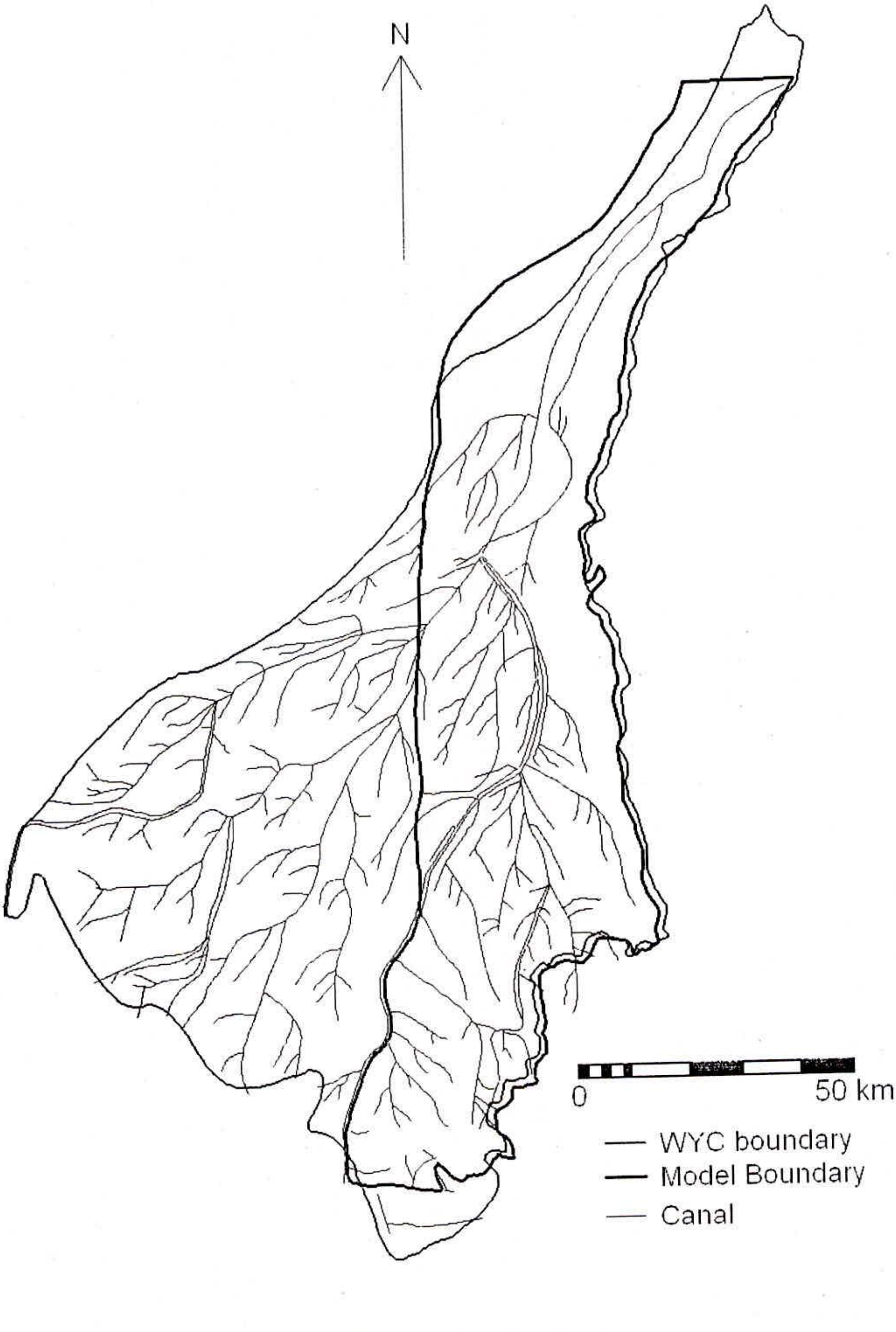


Fig. 3 Model area

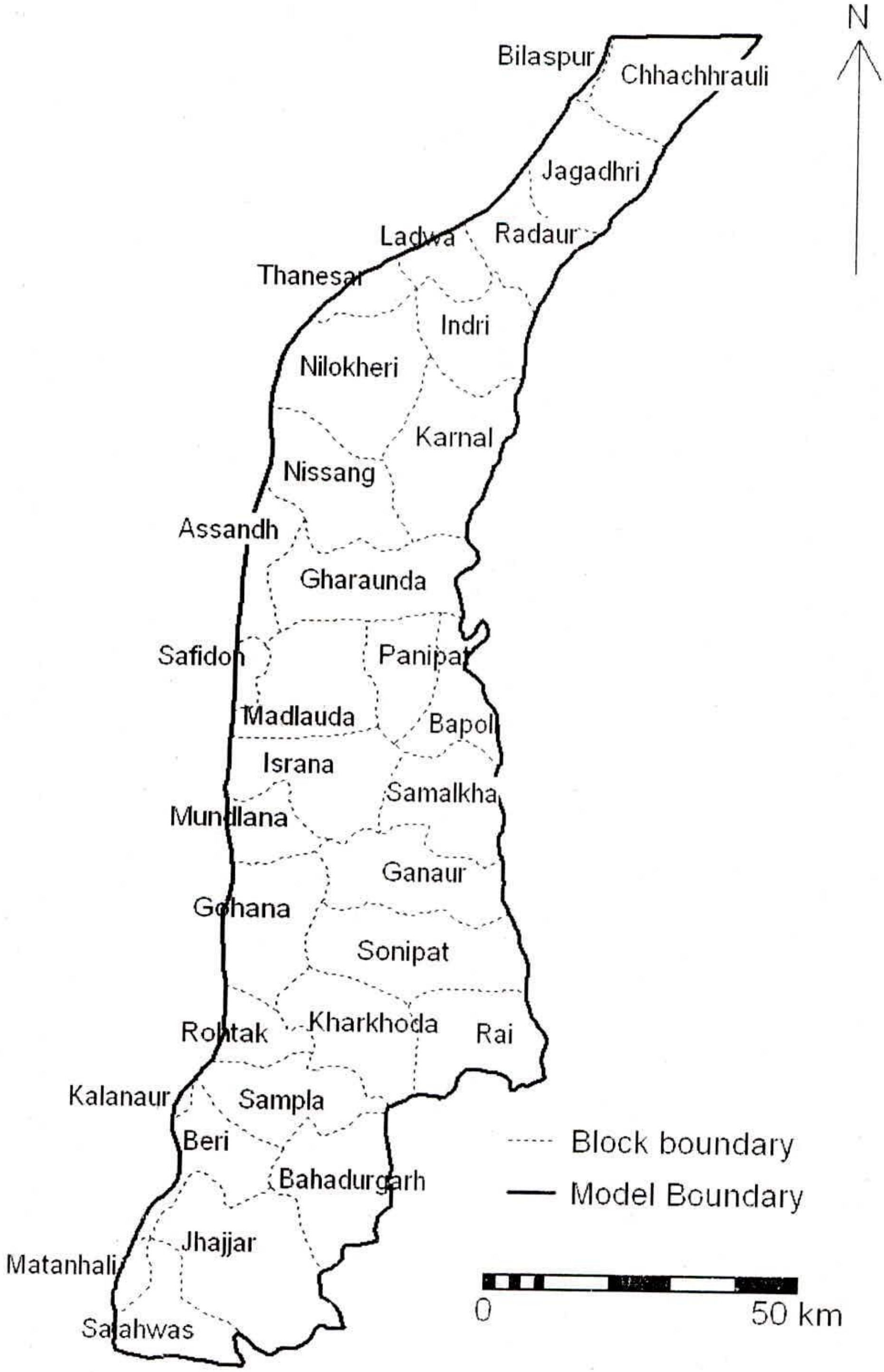


Fig. 4 Block map of model area

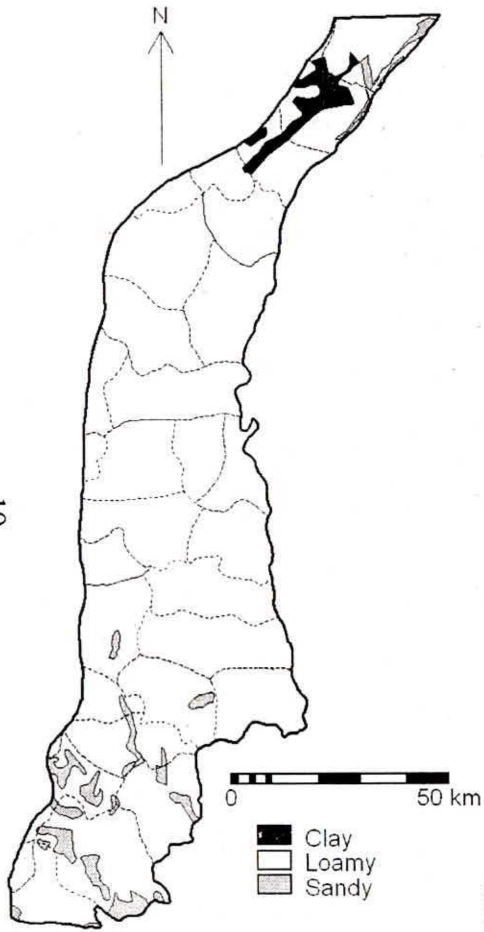


Fig.5 Soil map

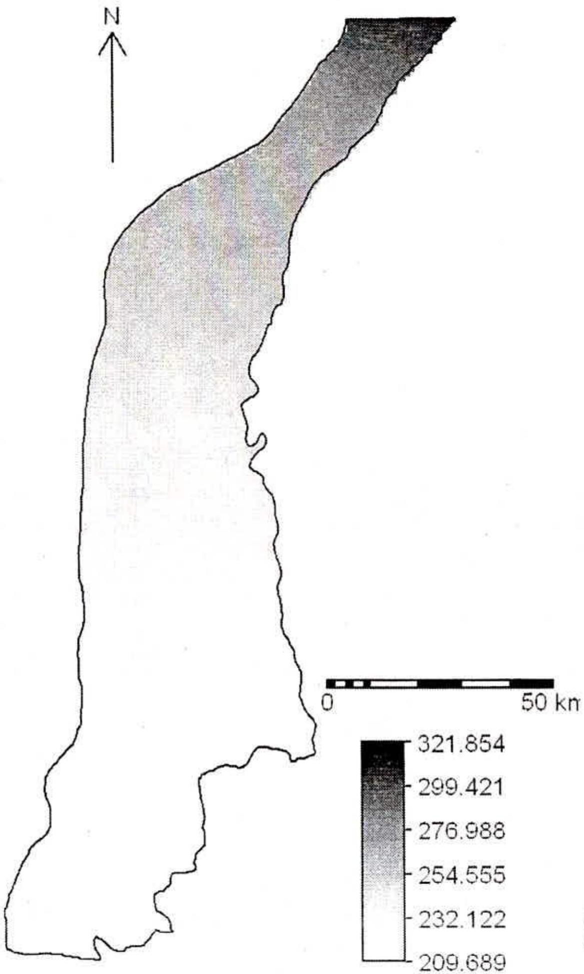


Fig.6 Digital Elevation Model (DEM)

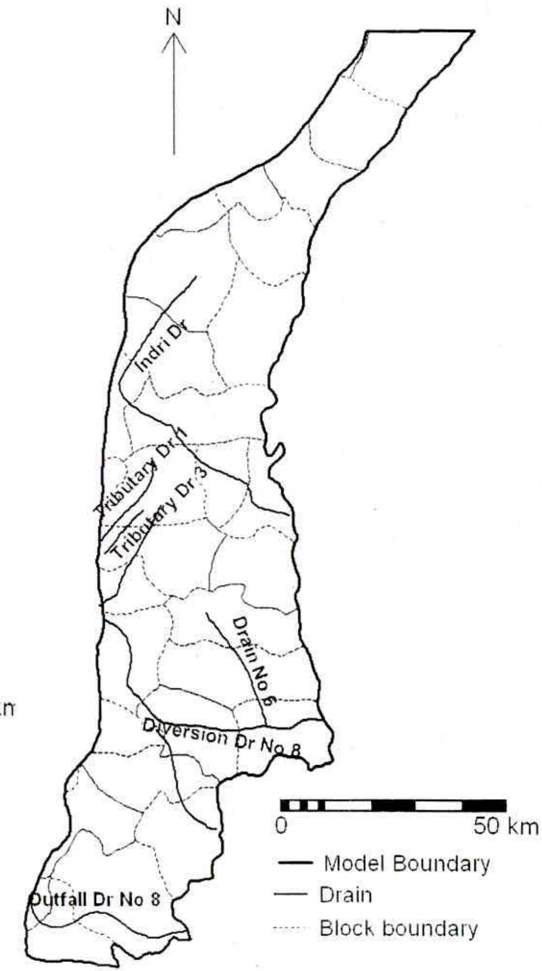


Fig.7 Main drains

5.0 WATER AVAILABILITY

5.1 Surface Water

The availability of surface water in the study area is through WYC system, rainfall, tanks, ponds and other depressions including drains. The WYC system comprises a storage reservoir located at Hathni Kund. The surface water diverted to the canal command area from the Hathni Kund reservoir is distributed through a network of canals of different capacities, viz., branches, distributaries, majors and minors. Table 5 presents season wise i.e. monsoon and non-monsoon releases of canal water for all the blocks falling in the model area. A total amount of 505.70 MCM water is being supplied in the model area on an average per year out of which 297.95 MCM is supplied during non-monsoon and 207.75 MCM is supplied during monsoon season. Bilaspur, Jagadhri, Radaur, Ladwa, Indri and Bapoli blocks get little or no canal water.

As per the CGWB reports, the normal rain fall of the WYC Command area is 608 mm. The runoff generated, considering 30% runoff generation from rain fall, for the model area will be 1370 MCM. Although 1370 MCM of surface water is available in the area during monsoon, it is not being used at present. If this water could be utilized for irrigation by any means, it would generate about 2740 sq km of irrigation potential considering an average depth of irrigation of 0.5m.

There are several ponds and depressions present in the command area. The water in these structures remains available only for few hours to through out the year. The water from these ponds and depression are used mainly for live stock and other uses except drinking purposes. As the water in these ponds and depressions are not used for irrigation or any useful purpose, the ponded water is lost in evaporation and seepage.

It is evident that the WYC system is the largest single source of usable surface water in the model area. Agriculture is the major sector in the area utilizing 90% of the total surface water released through the canal system.

Table-5 Block-wise canal water availability

S. No	Block	Canal Water Availability (MCM)		
		Monsoon	Non-monsoon	Total
1	Chhachhrauli	13.14	21.45	34.59
2	Bilaspur	0.00	0.00	0.00
3	Jagadhri	0.00	0.00	0.00
4	Radaur	0.00	0.00	0.00
5	Ladwa	0.00	0.00	0.00
6	Thanesar	1.60	1.56	3.16
7	Indri	0.00	0.00	0.00
8	Nilokheri	0.98	1.67	2.64
9	Karnal	1.87	1.33	3.20
10	Nissang	11.34	12.77	24.10
11	Assandh	4.54	6.80	11.34
12	Gharaunda	1.73	1.85	3.58
13	Panipat	1.44	1.77	3.21
14	Bapoli	0.00	0.00	0.00
15	Madlauda	15.95	17.55	33.50
16	Israna	9.04	12.25	21.28
17	Samalkha	3.21	3.98	7.18
18	Safidon	8.21	12.89	21.10
19	Ganaur	18.01	15.55	33.56
20	Gohana	18.62	28.24	46.86
21	Sonipat	15.73	20.04	35.77
22	Kharkhoda	15.18	23.57	38.75
23	Rai	11.93	13.88	25.81
24	Mundlana	5.79	10.48	16.26
25	Rohtak	9.63	15.93	25.57
26	Sampla	6.09	11.57	17.66
27	Kalanaur	0.36	0.43	0.80
28	Jhajjar	6.75	16.06	22.81
29	Bahadurgarh	17.84	28.94	46.78
30	Beri	4.41	8.32	12.73
31	Matanhali	0.97	1.74	2.71
32	Salahwas	3.39	7.35	10.74
TOTAL		207.75	297.95	505.70

5.2 Groundwater

The groundwater table elevation in the area varies from 205 m to 300 m amsl. The elevation is higher in northern parts in Chhachhrauli block and gradually reduces towards south and south-east. Minimum elevation is recorded in Sampla, Jhajjar, Salahwas and Bahadurgarh blocks where elevation is less than 210 m amsl. The ground water flow direction is towards south west in the Northern part, southerly in the Central part and easterly in the southern part of the Model area. The hydraulic gradient is steep in northern parts and gentle in southern and western part.

5.2.1 Groundwater availability

The dynamic groundwater resources of WYC command has been computed by the CGWB, Chandigarh, based on the Groundwater Estimation Committee Norms, 1997 (CGWB, 2005). For the estimation purpose, the block has been considered as basic unit. The dynamic groundwater resources for the model area have been estimated based on the proportional bases and is provided in Table 6. The total net ground water resource available in the Model area is 2104.39 MCM. The total ground water resource, thus computed would be available for utilization for irrigation, domestic and industrial uses.

5.2.2 Groundwater draft

The ground water draft is the quantity of ground water withdrawn from the ground water reservoirs. Block-wise groundwater draft is calculated based on the number of abstraction structures i.e. tubewells, present in a particular block. The annual ground water draft by a structure is computed by multiplying its average discharge and annual working hours. The tube well density is higher in the blocks underlain by fresh ground water. In Karnal and Panipat districts, tube well density is more than 25 tubewell/sq km and in Jhajjar, Sonipat and Jind districts tube well density is between 10 and 20 tube well /sq km. The low density of tube wells in these districts is due to poor quality of ground water and availability of canal water. The gross draft in model area is calculated to be 2762.29 MCM/yr (Table 6). For Karnal, Panipat and Sonipat districts ground water draft is comparatively higher.

5.2.3 Groundwater development status

The level of ground water development has been taken as the ratio of gross groundwater draft to net groundwater available resources. Groundwater development is computed as per following formula:

$$\text{Stage of ground water development} = \frac{\text{Gross Groundwater Draft}}{\text{Net Groundwater Available}} * 100$$

The perusal of data (Table 6) reveals that the present stage of block-wise ground water development in the model area varies from 56 % (Matanhali) to 190 % (Ladwa). The ground water development more than 85 % has been observed in 26 blocks out of total 32 blocks. The blocks falling in safe category are Bilaspur, Rohtak, Kalanaur, Beri and Matanhali. The low development of ground water in these blocks is due to presence of marginal to saline ground water and dense network of canals. In Chhachrauli block development of ground water is low as it falls in Kandi area where water level is deep and construction of well is expensive.

Table-6 Groundwater availability, draft, stage of development and category of development in different blocks in the model area

S N	BLOCK	GW Availability (MCM)			GW Draft (MCM)			Groundwater Development (%)	Category
		Monsoon	Non-monsoon	Total	Monsoon	Non-monsoon	Total		
1	Chhachhrauli	56.29	25.36	81.65	26.50	33.35	59.85	73	Semi Critical
2	Bilaspur	2.68	1.00	3.69	1.26	1.61	2.87	78	Safe with Caution
3	Jagadhri	46.04	23.05	69.09	48.68	61.36	110.04	159	Over Exploited
4	Radaur	40.34	17.82	58.16	28.49	35.66	64.15	110	Over Exploited
5	Ladwa	19.20	7.27	26.47	22.40	27.83	50.23	190	Over Exploited
6	Thanesar	14.41	8.44	22.85	16.90	21.11	38.01	166	Over Exploited
7	Indri	120.98	34.78	155.75	94.37	115.70	210.07	135	Critical
8	Nilokheri	80.88	33.65	114.53	72.65	89.24	161.90	141	Over Exploited
9	Karnal	110.56	59.47	170.03	97.76	120.82	218.58	129	Critical
10	Nissang	84.48	43.49	127.98	72.12	88.47	160.59	125	Critical
11	Assandh	32.13	12.94	45.07	30.10	36.83	66.93	148	Critical
12	Gharaunda	75.18	27.81	102.99	78.98	97.07	176.05	171	Over Exploited
13	Panipat	43.34	22.61	65.95	40.18	49.99	90.17	137	Over Exploited
14	Bapoli	42.92	18.25	61.17	51.06	62.54	113.60	186	Over Exploited
15	Madlauda	69.19	29.72	98.92	61.25	74.93	136.18	138	Over Exploited
16	Israna	50.20	22.16	72.36	45.93	56.18	102.11	141	Over Exploited
17	Samalkha	37.31	16.40	53.70	42.77	52.46	95.23	177	Over Exploited
18	Safidon	14.86	10.70	25.56	11.67	14.94	26.61	104	Critical
19	Ganaur	73.75	40.53	114.27	75.14	94.63	169.77	149	Over Exploited
20	Gohana	31.88	19.50	51.38	26.03	31.94	57.97	113	Over Exploited
21	Sonipat	69.18	38.13	107.32	67.63	85.45	153.08	143	Over Exploited
22	Kharkhoda	36.30	24.08	60.37	30.14	37.08	67.22	111	Critical
23	Rai	42.12	19.62	61.74	38.34	48.71	87.05	141	Over Exploited
24	Mundlana	23.31	14.19	37.50	18.17	22.20	40.37	108	Critical
25	Rohtak	21.33	17.44	38.77	6.53	26.11	32.64	84	Safe with Caution
26	Sampla	21.07	16.76	37.83	8.19	32.76	40.95	108	Critical

S N	BLOCK	GW Availability (MCM)			GW Draft (MCM)			Groundwater Development (%)	Category
		Monsoon	Non-monsoon	Total	Monsoon	Non-monsoon	Total		
27	Kalanaur	0.47	0.39	0.87	0.13	0.52	0.64	74	Safe with Caution
28	Jhajjar	45.80	42.10	87.90	18.66	74.36	93.02	106	Critical
29	Bahadurgarh	52.81	44.60	97.41	18.79	74.86	93.65	96	Critical
30	Beri	14.22	13.47	27.69	3.89	15.50	19.38	70	Safe
31	Matanhali	2.55	2.29	4.84	0.54	2.15	2.69	56	Safe
32	Salahwas	9.29	11.32	20.61	4.15	16.54	20.69	100	Critical
Total		**1385.1**	**719.3**	**2104.4**	**1159.4**	**1602.9**	**2762.3**		

The categorization of the area has been done based on the level of ground water development and long term trend in groundwater levels (Table 7).

Table-7 Criteria for categorizing ground water development

SAFE	If ground water development (GWD) ≤ 70% and no significant long term decline in pre and post monsoon water level (10-20cm/yr)
SAFE with CAUTION FOR FUTURE DEVELOPMENT	If ground water development (GWD) ≥ 70% but <90% and no significant long term decline in pre and post monsoon water level (10-20cm/yr)
SEMI-CRITICAL for cautious ground water development	If ground water development (GWD) ≥ 70% but <90% and either pre and post monsoon water level shows significant long term water level trend (10-20cm/yr)
CRITICAL	If ground water development (GWD) ≥ 90% but <100% and either pre and post monsoon water level shows significant long term water level trend (10-20cm/yr)
CRITICAL	If ground water development (GWD) <100% but both pre and post monsoon water level shows significant long term water level trend (10-20cm/yr)
CRITICAL	If ground water development (GWD) >100% and both pre and post monsoon water level DOES NOT show significant long term water level trend (10-20cm/yr)
OVER-EXPLOITED	If ground water development (GWD) >100% and both pre and post monsoon water level shows significant long term water level trend (10-20cm/yr)

It has been found that out of 32 blocks falling in study area, 5 blocks fall in safe category, one block in semi-critical, 11 blocks in critical and 15 blocks in over exploited category (Fig. 8). Almost half of the blocks of the model area fall under over exploited category. The blocks falling in over exploited category fall in Karnal and Panipat districts as a whole and in parts of Sonipat and Yamuna Nagar districts. In these block there is little or no canal irrigation. The entire requirement of domestic and irrigation is being met from ground water leading to over-exploitation.

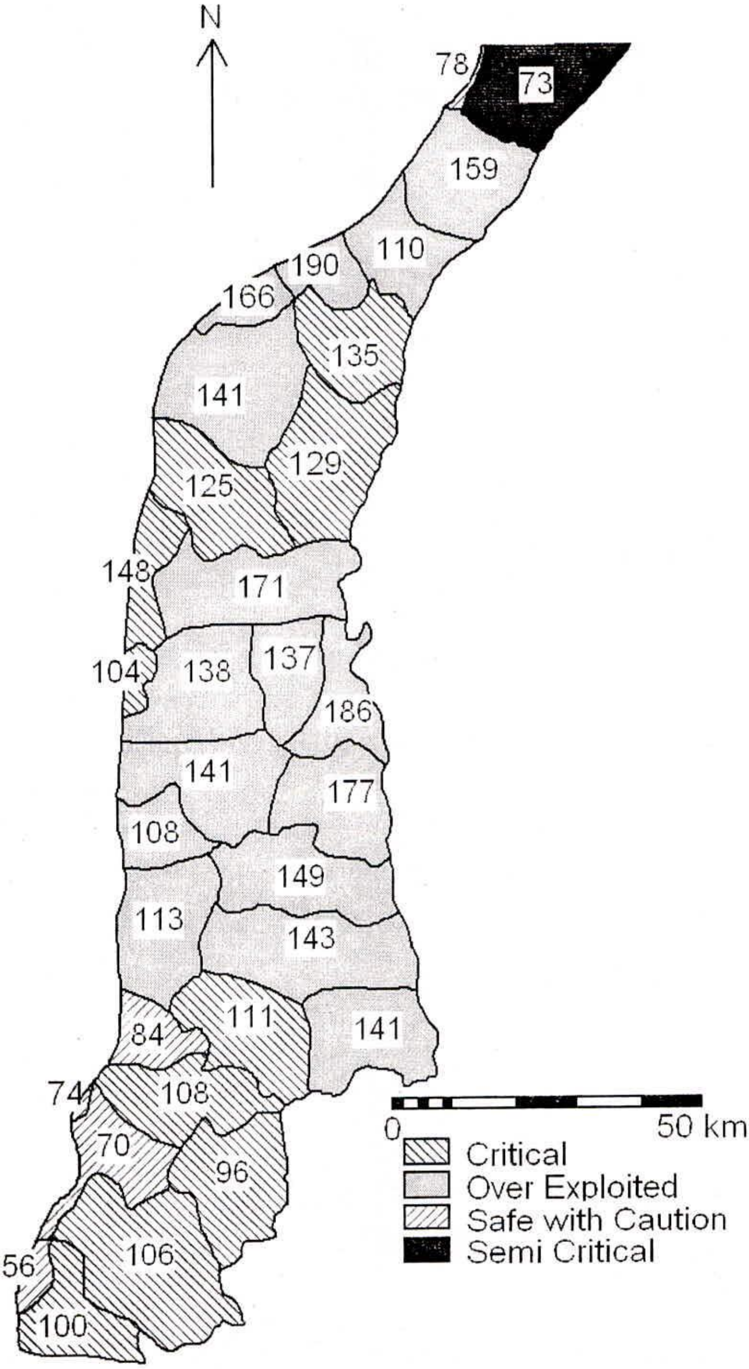


Fig. 8 Groundwater development status in model area

6.0 WATER DEMAND

The demand of water for various sectors namely domestic (rural and urban), livestock, agriculture (irrigation) and industrial have been computed for the year 2002 based on population and other data collected from various agencies. For this purpose, block has been considered as a basic unit.

Domestic water demand is the daily demand of water for human consumption (drinking) and for all their domestic activities such as cooking, bathing, washing, rinsing and cleaning, sanitation, gardening and cooling. The total block-wise demand of water for domestic consumption for rural area and urban towns for the districts falling in the model area have been computed based on the Census Data for the year 2001 provided by the Census Department, Govt. of India. The demand for domestic water has been calculated by considering 70 lt/head/day for rural population and 130 lt/head/day for urban population. The demand for domestic consumption for the year 2002 was 155.5 MCM. The block wise domestic water demand have been given in Table-8

Some of the districts in the study area are very important from industrial point of view. Paper and pulp, distilleries and breweries, food processing, soft drinks, textiles and yarn, pharmaceuticals and basic drugs, milk and milk products, refineries, petrochemical, thermal power plant etc are the main water intensive industries of the study area. Concentration of these industries is in the districts of Panipat, Sonipat, Yamuna Nagar, and Karnal etc. In the absence of block-wise details of industries (small, large & medium scale), the present industrial water demand has been taken as 10 % of domestic water demand.

Livestock is very well developed in the area. Diary, piggery, fishery, rearing of sheep and goats etc are taken up by the farmers along with agriculture as it provides them with an extra source of income and some protection from agriculture failure. The block-wise present water demand for the live stock for the year 2002 are worked out considering 80% of the domestic demand as the live stock demand, in the absence of any data.

In command area, various crops are grown in different seasons of the year. The growth of the crops depends upon the area, climatic conditions and water resources available for irrigation. Kharif crops include Paddy, Bajra, Sugar Cane, Cotton and Pulses etc. Rabi Crops includes Wheat, Gram, Oil Seeds and Pulses etc. Other crops such as Jowar, Barley, Fodder, vegetables etc are also grown but the area covered by these crops is insignificant as compared to the major crops (Kharif and Rabi). Wheat is a major Rabi crop and Paddy is the major kharif crop. Water requirement vary from crop to crop and from time to time for the same crop depending upon their physiological growth stages. An attempt has been made to work out the irrigation water demand based on the area under different crops and depth of watering. The block-wise details of area under various crops for the year 2002-03 were collected from the Agriculture Department, Government of Haryana. Accordingly, the water demand for irrigation sector for the year 2002 has been computed as 5327.9 MCM (Table 8).

Table 8 also presents block-wise details of overall requirement of water. A perusal of table reveals that the gross demand of water for all the sectors taken together works out to be 5623.3 MCM.

Table 9 compares water availability with water demand for all blocks in the model area. It is seen that out of 32 blocks, 27 blocks are water deficit blocks. The maximum deficit is observed in Karnal block.

Table-8 Block-wise water demand in model area

S No.	BLOCK	Water Demand (MCM)				
		Domestic	Industrial	Livestock	Irrigation	Total
1	Chhachhrauli	2.80	0.28	2.24	121.14	126.46
2	Bilaspur	0.13	0.01	0.11	0.47	0.72
3	Jagadhri	13.29	1.33	10.63	59.55	84.79
4	Radaur	2.08	0.21	1.67	98.22	102.18
5	Ladwa	1.94	0.19	1.55	19.22	22.90
6	Thanesar	2.09	0.21	1.67	15.10	19.06
7	Indri	4.10	0.41	3.28	338.26	346.05
8	Nilokheri	4.71	0.47	3.76	240.86	249.80
9	Karnal	14.76	1.48	11.81	451.10	479.15
10	Nissang	3.13	0.31	2.50	298.40	304.33
11	Assandh	1.66	0.17	1.33	146.59	149.76
12	Gharaunda	5.79	0.58	4.63	292.03	303.03
13	Panipat	16.08	1.61	12.87	221.46	252.02
14	Bapoli	2.73	0.27	2.18	236.25	241.44
15	Madlauda	2.89	0.29	2.31	354.04	359.53
16	Israna	2.63	0.26	2.10	263.81	268.80
17	Samalkha	4.54	0.45	3.63	238.95	247.57
18	Safidon	1.05	0.10	0.84	72.94	74.93
19	Ganaur	5.70	0.57	4.56	274.85	285.67
20	Gohana	4.49	0.45	3.59	170.27	178.79
21	Sonipat	15.44	1.54	12.35	340.50	369.84
22	Kharkhoda	4.67	0.47	3.73	153.43	162.30
23	Rai	4.37	0.44	3.50	215.99	224.29
24	Mundlana	1.21	0.12	0.97	94.90	97.20
25	Rohtak	8.14	0.81	6.52	91.63	107.10
26	Sampla	3.03	0.30	2.43	90.66	96.42
27	Kalanaur	0.07	0.01	0.05	2.55	2.68
28	Jhajjar	6.79	0.68	5.43	143.23	156.12
29	Bahadurgarh	12.37	1.24	9.89	184.83	208.33
30	Beri	1.83	0.18	1.47	71.72	75.20
31	Matanhali	0.24	0.02	0.20	2.78	3.24
32	Salahwas	0.71	0.07	0.57	22.19	23.54
Total		155.5	15.5	124.4	5327.9	5623.3

Table-9 Water availability Vs water demand in the model area

S. No.	BLOCK	Availability (MCM)			Demand (MCM)	Surplus (MCM)
		SW	GW	Total		
1	Chhachhrauli	34.59	81.65	116.24	126.46	-10.22
2	Bilaspur	0.00	3.69	3.69	0.72	2.97
3	Jagadhri	0.00	69.09	69.09	84.79	-15.70
4	Radaur	0.00	58.16	58.16	102.18	-44.02
5	Ladwa	0.00	26.47	26.47	22.90	3.57
6	Thanesar	3.16	22.85	26.00	19.06	6.94
7	Indri	0.00	155.75	155.75	346.05	-190.30
8	Nilokheri	2.64	114.53	117.17	249.80	-132.64
9	Karnal	3.20	170.03	173.23	479.15	-305.92
10	Nissang	24.10	127.98	152.08	304.33	-152.26
11	Assandh	11.34	45.07	56.41	149.76	-93.35
12	Gharaunda	3.58	102.99	106.57	303.03	-196.47
13	Panipat	3.21	65.95	69.17	252.02	-182.85
14	Bapoli	0.00	61.17	61.17	241.44	-180.26
15	Madlauda	33.50	98.92	132.41	359.53	-227.12
16	Israna	21.28	72.36	93.64	268.80	-175.16
17	Samalkha	7.18	53.70	60.89	247.57	-186.69
18	Safidon	21.10	25.56	46.66	74.93	-28.28
19	Ganaur	33.56	114.27	147.83	285.67	-137.84
20	Gohana	46.86	51.38	98.24	178.79	-80.55
21	Sonipat	35.77	107.32	143.09	369.84	-226.75
22	Kharkhoda	38.75	60.37	99.12	162.30	-63.17
23	Rai	25.81	61.74	87.55	224.29	-136.74
24	Mundlana	16.26	37.50	53.77	97.20	-43.43
25	Rohtak	25.57	38.77	64.33	107.10	-42.77
26	Sampla	17.66	37.83	55.49	96.42	-40.94
27	Kalanaur	0.80	0.87	1.66	2.68	-1.01
28	Jhajjar	22.81	87.90	110.71	156.12	-45.41
29	Bahadurgarh	46.78	97.41	144.19	208.33	-64.14
30	Beri	12.73	27.69	40.42	75.20	-34.78
31	Matanhali	2.71	4.84	7.55	3.24	4.31
32	Salahwas	10.74	20.61	31.35	23.54	7.80
Total		505.70	2104.39	2610.09	5623.28	-3013.19

7.0 STATUS OF WATER LOGGING IN THE MODEL AREA

With the passage of time, the irrational use of canal water has resulted in bringing and spreading waterlogging to a large area. Due to evaporation of subsoil water through capillary action and subsequent deposition of salt, the soil has turned saline at many places in the command. It has also been observed that, due to breach of the canals, over-flooding of the fields and poor surface drainage, water accumulates in the area adjoining the canals, roads and other natural depressions.

To decipher the status of waterlogging in the study area, observed data of depth to groundwater level at 69 observation wells were utilized. Fig. 9 shows the location of these observation points in the command area. Pre and post-monsoon depth to groundwater level data of the year 2002, 2003 and 2004 were plotted with respect to each observation point. With the help of ILWIS software water level contouring was carried out at different intervals. Fig. 10(a) shows the depth to groundwater level during pre-monsoon period of 2002, 2003 and 2004.

In general, depth to water varies from 2m to 20mbgl. Shallowest water level has been encountered at Kulasi (0.89m bgl) and deepest at Sewah (23.3m bgl) in pre-monsoon 2004. These maps depict that water levels are deeper (20-25m) in eastern and northern parts of the area. In Chhachhrauli block, water level was found to be deeper as the area falls in Kandi area (piedmont). Considerable area of deep water levels have been found in Ladwa, Thanesar, Samalkha, Ganaur, Sonipat, Panipat and Bapoli blocks. This area is situated along national highway no.1 where quality of water is good and a heavy ground water development has taken place. In southern parts of the area water levels are shallow. In some parts of Israna, Gohana, Kharkhoda, Rohtak, Sampla, Jhajjar, Beri, Salahwas and Bahadurgarh blocks water levels are very shallow and within the range of less than 2m below ground level causing water logging. Maps showing depth to water level for post-monsoon period of 2002, 2003 and 2004 (Fig. 10(b)) depicts that water level has risen due to recharge during monsoon period.

The distribution of areas under waterlogged (DTW less than 2m bgl) and prone to waterlogging (DTW 2-3m bgl) over the years were computed from the depth to water level maps are shown in Table 10 and 11.

Table-10 Waterlogged area (sq km) in the model area

Year	Pre-Monsoon		Post-Monsoon	
	Area	Percent	Area	Percent
2002	3.75	0.05	28.5	0.38
2003	6.00	0.08	81.25	1.09
2004	15.00	0.02	84.0	1.13

Table-11 Area (sq km) prone to waterlogging in the model area

Year	Pre-Monsoon		Post-Monsoon	
	Area	Percent	Area	Percent
2002	52.5	0.71	81.62	1.10
2003	37.25	0.50	181.75	2.44
2004	71.12	0.96	198.75	2.67

An area of 15 sq km around Israna, Gohana, Rohtak, Kharkhoda and Bahadurgarh blocks was found waterlogged in post-monsoon 2004. The waterlogged area in model area has increased from 3.75 sq km in pre-monsoon 2002 to 15 sq km in pre-monsoon 2004. The area prone to waterlogging has increased from 52.5 sq km to 71.12 sq km during the same period. In post-monsoon, waterlogged area was 28.5 sq km in 2002 which has increased to 84 sq km in 2004. The area prone to waterlogging has increased from 81.62 sq km to 198.75 sq km during the same period.

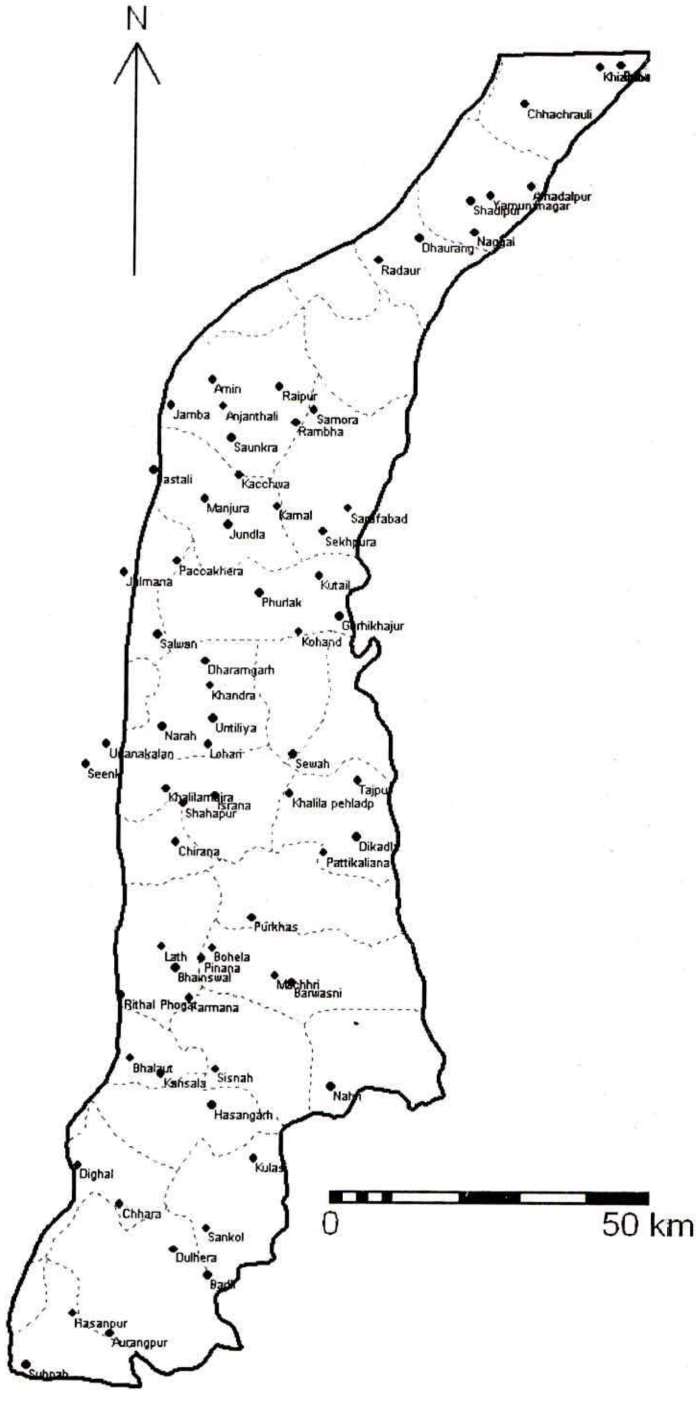


Fig. 9 Location of observation points which are used to decipher the waterlogged area

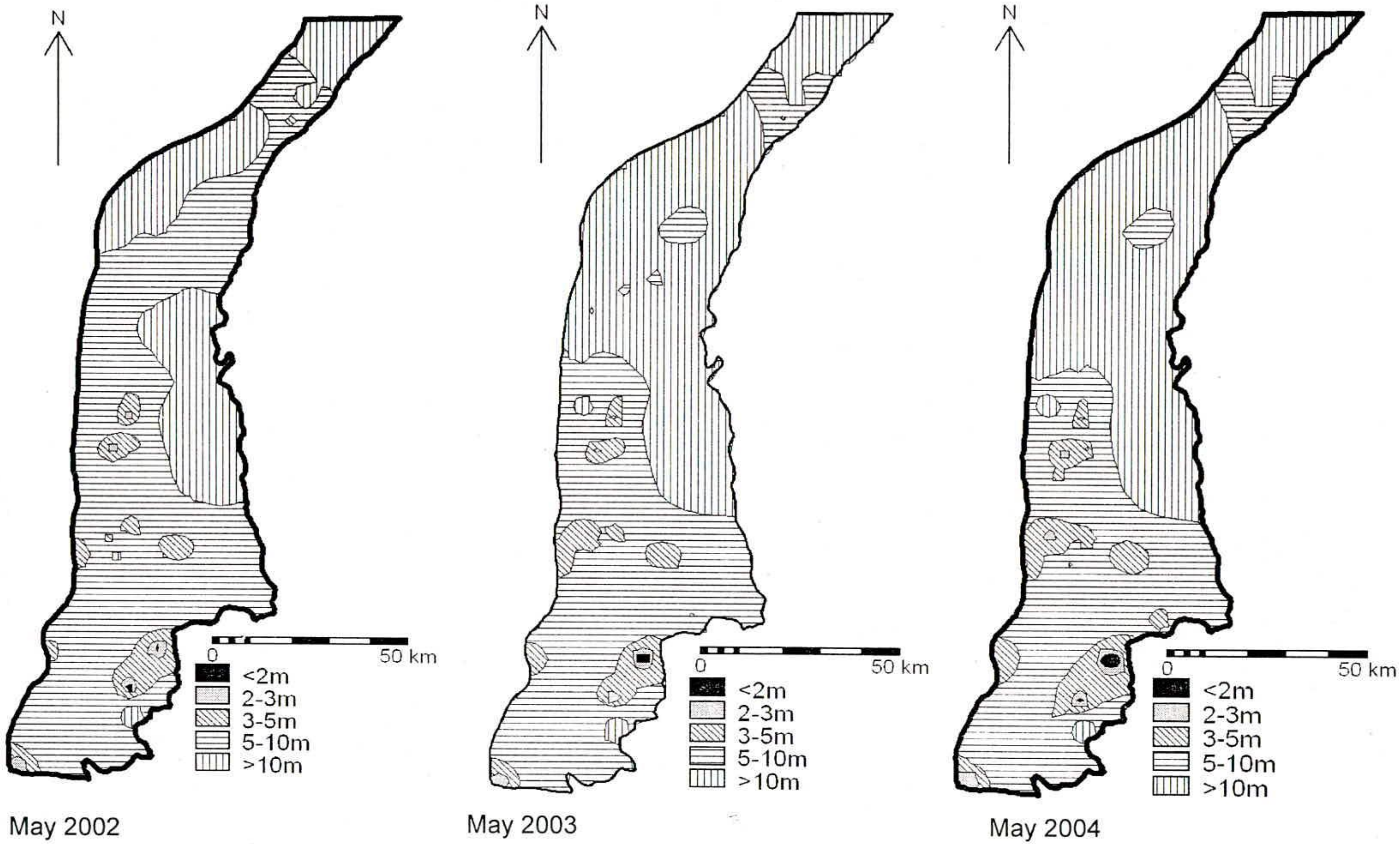


Fig.10(a) Depth to groundwater level map of WYC model area

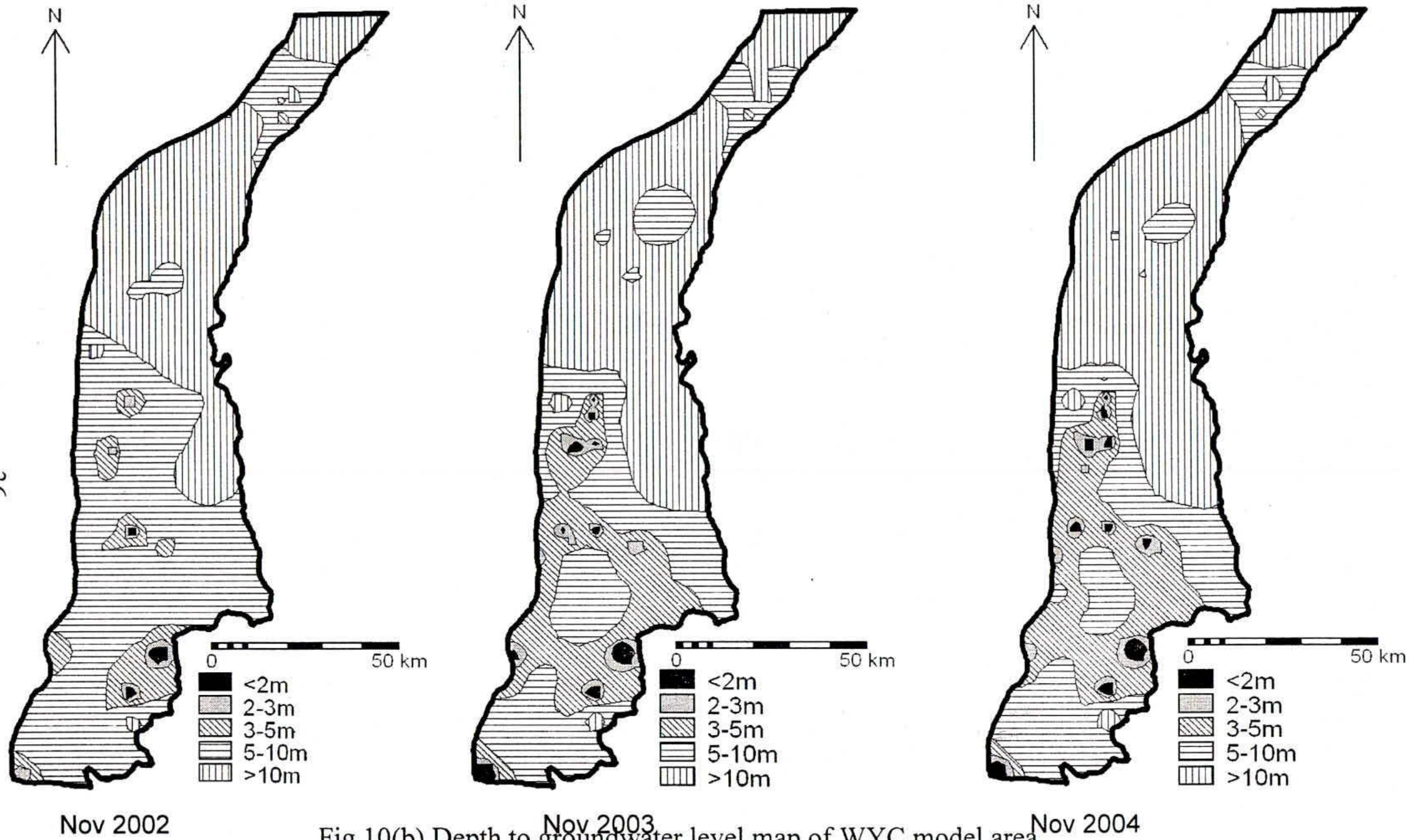


Fig.10(b) Depth to groundwater level map of WYC model area

8.0 AREAS SUITBLE FOR GROUNDWATER DEVELOPMENT

As discussed above in the ground water availability section, 15 blocks out of the 32 blocks in the model area fall in the over-exploited category. So there is not much scope for development of the ground water in the area. Rather there is necessity to regulate the use of groundwater in the area. How ever there is some scope for development of groundwater from the phreatic aquifer in areas where there is water logging at present (Parts of Kharkhoda, Rohtak, Israna, Bahadurgarh blocks) and where there is no supply of canal water (like parts of Radaur and Chhachrauli blocks). Further in the northern part of the model area there is scope for development (in the recharge area). This area is to be developed by community/ Government as the drilling in this area needs expertise.

The development of the highly potential deeper aquifers (Confined/Semi-Confined) is possible, but with caution and in a sustainable manner. Bhatnagar and Romani (1981) has advocated urgent development of the deep aquifers, not to get more water but also because the hydrochemical behaviour of water in deep aquifers indicate quality deterioration with time and in long term threatens to deteriorate the quality of water in shallow aquifer due to upward leakage. The development of this aquifer is to be monitored regularly through piezometers especially meant for this purpose. A model is to be developed for updating and to study the impact of this development in the phreatic aquifer and the river flow/river regeneration etc.

9.0 MATHEMATICAL MODELLING

The ground water flow modelling include the development of mathematical model to simulate hydrogeological conditions of ground water flow systems in the area. For success of any simulation studies, it is necessary that the input data are accurate, are of long duration, and have a reasonable frequency. The steps in groundwater simulation studies include devising a model and calibration of the model.

Devising a model involves developing a conceptual model, using the data available as mentioned above, including finalization of the boundary conditions, the hydrostratigraphic units and the flow system. Then the modeling steps involves laying out the grid, defining model layers, orientation of the grid, assignment of aquifer parameters, assignment of initial heads, finalization of packages and assigning data as per the requirement of these packages, assigning stress period and then finally running the model. In model calibration, selected model input parameters are adjusted to produce field measured heads and flows. After calibration of the model, the calibrated model can be used to generate alternate management scenarios and develop optimal allocation plan of water resources.

9.1 Model Description

The 3-D Modular Finite Difference Groundwater Flow Package MODFLOW (McDonald and Harbaugh, 1988) was used. Visual MODFLOW (Waterloo Hydrogeologic, 2002) was used as an interface to the MODFLOW model. MODFLOW is a computer program that numerically solves the three-dimensional ground-water flow equation for a porous medium by using a finite-difference method. MODFLOW was originally documented by Mc Donald and Harbaugh (1984). This was subsequently modified and is known as MODFLOW-88, MODFLOW-96, MODFLOW-2000.

MODFLOW solves the following partial differential equation describing the three-dimensional movement of groundwater of constant density through porous material:

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

where, K_{xx}, K_{yy}, K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T); h is the potentiometric head (L); W is a volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1}); Ss is the specific storage of the porous material (L^{-1}); and t is time (T).

S_s, K_{xx}, K_{yy}, and K_{zz} may be functions of space and W may be a function of space and time. This equation, combined with specification of boundary and initial conditions, is a mathematical expression of a groundwater flow system. MODFLOW uses the finite difference method to obtain an approximate solution to this equation. Hydrogeologic layers can be simulated as confined, unconfined, or a combination of confined and unconfined. External stresses such as wells, areal recharge, evapotranspiration, drains and streams can also be simulated. Boundary conditions include specified head, specified flux, and head-dependent flux.

9.2 Development of Mathematical Model for Part of WYC Command Area

9.2.1 Conceptual model of the area

The conceptual model of the hydrogeologic system was based on detailed study of the hydrogeological and subsurface geological data available in various reports of UYB of CGWB, drilling details, fence diagram, geophysical surveys, field visits and especially based on discussions with the Scientists who have worked in the area. Based on the sub-surface geology of the area, three distinct groups of permeable granular zones separated by two different poorly permeable/impermeable horizons were identified as discussed above in detail. As little data was available about the various parameters and the ground water behaviour for the lowest aquifers, only three layers (two aquifers separated by an aquitard) were considered during the development of the model. The upper unconfined aquifer was considered to be extending from the water table to various depths with a maximum depth of 167 m bgl. and as occurring all over the study area. This aquifer is underlain by a regionally extensive 10 to 15 m thick predominantly clay horizon. Aquifer II (confined/semi-confined) consists of different sand and clay lenses occurring at variable depths ranging from 65 m to 283 m bgl. The sediment of this aquifer is lesser course than aquifer I. This aquifer is under confined to semi-confined condition and is underlain by another clayey horizon.

The Visual MODFLOW does not allow setting any of the model layers as confining beds as it desires to represent confining bed layers as physical layers for accurate physical representation of the system being simulated in a meaningful way. (Once simulated as confining layer MODFLOW-2000 does not calculate head or draw down values for this layer.). From the lithologs of the drilling data of the area under study, it is observed that the confining layer also does contain number of thin sand layers apart from clay layer. Further the thickness of this confining layer also varies from 10 - 15 m. Simulation of such layer as a confining layer without giving any importance to the thickness of the bed does not seem to be justified. So keeping in view all the above factors, finally it was decided to simulate the model area as a three layer model with

Layer-I	Upper-Phreatic aquifer
Layer-II	Confining layer as Confined /Unconfined layer
Layer-III	as Confined/Unconfined Aquifer

How ever the area around Yamuna Nagar, where phreatic aquifer is connected with the confined aquifer below (as per the Upper Yamuna Report) was simulated accordingly.

9.2.2 Spatial discretization of the area

The model area was digitized in GIS environment and was imported in the Visual MODFLOW. Horizontally the model area was discritized in a square grid of 1km×1km, resulting in 7653 active grid cells. Vertically, the aquifer system hydrogeologic units are modeled by three Modflow layers. The unconfined aquifer is modeled as an unconfined Modflow layer (model layer 1). The clay aquitard is modeled as a convertible confined/unconfined Modflow layer (model layer 2). The second aquifer is also modeled as a convertible confined/unconfined layer (model layer 3).

The map of surface elevation (top of layer 1) is created in GIS environment. The surface elevations compiled using the data of reduced levels of all observation wells, piezometers, exploratory tube wells were digitized as point map in ILWIS software. The contour map of surface elevation as available in Upper Yamuna Basin Report was also digitized in ILWIS. This digitized contour map along with the digitized point map is used to interpolate the surface elevation at every grid point in the study area. This is exported to an ASCII file and subsequently imported in to the Visual MODFLOW. The bottom of the first layer (i.e. top of the second confining layer) and similarly top and bottom of the third layer (Aquifer II) are created in MODFLOW based on the available drilling data, geophysical survey data and fence diagram available in the Upper Yamuna Basin Report.

9.2.3 Temporal horizon and discretization

The simulation period is three years from June 2002 to May 2005. Some data like recharge and discharge (pumping data) are available on monsoon and non-monsoon basis and accordingly assigned on monsoon and non-monsoon basis. Some data like river gauge (boundary) is available and assigned on monthly basis in the model. Visual MODFLOW automatically merge all of the different time period data defined for each pumping well and boundary condition into the stress period required by MODFLOW. Accordingly, the Visual MODFLOW has divided the three year period into 36 stress period, each stress period of one month.

9.2.4 Boundary conditions

The eastern part of the study area is bounded by the Yamuna river which is taken as river boundary. The western boundary of the study area is the watershed boundary of the Upper Yamuna basin. The flow across this boundary is negligible and hence it is considered as no-flow boundary. The south western portion of the study area does not coincide with the watershed boundary and instead a canal is running along this portion. This portion of the boundary is considered as river boundary (Fig. 11). Northern and southern sides of the study area do not have any conventional hydraulic boundaries. These two sides were hence considered as flux boundaries.

9.2.4.1 Assigning River Boundary

The river Yamuna and the canal in the south-western portion of the study area were digitized in GIS environment. This digitized map was exported into visual MODFLOW and was used as a overlay to position the river grid cells. The river boundary was assigned based on the gauge data (collected from the field), various L sections and ground elevation data. The river boundary representing Yamuna from Kalanaur to Delhi, bordering the eastern part of the model area was assigned using the data of Central Water Commission (CWC). Gauge data at four locations namely, Kalanaur, Mawi, Bhagpat and Delhi Railway Bridge collected by CWC was used. After assigning river (eastern boundary) and canal boundary (some part of south- western boundary) all the cells falling outside this boundary were made inactive.

9.2.4.2 Flux Computation

Flux computation was carried out based on Darcy's equation Q = KIA, where Q is flow rate, K is hydraulic conductivity, I is hydraulic gradient and A is cross-sectional area. The area A was taken as the cell area computed using the width of the cell through which flux is applied and thickness (h or depth) of the layer. The hydraulic gradient I, was computed from the water table contour maps drawn using the data of CGWB. This was computed using the perpendicular distance between the contours and the contour interval. The observation wells falling outside the model area were also considered to get the hydraulic gradient. The average "K" value was computed using the Kx from the model cells. The flux was computed for northern boundary as well as for southern boundary for both phreatic and the confined aquifer.

These flux values were assigned as well (either recharge (positive flux) or discharge (negative flux)) in the northern and southern boundary cells. After assigning flux in the northern and southern boundary all the cells falling outside this (north of flux cells in northern part and south of flux cells in the southern part) were made inactive.

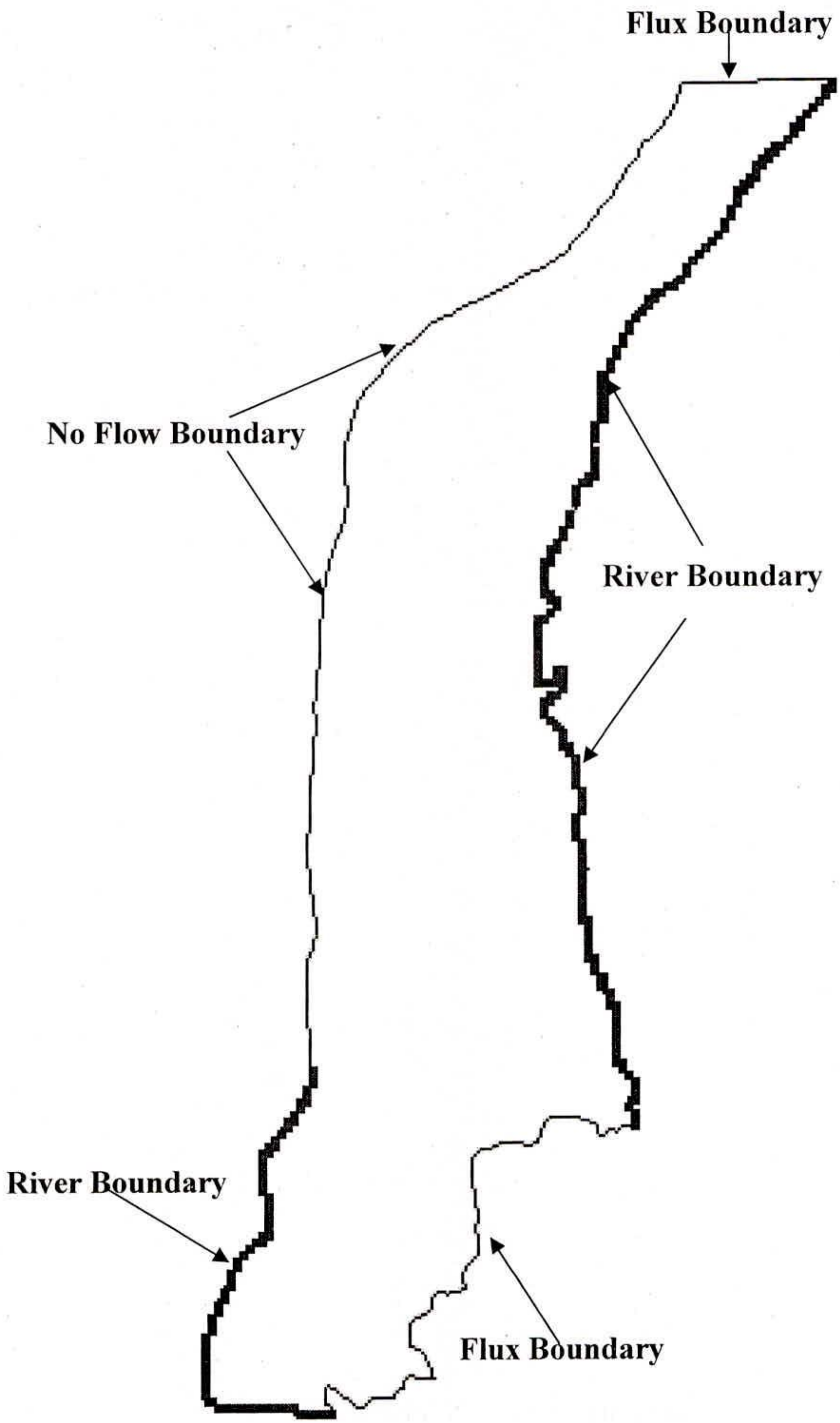


Fig. 11 Boundary conditions in the model

9.2.5 Initial conditions

To start the computations in the model, the initial ground water heads for various layers throughout the model area is to be known. The initial conditions for groundwater heads in the Aquifer I were derived from the groundwater observations well measurements taken in May, 2002. The data of CGWB and the Govt. of Haryana were used and the data file made as *.txt file. These point values were imported in to the Visual MODFLOW where they were interpolated for the grid points. The initial heads for the confining layer is assigned similar to that of the first layer. Originally, a set of confined aquifer hydraulic head measurements of May 2002, were utilized to derive the initial head condition for the confined aquifer (Layer-III). How ever as the data was inconsistent and sparse in spatial distribution, the initial conditions for the confined aquifer were assigned as that of the unconfined aquifer. The initial hydraulic heads in the unconfined aquifer vary from 200 m in the southern part of the model area to over 285 m along the northern boundary.

9.2.6 Model inputs

The model inputs include hydrogeological parameters, areal recharge, evaporation, groundwater abstraction and river influence.

9.2.6.1 Hydrogeological Parameters

The hydrogeological parameters defining each model layer are the horizontal hydraulic conductivity (Kx and Ky), the vertical hydraulic conductivity (Kz) and the storage coefficient (S). The storage coefficient for the unconfined aquifer is specific yield (Sy) and the storage coefficient for the confined aquifer is the product of the storativity (Ss) and the confined aquifer thickness.

Transmissivity and specific yield/storativity for aquifer I and II as determined under Upper Yamuna Project (Bhatnagar et al, 1982b) was used in assigning the hydraulic parameters to different layers. The values of hydraulic conductivity were computed by dividing the transmissivity value by thickness of the aquifer. The locations at which the hydraulic conductivity and specific yield are available for aquifer I are shown in Fig. 12 and its values are provided in Table 12. Similarly, the pump test sites for IInd aquifer are shown in Fig 13 and values of parameters are given in Table 13. These values are imported into Visual MODFLOW and then interpolated by inverse square distance method.

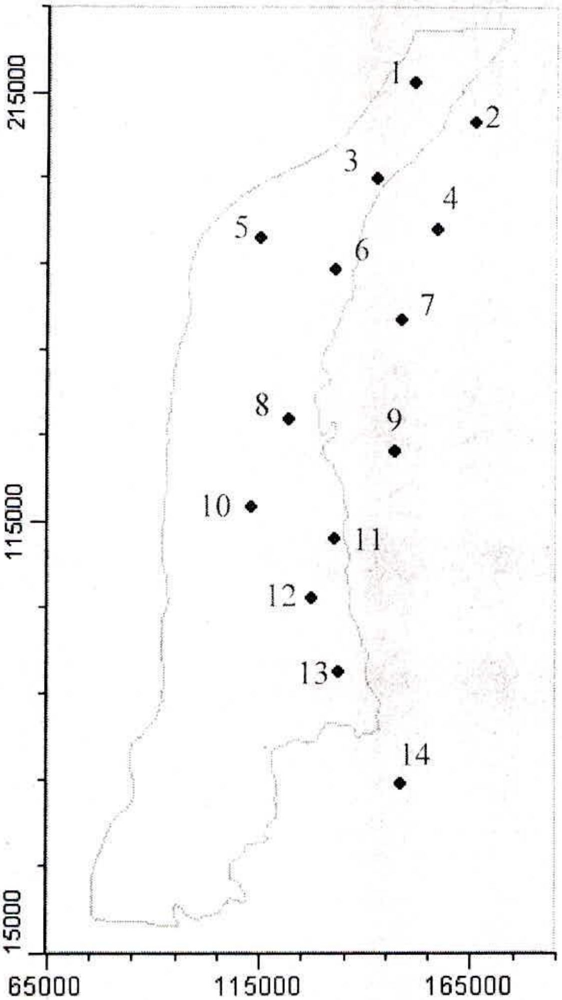


Fig. 12 Location of hydrogeological parameters in Aquifer I

Table 12 Hydrogeological parameters of Aquifer I

No	Kx (m/day)	Specific Yield	No	Kx (m/day)	Specific Yield
1	31.0	0.021	8	8.75	0.095
2	15.4		9	17.0	0.059
3	16.1		10	17.0	0.07
4	14.0	0.13	11	40.0	0.24
5	20.3	0.028	12	19.5	
6	16.0		13	36.3	0.215
7	31.75	0.18	14	47.1	0.17

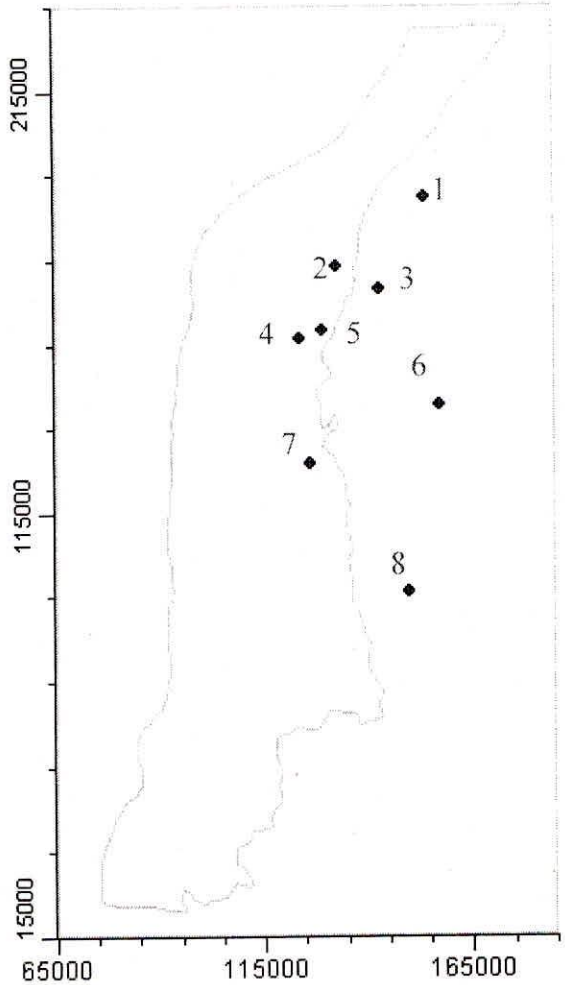


Fig. 13 Location of hydrogeological parameters in Aquifer II

Table 13 Hydrogeological parameters of Aquifer II

No	Kx (m/day)	Storativity (1/m)
1	10.7	0.000006
2	9.4	0.000035
3	7.0	0.000007
4	4.4	0.000007
5	8.1	0.000008
6	9.15	0.000007
7	3.95	0.000011
8	6.85	0.000008

The vertical hydraulic conductivity of aquifer I was taken as 0.15 m/day as reported in UYP reports, whereas for aquifer II, it was taken as 1/10 times of the horizontal hydraulic conductivity of that aquifer. The hydraulic conductivity (both horizontal and vertical) of second layer was taken as 0.0002 m/day as reported in UYP reports.

9.1.6.2 Evaporation Data

The pan evaporation data was first compiled month-wise for the period June, 2002 to May 2005. A pan coefficient of 0.7 was used to get the evaporation for pan evaporation. The resulting values are assigned to the model layer 1.

9.2.6.3 Recharge Data

Recharge to groundwater in the study area is taking place from rainfall, canals, irrigation, water conservation structures, lakes and ponds, if exist any. The rainfall data for the period June 2002 to May 2005 was first compiled to get the rain fall as monsoon (June-Sept) and non-monsoon rain fall for each year. The Rainfall Infiltration Factor (R.I.F) of 22% as used in the Groundwater Estimation Report of CGWB, North Western Region, Chandigarh (CGWB, 2005) is used to compute monsoon and non-monsoon rain fall recharge for each block. Recharge from other sources such as canals, surface water irrigation, groundwater irrigation, water conservation structures, lakes and ponds were also compiled monsoon and non-monsoon wise from the CGWB Groundwater Estimation Report. The rain fall recharge (monsoon and non-monsoon) and recharge from other sources (monsoon and non-monsoon) were summed up to get the block wise total groundwater recharge in monsoon and non-monsoon period. This data was assigned selecting each block and assigning two values for monsoon and non-monsoon for each of the three years 2002-2005.

9.2.6.4 Assigning River Boundary for Canals to Account Recharge

Major canals and drains are simulated in the model to account for their recharge/discharge to the ground water system. The recharge from minor canals was considered in areal recharge as reported under recharge data above. The WYC canal, the augmentation canal, Delhi parallel/Delhi branch (up to Delhi) and part of the Jawaharlal Nehru feeder was simulated in the model using the river boundary option as these must be contributing to recharge of ground water. These canals were digitized in GIS environment and imported into Visual MODFLOW as an overlay to assign river grid cells. The required data were assigned based on the gauge data (collected from the field), various L sections and ground elevation data available. The drains as digitized earlier were simulated in the model as river with water column as 0.5 m.

10.2.6.5 Groundwater Abstraction Data

Groundwater Estimation Report of CGWB, NWR, Chandigarh (CGWB, 2005) provides information on the number of groundwater abstraction structures and their pumping rate for each block. Based on this data, the report provides the groundwater draft from each block for monsoon and non-monsoon period considering 33% of total annual draft in monsoon and 67% in non-monsoon for domestic purposes and 45% in monsoon and 55% in non-monsoon for agriculture requirement. From this the actual pumping rate (m^3/day) in the monsoon and non-monsoon period for each block was computed. A FORTRAN program was then developed and the water withdrawn from each block was divided uniformly among the grids falling in that block. The depth of the screen of these wells (block wise) was decided based on successful depth of the private wells as compiled from District Atlas of Ground water Cell of the Govt. of Haryana. The example of the ASCI file generated from the program is given below.

				Screen		Time	Discharge
Well No.	X	Y	Well No	Top	Bottom	Days	m^3/day
W0001	152500	229500	W0001	286.00	276.00	122	-766.48
W0001	152500	229500	W0001	286.00	276.00	365	-470.33
W0002	153500	229500	W0002	288.00	278.00	122	-766.48
W0002	153500	229500	W0002	288.00	278.00	365	-470.33
W0003	154500	229500	W0003	288.00	278.00	122	-766.48
W0003	154500	229500	W0003	288.00	278.00	365	-470.33
W0004	155500	229500	W0004	289.33	279.33	122	-766.48
W0004	155500	229500	W0004	289.33	279.33	365	-470.33
W0005	156500	229500	W0005	289.33	279.33	122	-766.48
W0005	156500	229500	W0005	289.33	279.33	365	-470.33
W0006	157500	229500	W0006	289.33	279.33	122	-766.48

This file is then imported in the Visual MODFLOW in Pumping Well option using the File-Import and then the data were verified for the screen and withdrawal of ground water through these wells assigned in each cell.

9.3 Observation Wells

A total of 29 observation (20 in aquifer I and 9 in aquifer II (Fig. 14)) wells were selected for calibration of the model. The required data was first compiled in Microsoft Excel sheets and then was saved as .txt file. This data file was then imported in to observation well option of the Visual MODFLOW. These imported values are then checked (using Edit option) for verification of data and screen position with respect to G.L. (Some minor modification of screen position was done in case of Karnal to match the realistic value of R.L of CGWB.).

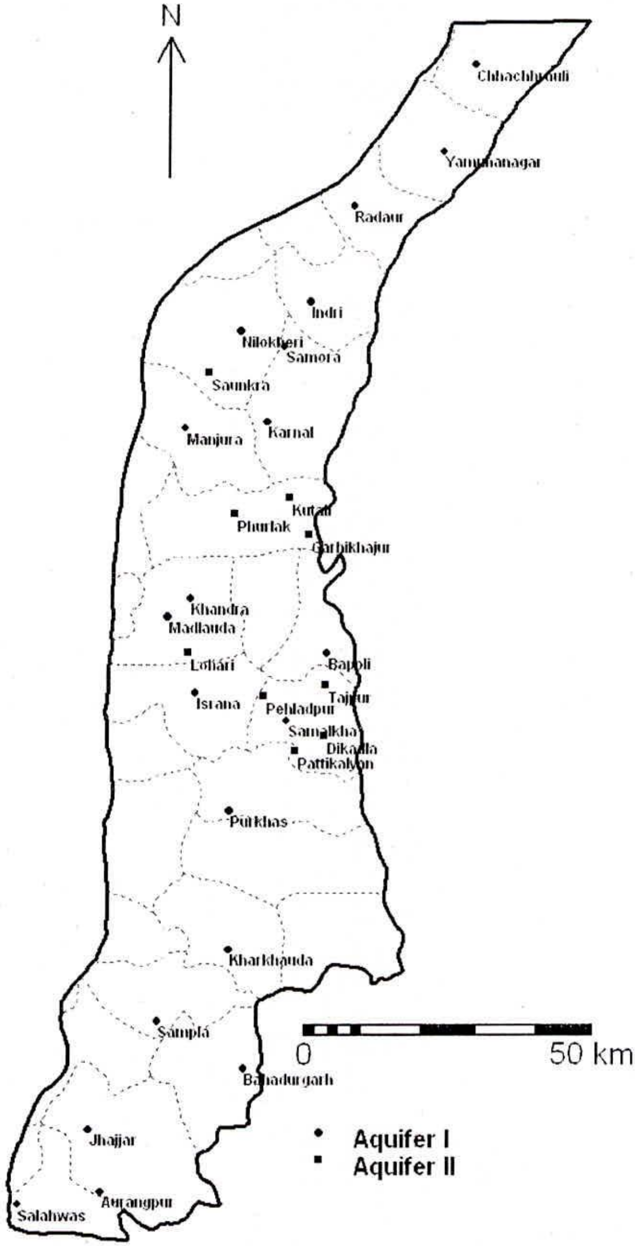


Fig. 14 Location of observation wells in aquifer I and II used in calibration

9.4 Model Running

The model was run keeping the PCG2 (Pre-conditioned Conjugate Gradient) package as solver and Layers as

Layer-I as Unconfined ("1")
Layer-II as Confined/Unconfined ("2") (Confining layer, with some clay and sand layer)
Layer-III as Confined/Unconfined ("2") (Aquifer-II, Confined/ Semi-confined)

PCG2 solver was run with maximum outer and inner iterations as 25 and 10, respectively. The head change and residual criteria for convergence was kept as 0.01m and $0.01 m^3/sec$, respectively.

9.5 Model Calibration

The main purpose of the model is to predict the future situations and for that it is essential to establish that the model can reproduce field-measured heads and flows. Calibration refers to demonstration that the model is capable of producing field measured heads and flows. Model calibration is the process whereby selected model input parameters are adjusted within reasonable limits to produce simulation results that best match the known measured values. Model calibration is the most critical process in building the ground water flow model. The acceptability of model's calibration is usually a subjective measure because each model has different objective and must be calibrated to different conditions. How ever there are some generally accepted methods of evaluating and interpreting the model calibration using both qualitative and quantitative measures. In this study, the scatter plot between simulated and observed groundwater heads and the comparison between the observed and simulated contour map of groundwater levels were used as qualitative measures. The simulated and observed groundwater heads were compared quantitatively by calculating maximum, minimum and mean error, absolute mean error, standard error of estimate, root mean square error and normalized root mean square error. These values are calculated by using following equations.

The Mean Error (ME) is a measure of the average Residual value defined by the equation:

$$\text{ME} = \overline{E} = \frac{1}{n}\sum_{i=1}^{n} E_i$$

where, $E = (X_{cal} - X_{obs})$, X_{obs} is the observed value, X_{cal} is the calculated value for a data series and n is the total number of observations. The Absolute Mean Error (AME) is similar to the mean error except that it is a measure of the average absolute error value defined by the equation:

$$\text{AME} = \left|\overline{E}\right| = \frac{1}{n}\sum_{i=1}^{n} \left|E_i\right|$$

The Standard Error of the Estimate (SEE) is a measure of the standard deviation of the estimate and is expressed by the equation:

$$SEE = \sqrt{\frac{\frac{1}{n-1}\sum_{i=1}^{n}\left(E_i - \overline{E}\right)}{n}}$$

The root mean squared error (RMSE) is defined by the equation:

$$RMSE = \frac{1}{n}\sqrt{\sum_{i=1}^{n} E_i^2}$$

The Normalized Root Mean Squared Error (NRMSE) is the RMSE divided by the maximum difference in the observed head values and is expressed by the equation:

$$NRMSE = \frac{RMSE}{(X_{obs})_{\max} - (X_{obs})_{\min}}$$

The NRME is expressed as a percentage and is a more representative measure of the fit than the standard RMS because it accounts for the scale of the potential range of data values.

The model was calibrated using initial input data under steady and transient state. The aquifer condition of May 2002 was considered as the initial condition. MODFLOW-2000 allows individual stress periods in a single simulation to be either transient or steady state instead of requiring the entire simulation to be either steady state or transient. Steady-state and transient stress periods can occur in any order. Commonly the first stress period is steady state and produces a solution that is used as the initial condition for subsequent transient stress periods. Accordingly, the first stress period was run under steady condition. For this period, average values of recharge and pumping are assigned to the model. The transient simulation was run with first stress period under steady state condition and as such the transient simulation started from stress period 2 and completed after 37 stress period. The calibration process was made using a trial and error procedure.

The model was run initially several times under steady state condition by rectifying the errors of assigning data etc. After running the model for steady state the draw down, heads and the flow path etc were evaluated and the result was found to be satisfactory and the flow was also found to be logical. The model was run for transient state and the trends of the individual hydrographs of CGWB were also found to be very much tallying with the observed values in a number of cases.

However, the model was first calibrated for steady state before proceeding further. For this, the Model was run for steady state and the calibration of heads in Layer-I and Layer-III was attempted using the calculated Vs observed head plot. The observation points where greater error was noticed (like Chhachhrauli, Madlauda, Israna) were analyzed. The reasons explored and several runs were carried out trying with some minor changes around the area. The water level of Chhachrauli observation well was rectified to tally with the surface elevation. Initially, some modifications were made in the assigned values of hydraulic conductivity in some parts of the model area. Then modifications were made in recharge and pumping rates. The result was noted by running the model with each modification and the decisions were taken based on the justification of the real field conditions. This process takes a lot of time as the decision of fine tuning is to be taken based on the scientific ground, field conditions and experience. After achieving some calibration on regional scale, the wells calibration was taken up one by one and some fine tuning of the parameters were undertaken. The resultant scatter plots of the goodness of fit between observed and simulated heads are presented in Fig. 15 for aquifer I and II. The simulated and the observed groundwater heads for steady state condition is given in Fig. 16.

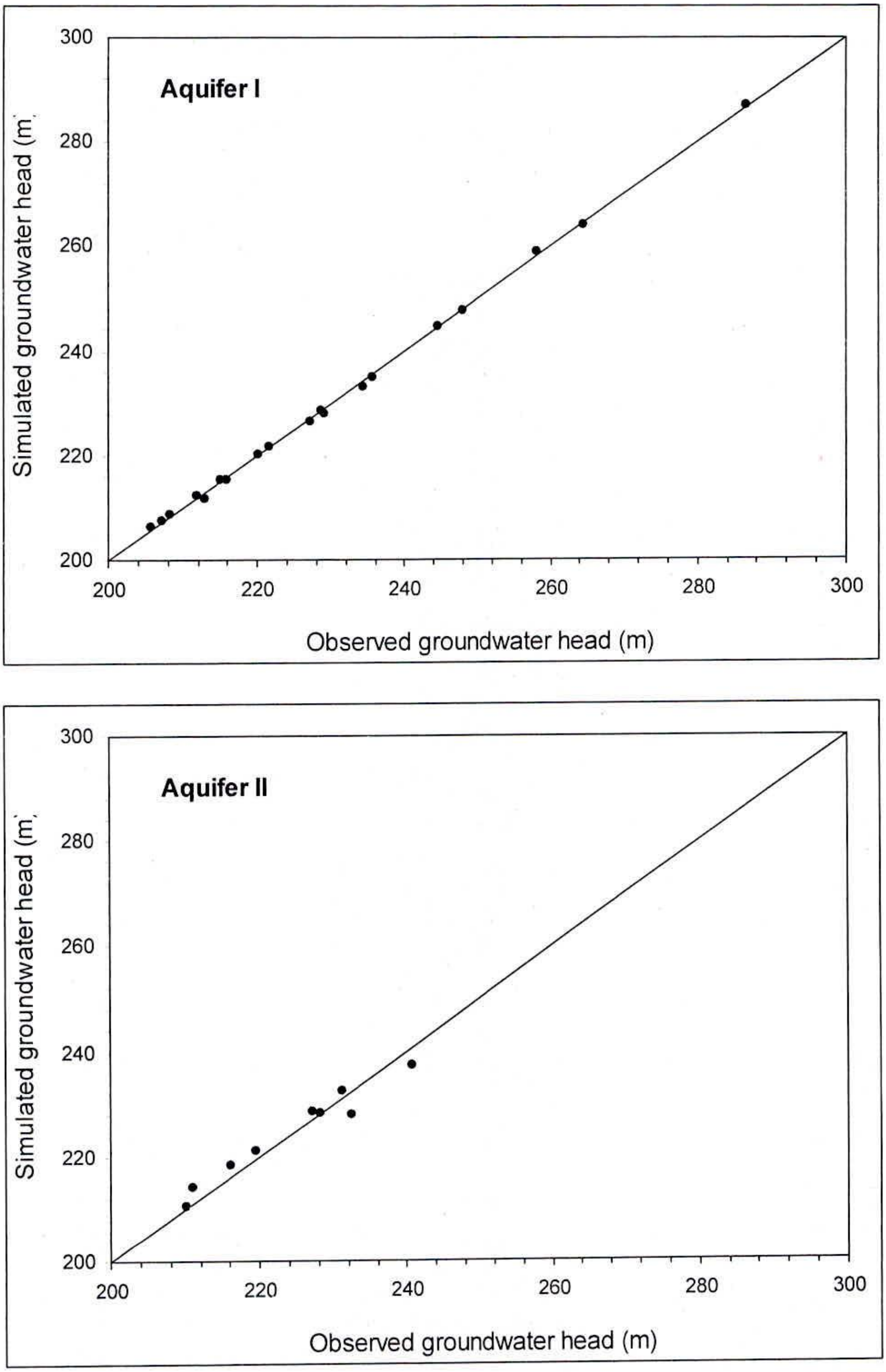


Fig. 15 Scatter plot of simulated and observed groundwater levels for steady state

Fig. 16 Simulated and observed groundwater heads for aquifer I for steady state

The mean error between simulated and observed heads, ideally zero for all the aquifers, was found to be close to zero. The absolute mean error and root mean square error was low, which indicates that the model was well calibrated (Table 14).

The steady state calibration was continued and then preceded with running the model for transient state. This has also involved hundreds of run of the model and the fine tuning of parameters as done in the case of steady state condition to ultimately achieve the goal of simulating the field condition.

Table 14 Summary of calibration error for aquifer I

Time	Error (m)				SEE	RMSE	NRMSE
	Max	Min	Mean	Abs. Mean	(m)	(m)	(%)
Steady State	-1.26	0.02	-0.10	0.45	0.13	0.57	0.71
August02	1.84	-0.02	0.37	0.54	0.14	0.71	0.86
May03	1.53	-0.02	0.10	0.32	0.10	0.47	0.57
August03	-1.00	-0.03	-0.07	0.41	0.11	0.49	0.60
May04	1.12	-0.01	0.02	0.34	0.10	0.46	0.57
August04	1.14	0.03	0.16	0.33	0.10	0.46	0.57
May05	-1.91	-0.03	-0.36	0.66	0.17	0.82	1.02

The scatter plots of simulated and observed groundwater heads for August 2002, May 2003, August 2003, May 2004, August 2004 and May 2005 are shown in Fig. 17. The simulated and observed groundwater levels for the same periods for aquifer I are shown in Fig. 18. Fig. 19 shows the observed and simulated groundwater level hydrographs at all observation wells in aquifer I. As seen the quality of calibration varies from one observation well to another. The quantitative results of comparison of observed and simulated results are provided in Table 14 for aquifer I. This table also indicates good calibration for aquifer I. The observed and simulated groundwater head hydrographs for aquifer II (model layer 3) is shown in Fig. 20 and the quantitative results in Table 15. Fig. 20 indicates that the simulated heads are higher than the observed heads at some points and are lower than the observed heads at other points. As seen from both of these results, the calibration is not as good as required. But in the absence of sufficient data for aquifer II, the results were considered good. The simulated groundwater levels does not show the fluctuations as seen in observed heads but it simulates the falling trend in groundwater levels over a period of three years. In the developed model, it was considered (as no data was available) that there was no pumping from aquifer II, but from the groundwater hydrograph it looks that some pumping is also taking place from this aquifer.

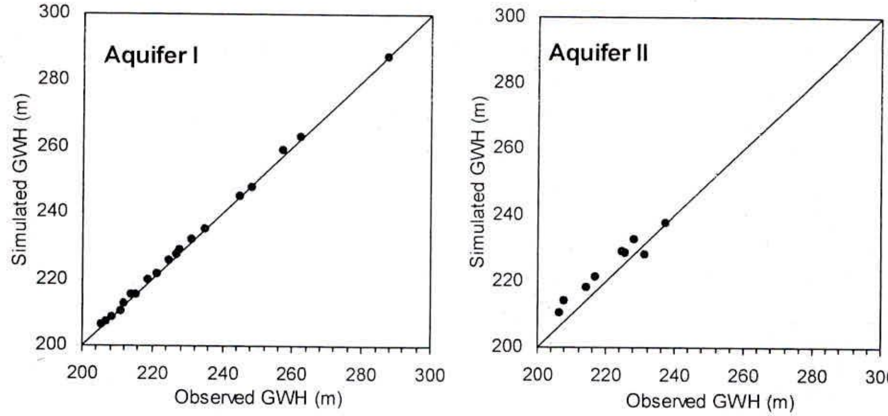


Fig.17(a) Scatter plot of simulated and observed groundwater levels (Aug 2002)

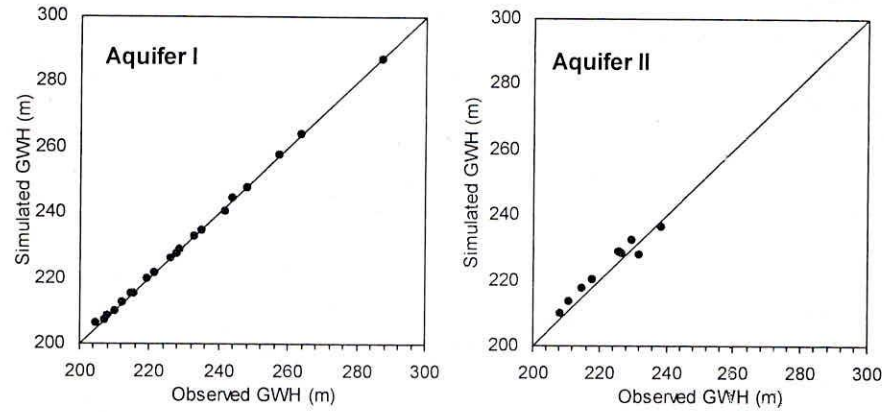


Fig. 17(b) Scatter plot of simulated and observed groundwater levels (May 2003)

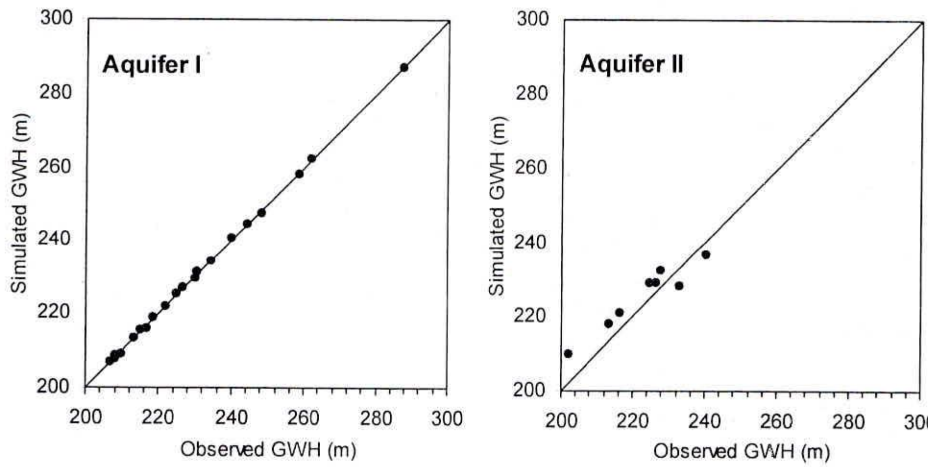


Fig. 17(c) Scatter plot of simulated and observed groundwater levels (Aug 2003)

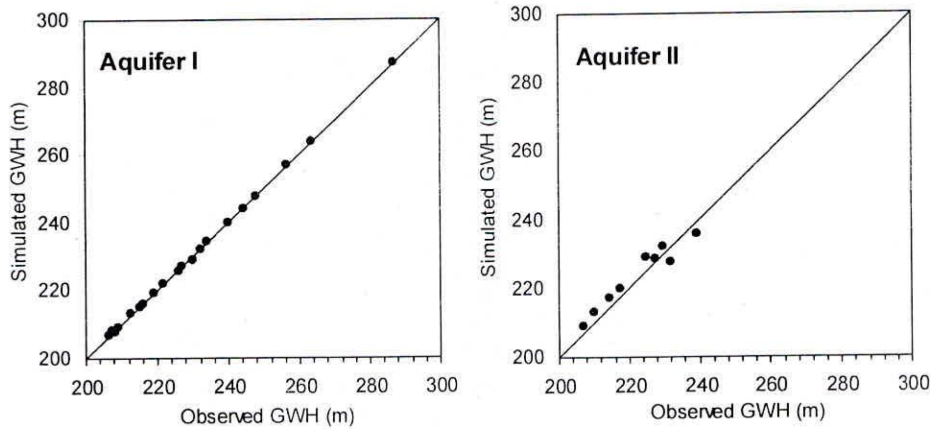


Fig. 17(d) Scatter plot of simulated and observed groundwater levels (May 2004)

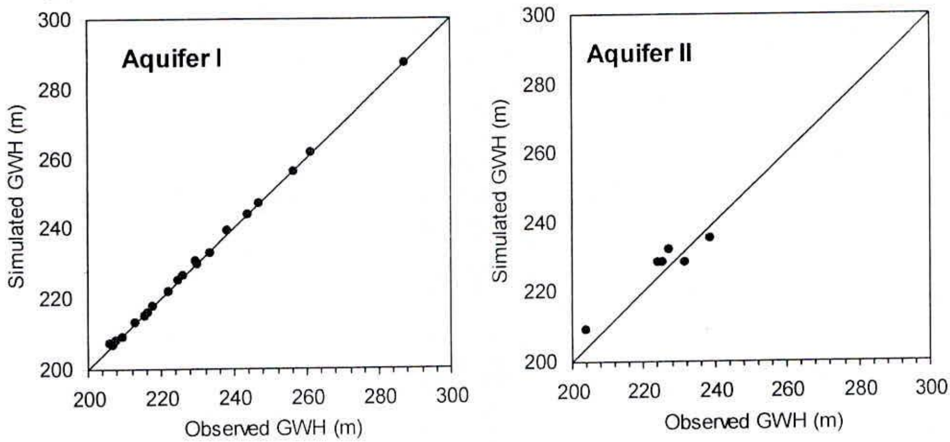


Fig. 17(e) Scatter plot of simulated and observed groundwater levels (Aug 2004)

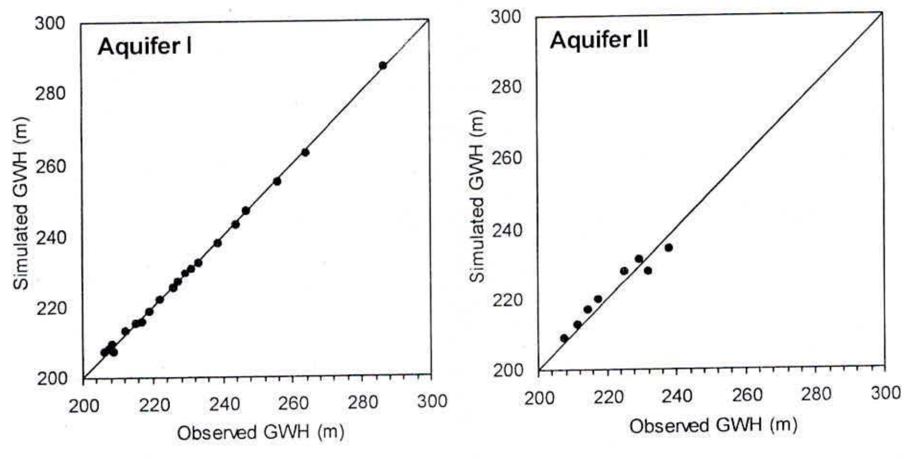


Fig. 17(f) Scatter plot of simulated and observed groundwater levels (May 2005)

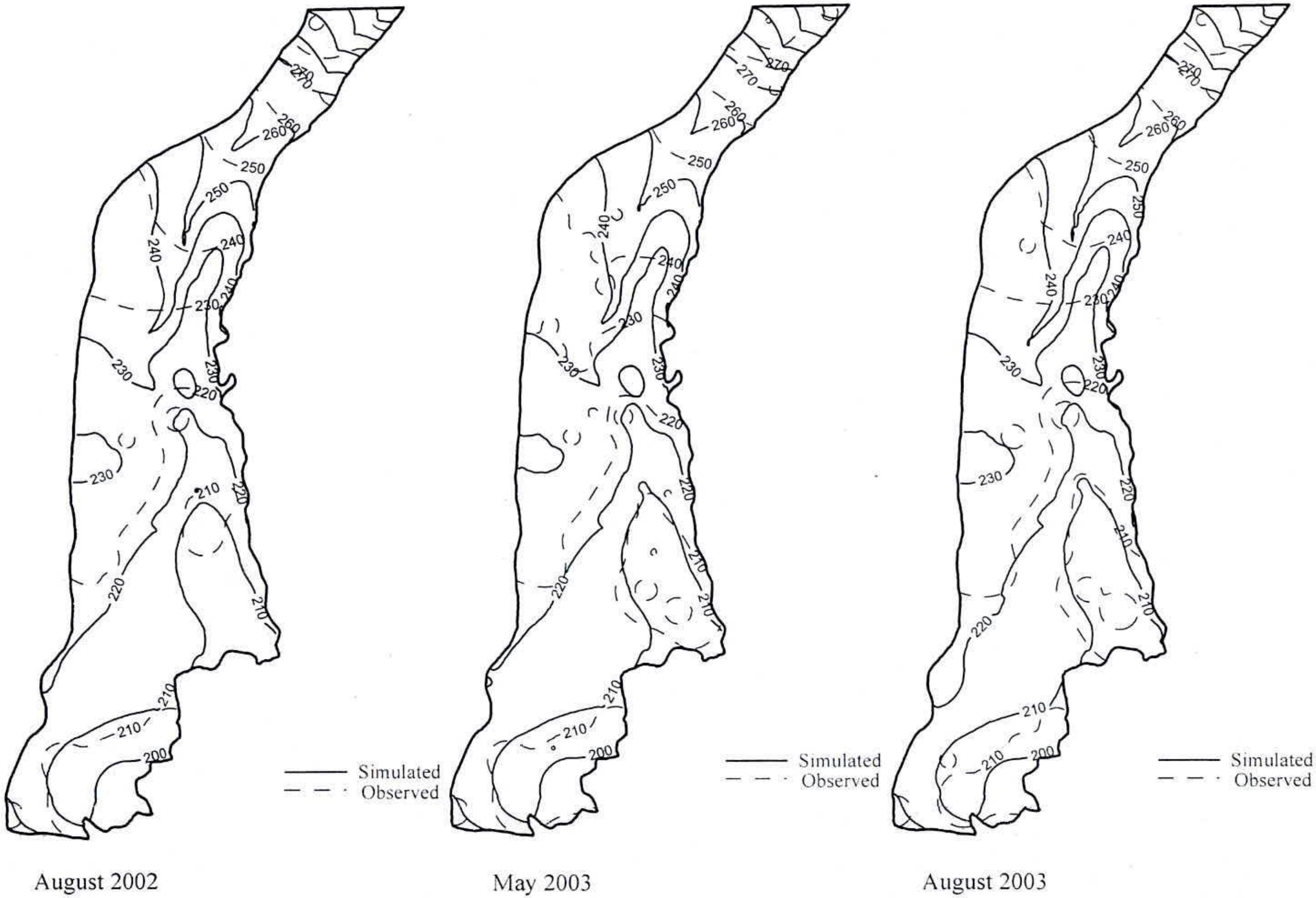


Fig. 18 (a) Simulated and observed groundwater heads for aquifer I

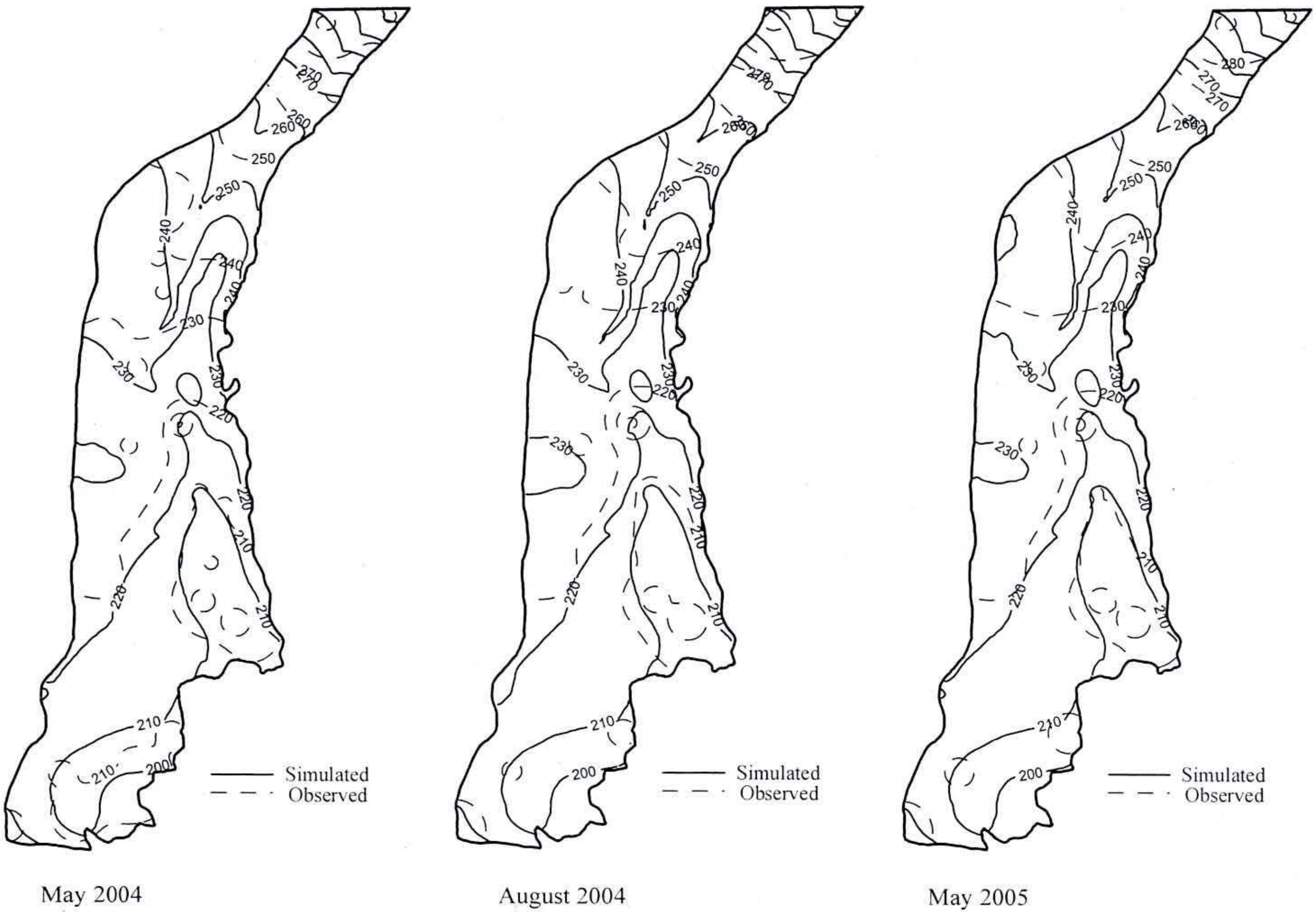


Fig. 18(b) Simulated and observed groundwater heads for aquifer I

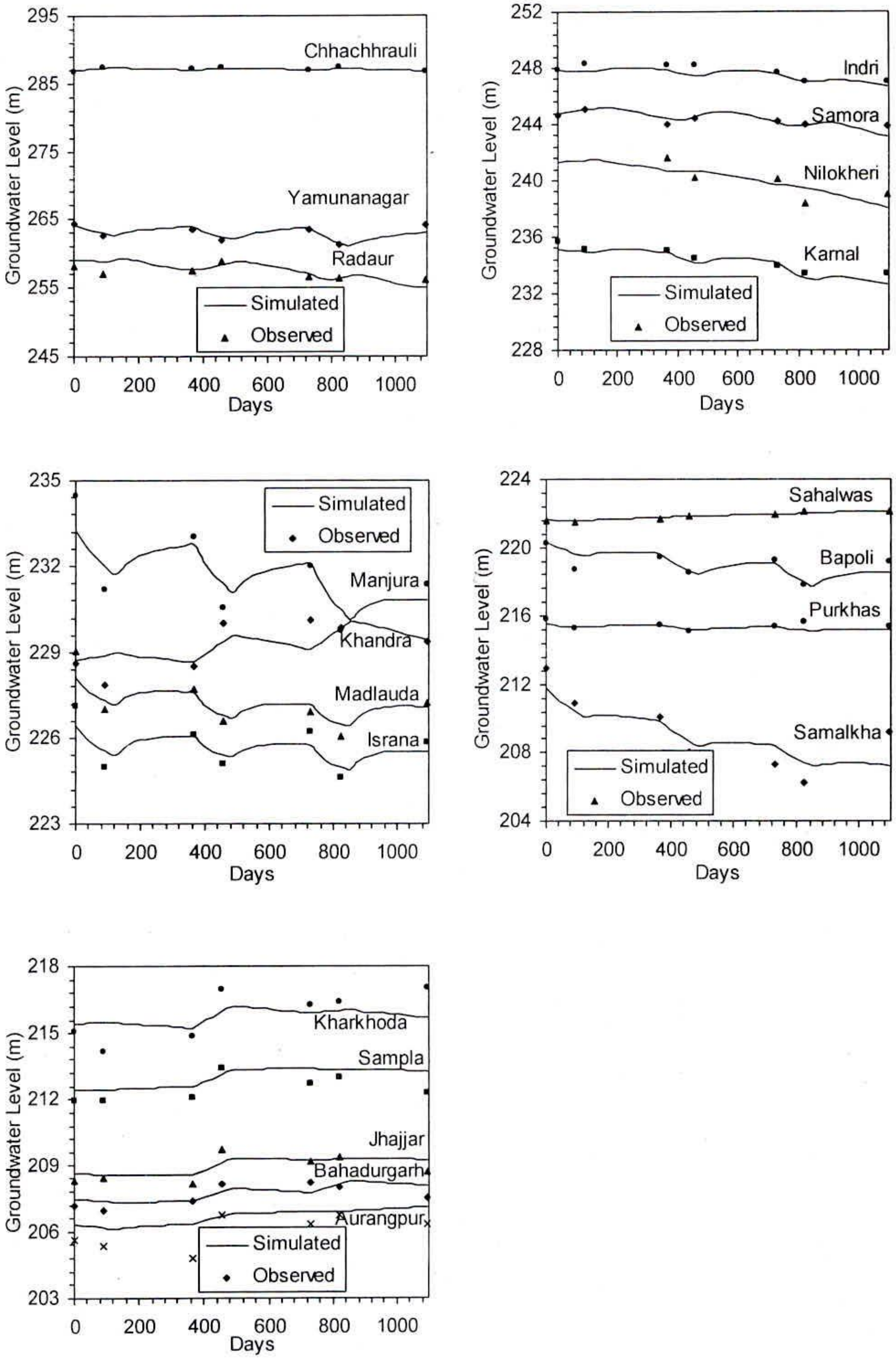


Fig 19 Observed and simulated groundwater level hydrographs for Aquifer I

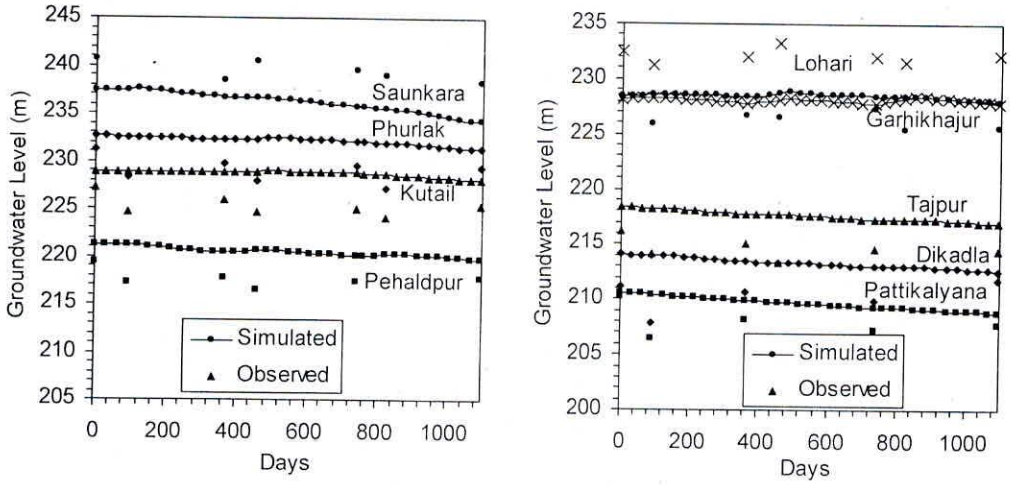
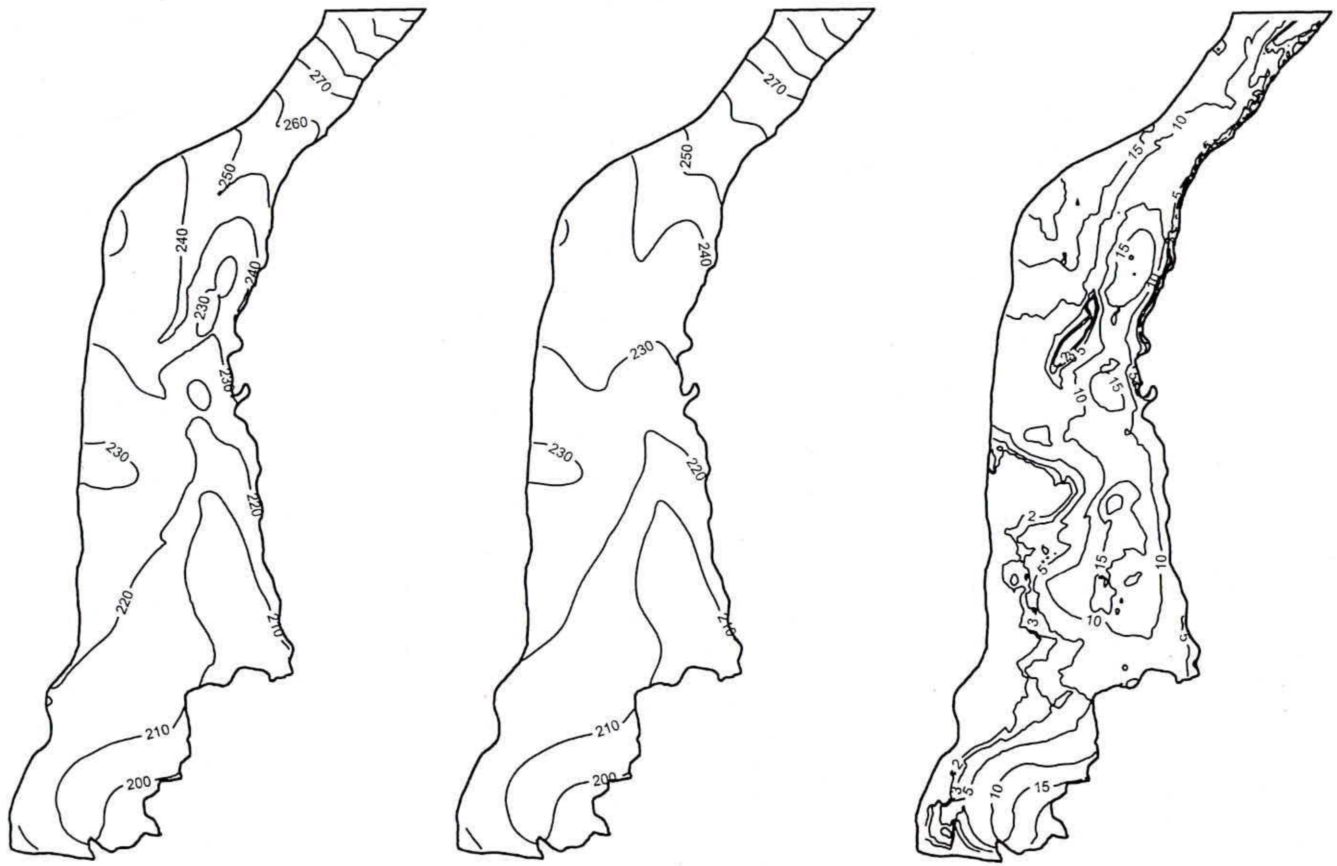


Fig 20 Observed and simulated groundwater level hydrographs for Aquifer II

Table 15 Summary of calibration error for aquifer II

Time	Error (m)				SEE (m)	RMSE (m)	NRMSE (%)
	Max	Min	Mean	Abs. Mean			
Steady State	-4.26	0.12	0.30	1.99	0.83	2.36	7.78
August02	6.06	0.01	2.89	3.57	0.92	3.90	12.58
May03	-4.12	1.7	1.22	2.53	0.82	2.63	8.68
August03	7.57	2.2	2.32	4.29	1.37	4.52	11.88
May04	-4.31	1.16	1.09	2.88	0.99	3.02	9.35
August04	5.36	2.6	2.10	3.6	1.08	3.73	10.62
May05	-4.3	0.85	0.57	2.45	0.93	2.69	8.77

Fig. 21 presents the simulated groundwater table contour maps of aquifer I and II and the contour map of the groundwater depth of aquifer I for May 2005. As per the simulated groundwater model of May 2005, an area of 13%, 18%, 29%, 61%, 87%, 98% and 100% of the modeled area falls under 2m, 3m, 5m, 10m, 15, 20m, and 25m groundwater depths below ground level, respectively. These figures and results are used for comparison with figures and results of various scenario created.



Groundwater table (Aquifer I) | Groundwater table (Aquifer II) | Depth to groundwater level (Aquifer I)

Fig. 21 Simulated groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2005

9.6 Groundwater Balance

The groundwater budget of the entire study area for steady state (stress period 1) and end of calibration period (May 2005, stress period 37) obtained from the groundwater flow model is presented in Table 16. The steady state total water budget over the entire aquifer shows a balance between inflows and outflows of water, which is consistent with the steady state modelling hypothesis.

The steady state groundwater balance shows that the groundwater inflow from the recharge (rainfall and other sources like irrigation, lakes, ponds etc) supplies the model area with most of its water. This amounts to 4.94 MCM, or about 62% of the total input to the aquifer. A second important source of water is the river leakage. However, the total amount of river leakage is much less than the groundwater inflow from the recharge. The river leakage amounts to only 2.97 MCM, which only represents 37% of the total inflow of water in the aquifer on average. There is small amount of recharge (0.08 MCM, about 1%) through flux boundaries. The main outputs of water from the aquifer are groundwater abstraction by pumping wells. The groundwater abstraction by wells amounts on average to 7.73 MCM, which represents about 97% of the total outflow. Output of water through river leakage and evapo-transpiration is rather small compared to the abstraction by wells, i.e. on average only 0.26 MCM, or 3% of the total outflow.

Table 16. Groundwater budget achieved from the groundwater flow model

Water Balance Term		Steady State (Stress Period 1)	End of Calibration (Stress Period 37)
Model Inflow (MCM)	Storage	0.0	1475.52
	Wells (Flux)	0.08	81.66
	River leakage	2.97	3155.96
	Recharge	4.94	5810.61
	Total	7.99	10523.75
Model Outflow (MCM)	Storage	0.00	882.35
	Wells	7.73	9299.65
	River leakage	0.11	161.95
	ET	0.15	179.81
	Total	7.99	10523.76
Inflow-outflow (MCM)		0.0 (0 %)	-0.01 (0 %)

9.7 Testing of Various Scenarios

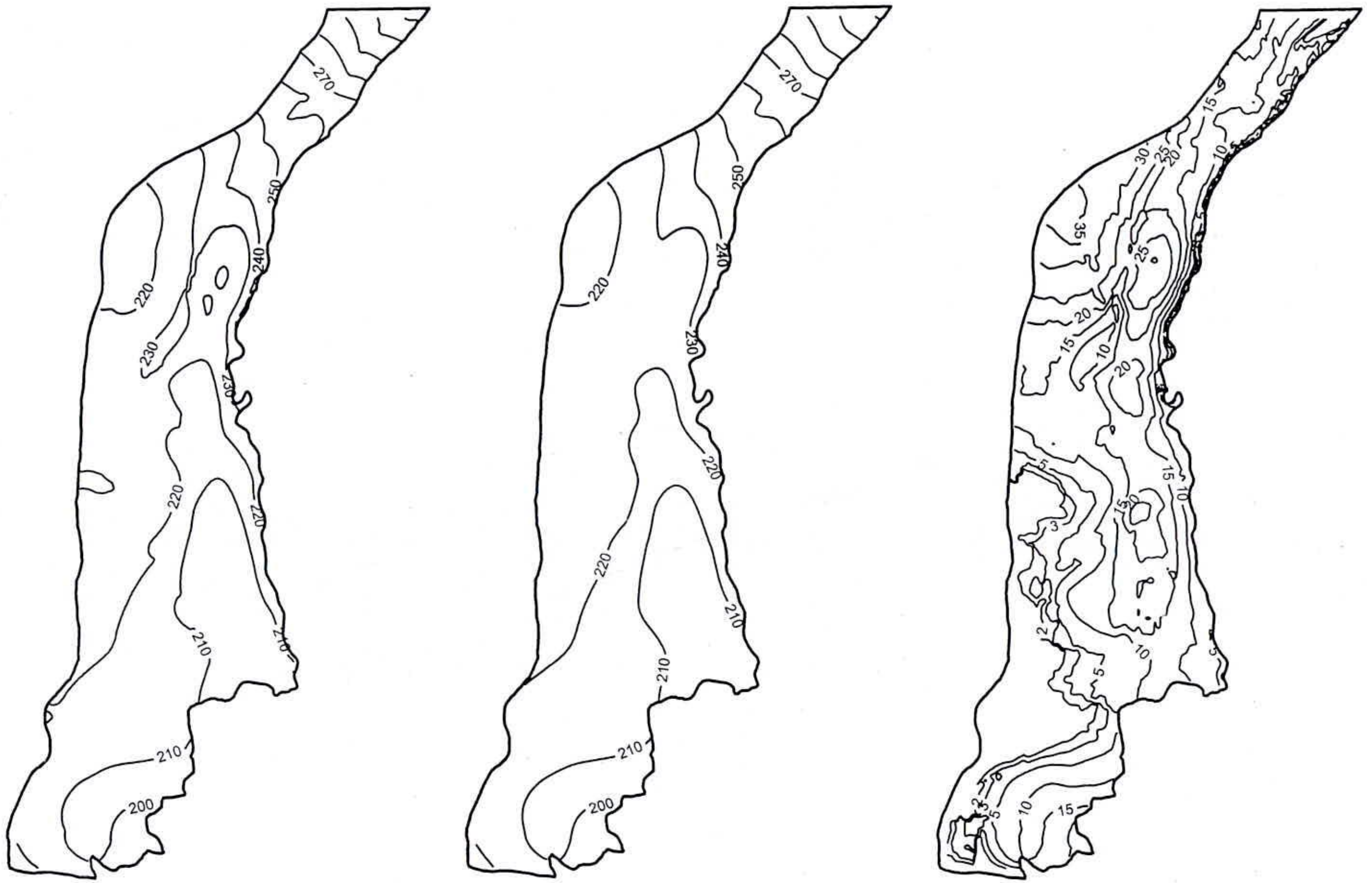
The study area faces the problem of declining water level in some area and water logging (rising water level) in some other areas. The north and central part of the study area covering the districts of Yamunanagar, Karnal, Panipat and Sonipat are generally facing declining groundwater levels and southern part covering Rohtak and Jhajjar districts experiences rising groundwater levels. Almost 50% of the blocks falling in the study area are already under over-exploited category. Overall, the phreatic aquifer (Layer 1) showed over-development. The decreasing groundwater levels can be arrested by reducing the pumping from such area and the problem of waterlogging can be decreased by pumping more water from such area. The semi-confined aquifer (Layer III) is to be tested for sustainability if the water is to be withdrawn from this aquifer, in lieu of pumpage from phreatic aquifer.

Keeping the above points in view, various future scenarios were created and tested for next 10 years (2005-2015) by running the calibrated model. The average values of three years (2002-2005) of recharge and river stages were calculated and used for future scenarios.

9.7.1 Scenario I

In this Scenario, the existing groundwater pumping conditions were allowed to continue for next ten years. The model results indicated deterioration in ground water regime in the study area. The groundwater table declined further in the already declining water level area. The resulting groundwater level contour maps of both the aquifers are shown in Fig. 22. Fig. 22 also shows the contour map of the depth to groundwater level of phreatic aquifer. Comparison of these maps with respective maps of year 2005 indicates that there is decline in groundwater level in north and central part of the study area but not much change in southern part.

The area falling in different depth below ground level (in percentage) is given in Table 17 along with the respective area in year 2005. This table indicates that there is not much change in the waterlogged/prone to waterlogging area but the area falling under <10m depth has reduced from 61% to 44%. Similar decrease was noticed for other depths also. The maximum depth of groundwater in the study area which was about 25m in year 2005 has gone upto 37m.



Groundwater table (Aquifer I) Groundwater table (Aquifer II) Depth to groundwater level (Aquifer I)

Fig. 22 Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario I)

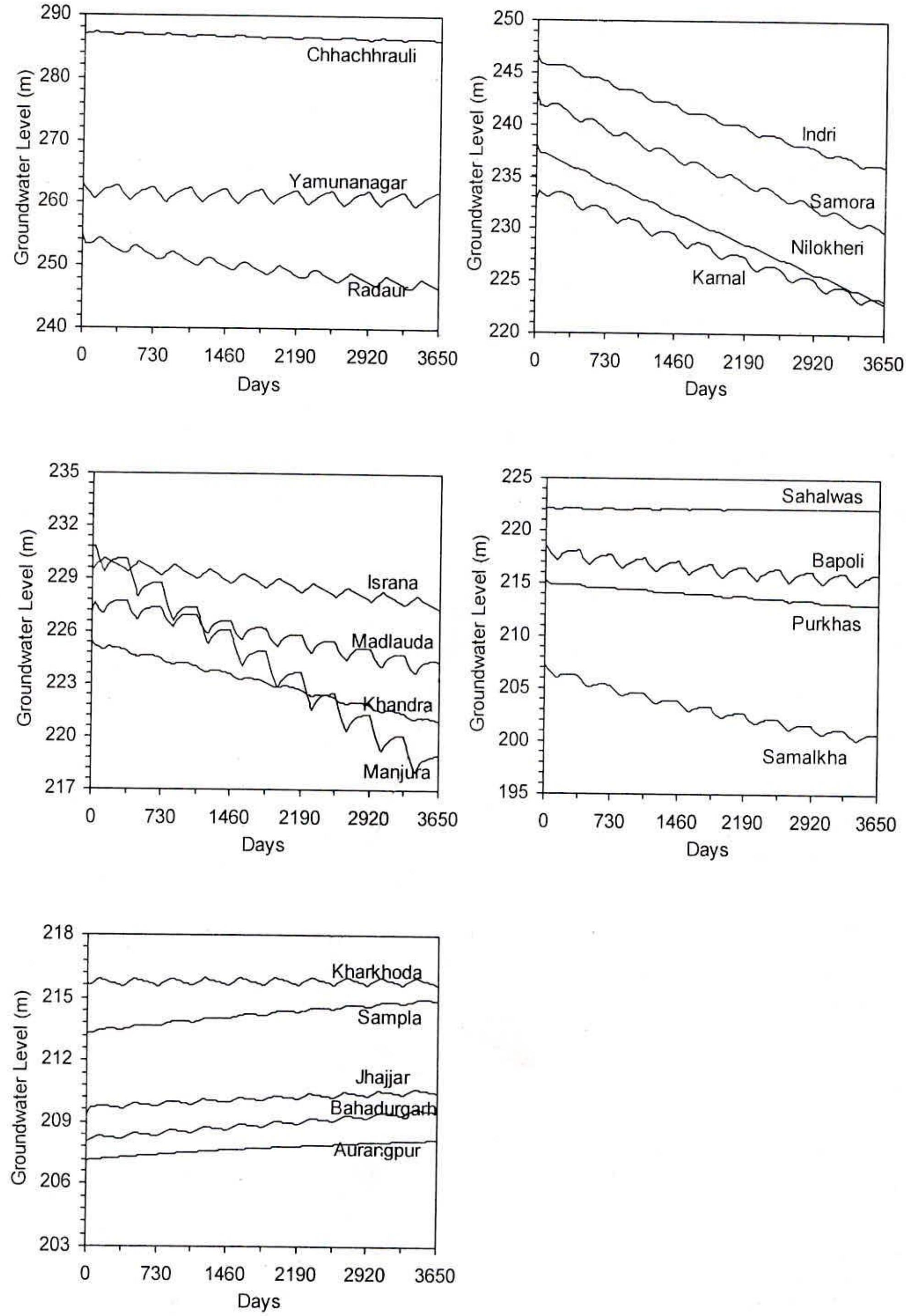


Fig. 23. Predicted groundwater level hydrographs for Aquifer I (Scenario-I)

Table 17. Area (%) falling under different groundwater depths (Scenario I)

Groundwater Depth below Ground Level	2005	2015
2 m	12.8	12.8
3 m	18.2	17.6
5 m	28.6	25.9
10 m	61.1	43.7
15 m	87.0	65.6
20 m	98.5	82.2
25 m	100.0	90.2
30 m		95.5
35 m		99.0
40 m		100.0

Thus, there is overall deterioration in the ground water scenario in the whole area. The simulated groundwater hydrograph at different observation wells in aquifer I and II are shown in Fig. 23 and 24, respectively. These graphs also indicate declining groundwater levels at most of the wells. The groundwater level in wells namely Chhachhrauli, Yamunanagar, Radaur, which are located in the northern part of the study area, show no/little trend, whereas groundwater level in wells Indri, Samora, Nilokheri, Karnal, Israna, Madlauda, Khandara, Manjura, Bapoli, Purkhas,and Samalkha, which are located in the central part of the study area show decling trend. The wells located in the southern part of the study area namely, Kharkhoda, Sampla, Jhajjar, Bahadurgarh, Aurangpur show rising groundwater levels over the years. The wells in the second aquifer also show decling groundwater levels.

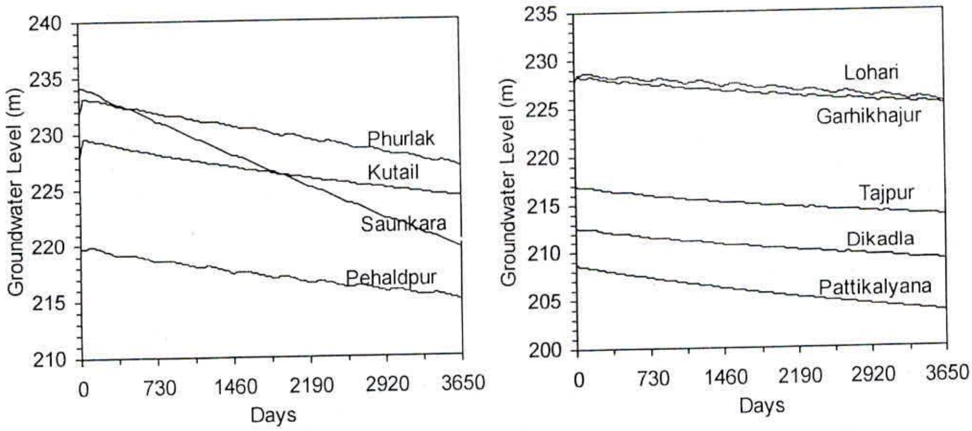


Fig. 24. Predicted groundwater level hydrographs for Aquifer II (Scenario I)

9.7.2 Scenario II

The pumpage from the phreatic aquifer is reduced by the following given percentages for whole of the study area to observe the ground water behaviour in the year 2015.

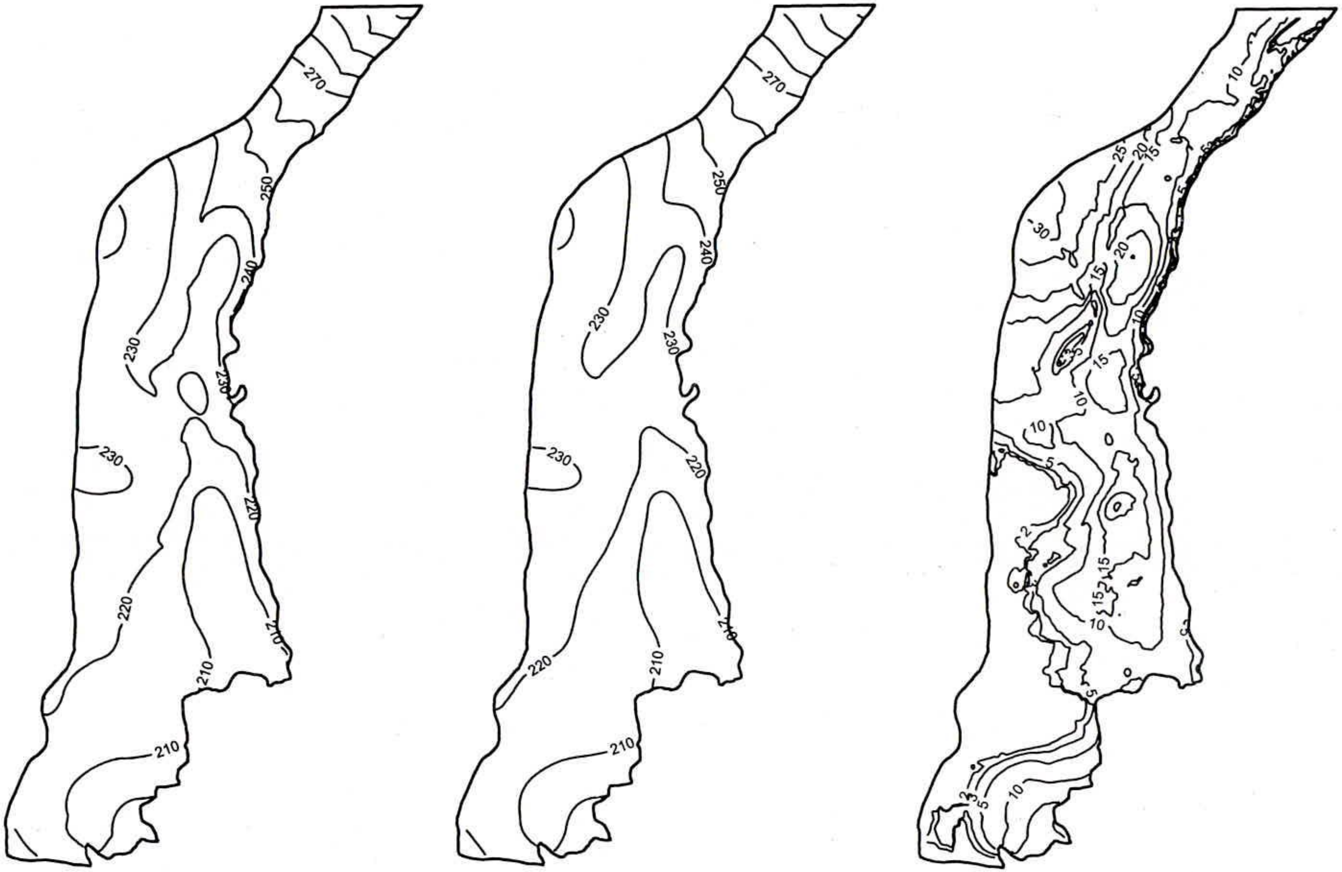
(A) Decrease in pumpage by 10%

(B) Decrease in pumpage by 20%

(C) Decrease in pumpage by 30%

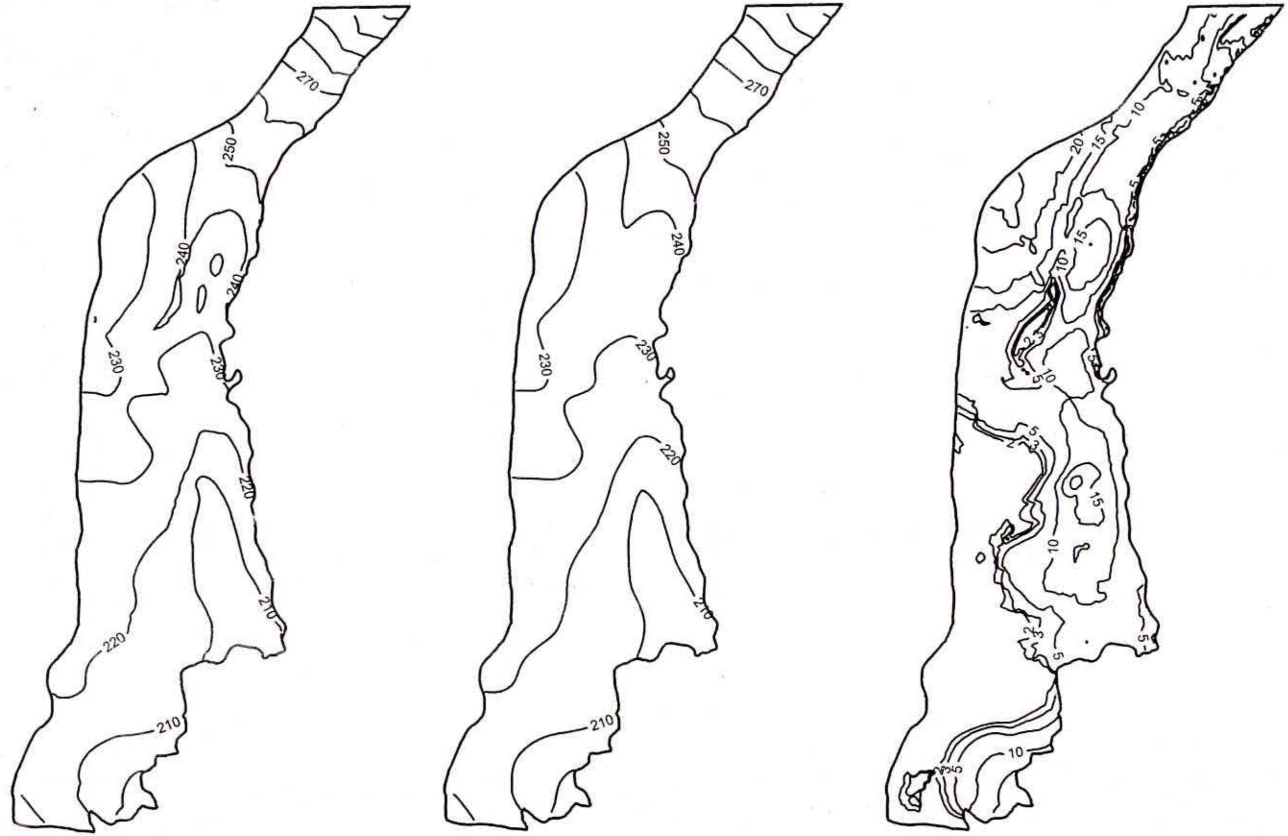
The results of this scenario in terms of groundwater table contour maps of both the aquifers and depth to water level of phreatic aquifer are presented in Fig. 25. The area falling under different depth to water level below ground level is given in Table 18. As expected, there is successive increase in the area falling under different depths under successive decrease in pumping from phreatic aquifer. The waterlogged/prone to waterlogging area has increased with successive decrease in pumping. Comparing the results with 2005, it is found that by reducing the pumping by 10%, there is still reduction in the area falling under depth of <10m and more. But with a reduction of 20% in pumping, the area under depth <10m and more has increased.

The simulated groundwater hydrographs at various observation wells in aquifer I and II are shown in Fig. 26 and Fig. 27. As in Scenario I, there is no trend in the groundwater levels in the wells namely Chhachhrauli, Yamunanagar and Radaur located in the north part of the study area. The wells falling in the middle of the study area show reduction in groundwater levels decline with successive reduction in pumping. The wells falling in the southern part of the study area show the opposite trend as that of central part indicating progressive increasing water levels with successive reduction in pumping. The reduction in pumping by 20% from aquifer I also stabilizes the groundwater levels in aquifer II. The outcome of this scenario is that the reduction of pumping by about 20% arrests the declining water level in the area facing declining water levels.



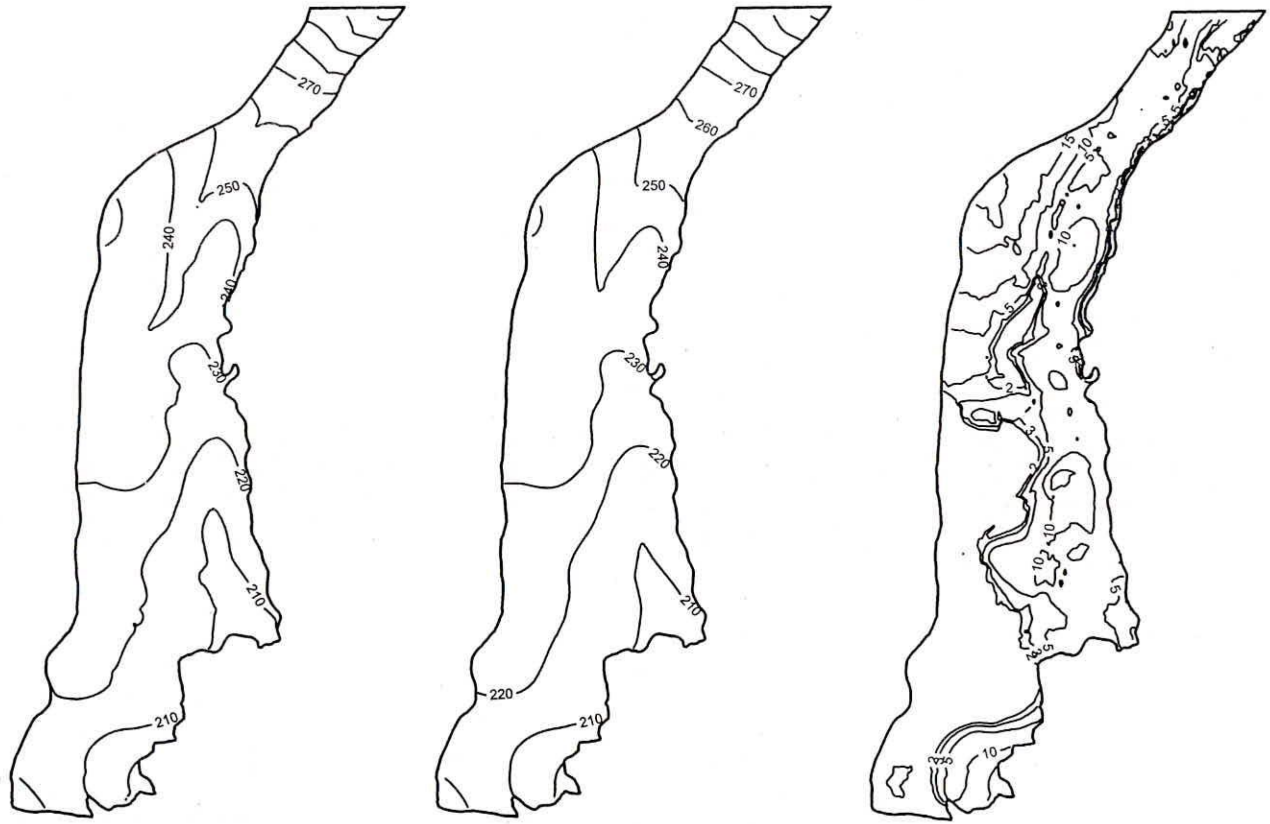
Groundwater table (Aquifer I) Groundwater table (Aquifer II) Depth to groundwater level (Aquifer I)

Fig. 25(a) Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario II-A)



Groundwater table (Aquifer I) Groundwater table (Aquifer II) Depth to groundwater level (Aquifer I)

Fig. 25(b) Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario II-B)



Groundwater table (Aquifer I) Groundwater table (Aquifer II) Depth to groundwater level (Aquifer I)

Fig. 25(c) Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario II-C)

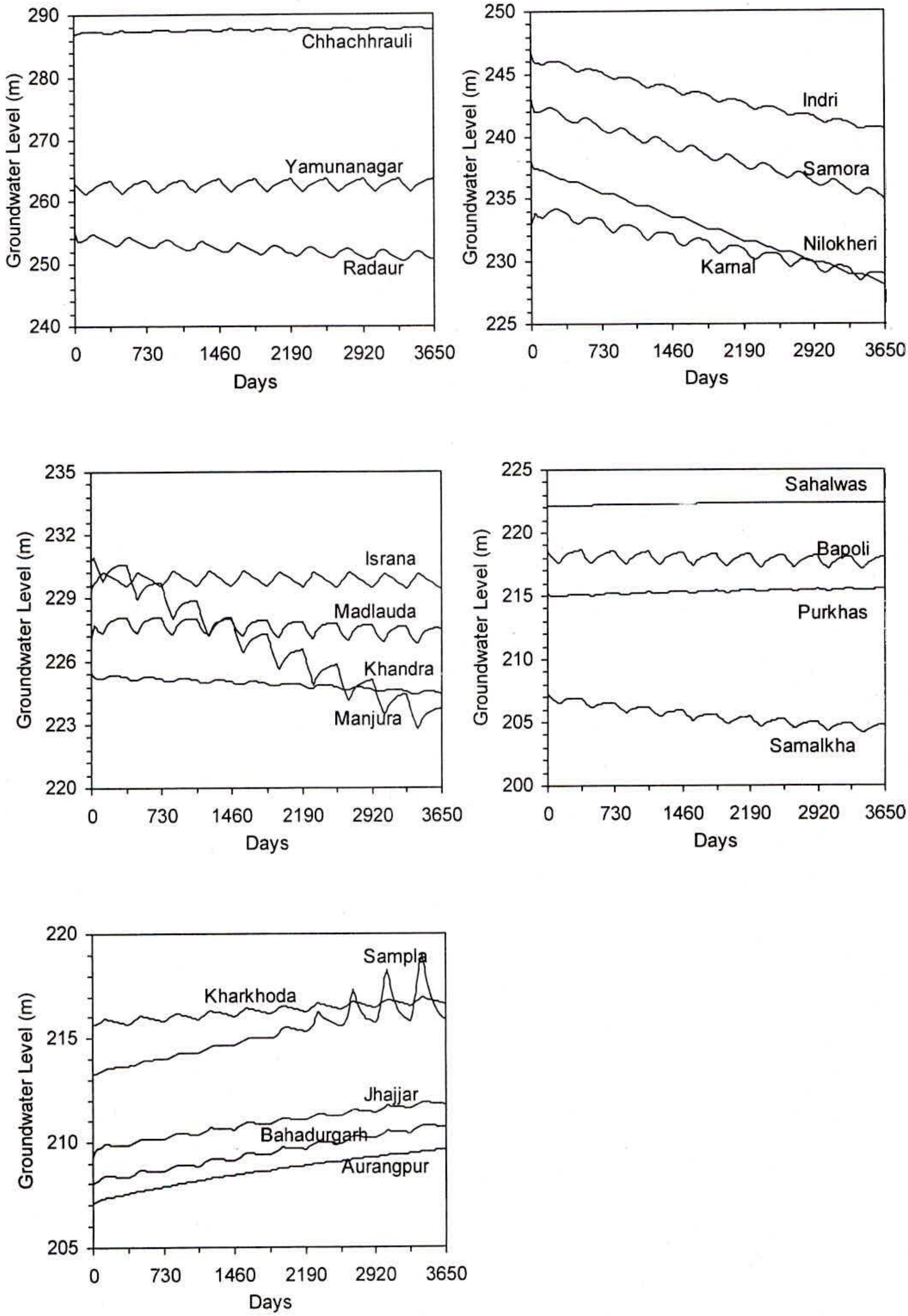


Fig. 26(a). Predicted groundwater level hydrographs for Aquifer I (Scenario II-A)

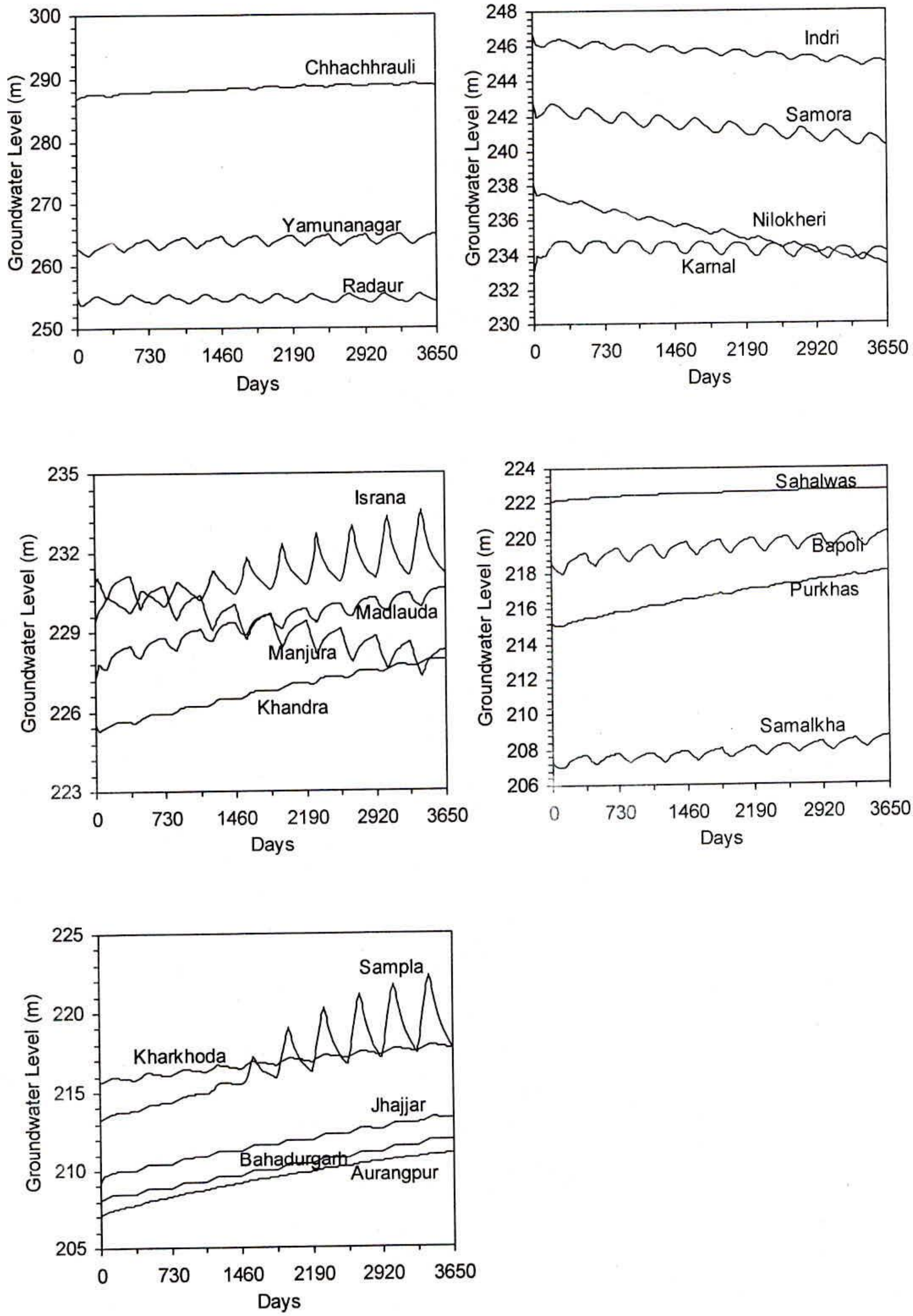


Fig. 26(b). Predicted groundwater level hydrographs for Aquifer I (Scenario II-B)

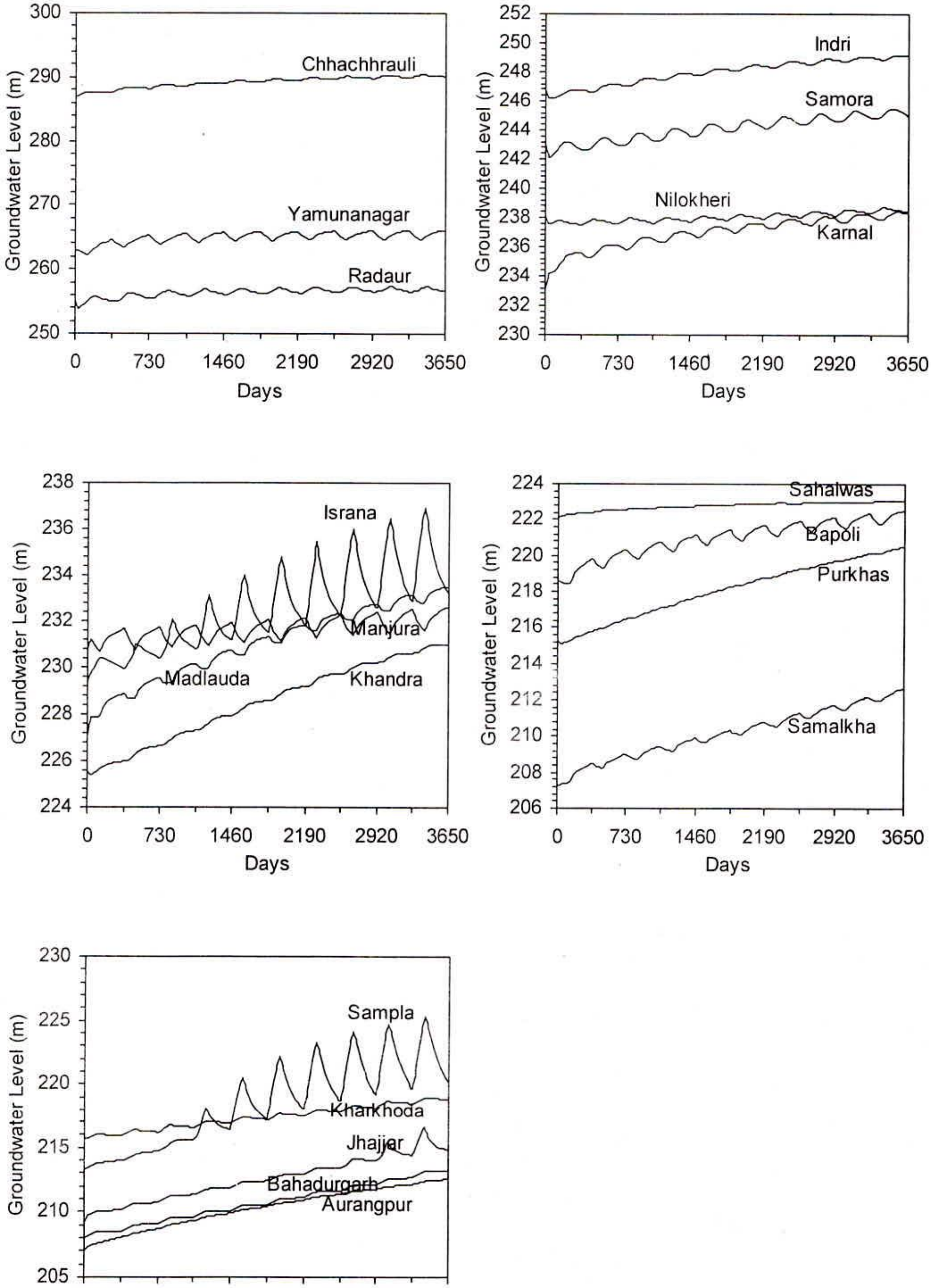


Fig. 26(c). Predicted groundwater level hydrographs for Aquifer I (Scenario II-C)

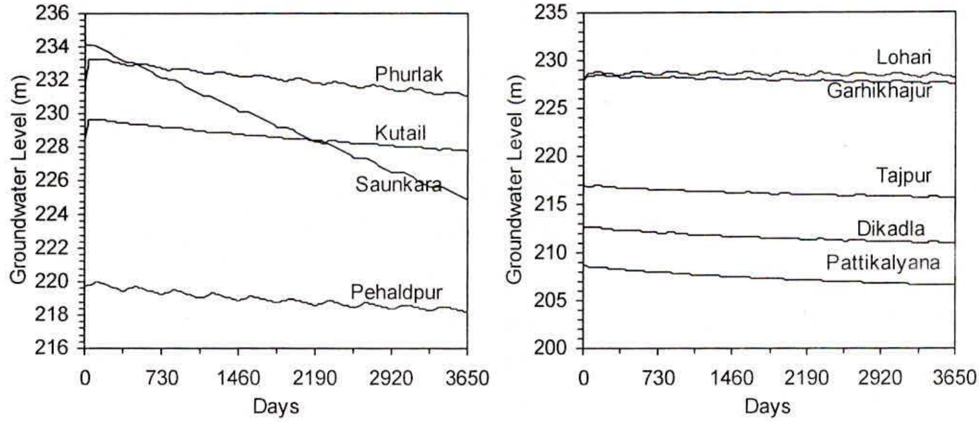


Fig. 27(a). Predicted groundwater level hydrographs for Aquifer II (Scenario II-A)

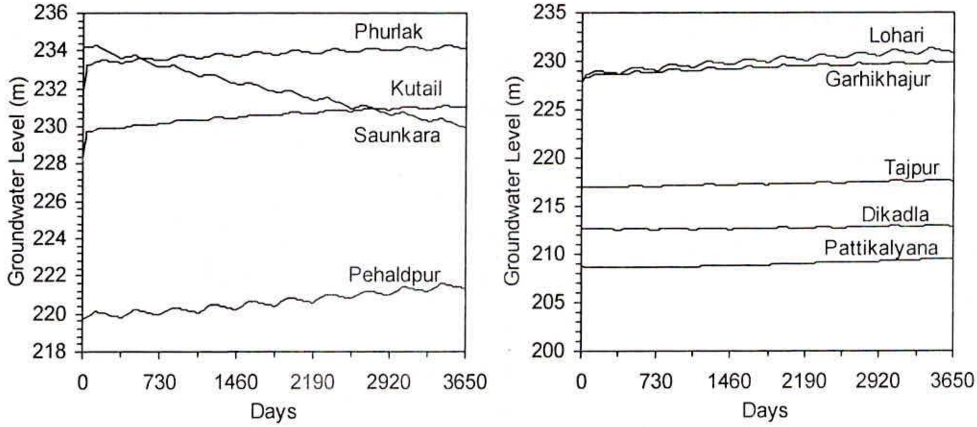


Fig. 27(b). Predicted groundwater level hydrographs for Aquifer II (Scenario II-B)

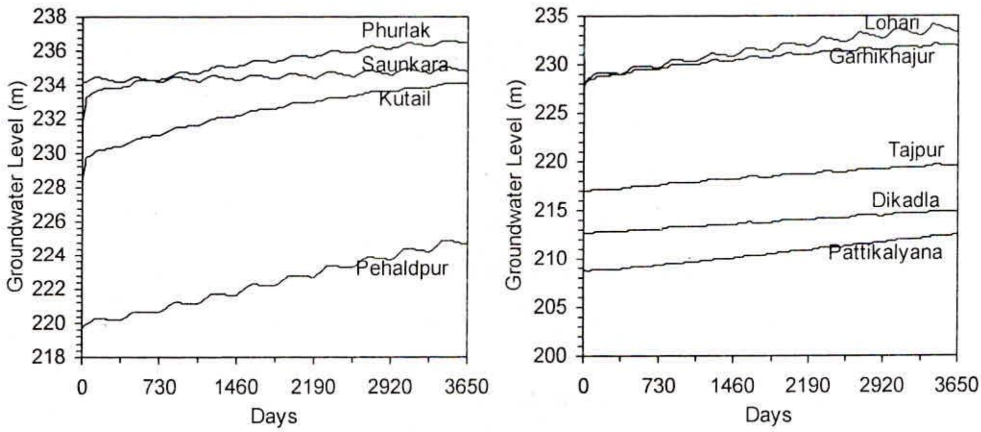


Fig. 27(c). Predicted groundwater level hydrographs for Aquifer II (Scenario II-C)

Table 18. Area (%) falling under different groundwater depths (Scenario II)

Groundwater Depth below Ground Level	2005	2015		
		II-A	II-B	II-C
2 m	12.8	18.1	24.3	31.6
3 m	18.2	22.8	28.9	37.2
5 m	28.6	31.2	37.6	50.3
10 m	61.1	53.9	69.1	82.9
15 m	87.0	78.5	88.0	95.1
20 m	98.5	89.9	95.7	99.3
25 m	100.0	95.7	99.3	100.0
30 m		99.1	100.0	
35 m		100.0		

9.7.3 Scenario III

This scenario was created to look into the ways to reduce the problem of waterlogging in the study area. In this scenario, four sub-scenarios were tested as detailed below:

(A) Reduction in recharge (by stopping surface water irrigation, thus reducing return flow from surface water irrigation and seepage from canals) in the blocks facing waterlogging/ prone to waterlogging or rising water level problem (Israra, Gohana, Rohtak, Kharkhoda, Kalanur, Sampla, Beri, Jhajjar, Bahadurgarh, Matanhali, Salahwas Blocks).

(B) As in III (A) and by increasing pumpage by 10% from phreatic aquifer in waterlogged blocks only.

(C) As in III (A) and by increasing pumpage by 20% from phreatic aquifer in waterlogged blocks only.

(D) As in III (A) and by increasing pumpage by 30% from phreatic aquifer in waterlogged blocks only.

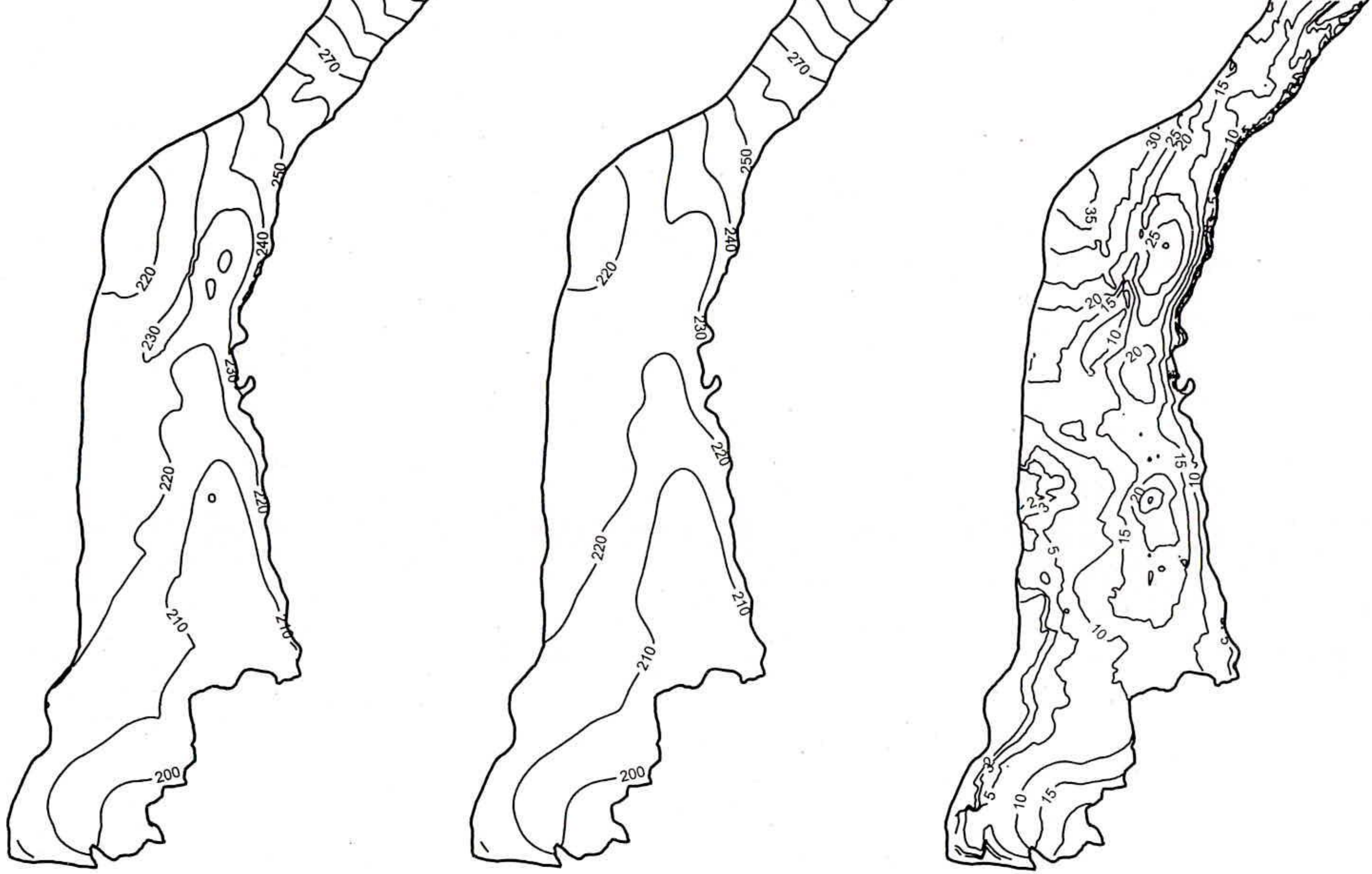
Fig. 28 to 30 and Table 19 gives the modeled results of this scenario. The reduction in groundwater recharge by way of stopping the canal irrigation in the blocks facing problem of rising groundwater levels show an apparent improvement in the condition of waterlogging in these blocks. Table 19 indicates a decrease in waterlogged area from 13% to 6% of the study area just by stopping surface water irrigation in these blocks. But, further increase in pumping by 10%, 20% and 30% for these blocks does not show much effect as there is only some impact in terms of marginal reduction in water logged areas. The reduction in recharge only (Scenario III-A) resulted in decline in groundwater level at some waterlogged area wells namely, Kharkhoda, but further increase in pumping by 10%, 20% and 30% resulted in declining groundwater levels in all waterlogged blocks.

Table 19. Area (%) falling under different groundwater depths (Scenario III)

Groundwater Depth below Ground Level	2005	2015			
		III-A	III-B	III-C	III-D
2 m	12.8	6.1	4.5	3.4	2.7
3 m	18.2	9.8	7.6	5.7	4.5
5 m	28.6	19.3	15.7	12.6	10.3
10 m	61.1	40.1	38.1	36.1	33.7
15 m	87.0	63.9	62.8	61.5	60.2
20 m	98.5	81.8	81.4	80.9	80.3
25 m	100.0	90.2	90.1	90.0	89.8
30 m		95.5	95.5	95.5	95.5
35 m		99.0	99.0	99.0	99.0
40 m		100.0	100.0	100.0	100.0

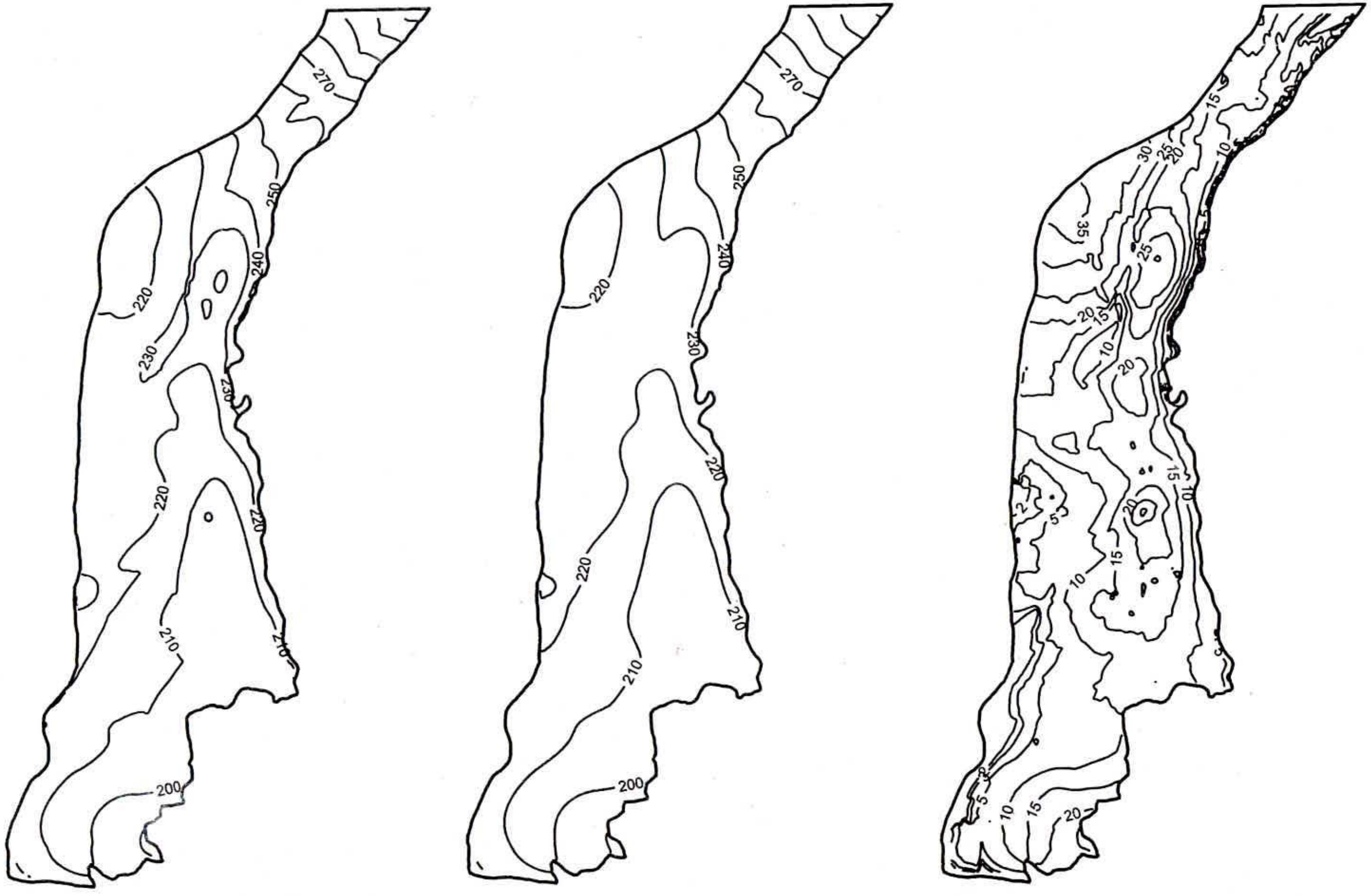
Groundwater table (Aquifer I) Groundwater table (Aquifer II) Depth to groundwater level (Aquifer I)

Fig. 28(a) Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario III-A)



Groundwater table (Aquifer I)   Groundwater table (Aquifer II)   Depth to groundwater level (Aquifer I)

Fig. 28(b) Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario III-B)



Groundwater tables (Aquifer I) Groundwater table (Aquifer II) Depth to groundwater level (Aquifer I)

Fig. 28(c) Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario III-C)

Groundwater table (Aquifer I) Groundwater table (Aquifer II) Depth to groundwater level (Aquifer I)

Fig. 28(d) Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario III-D)

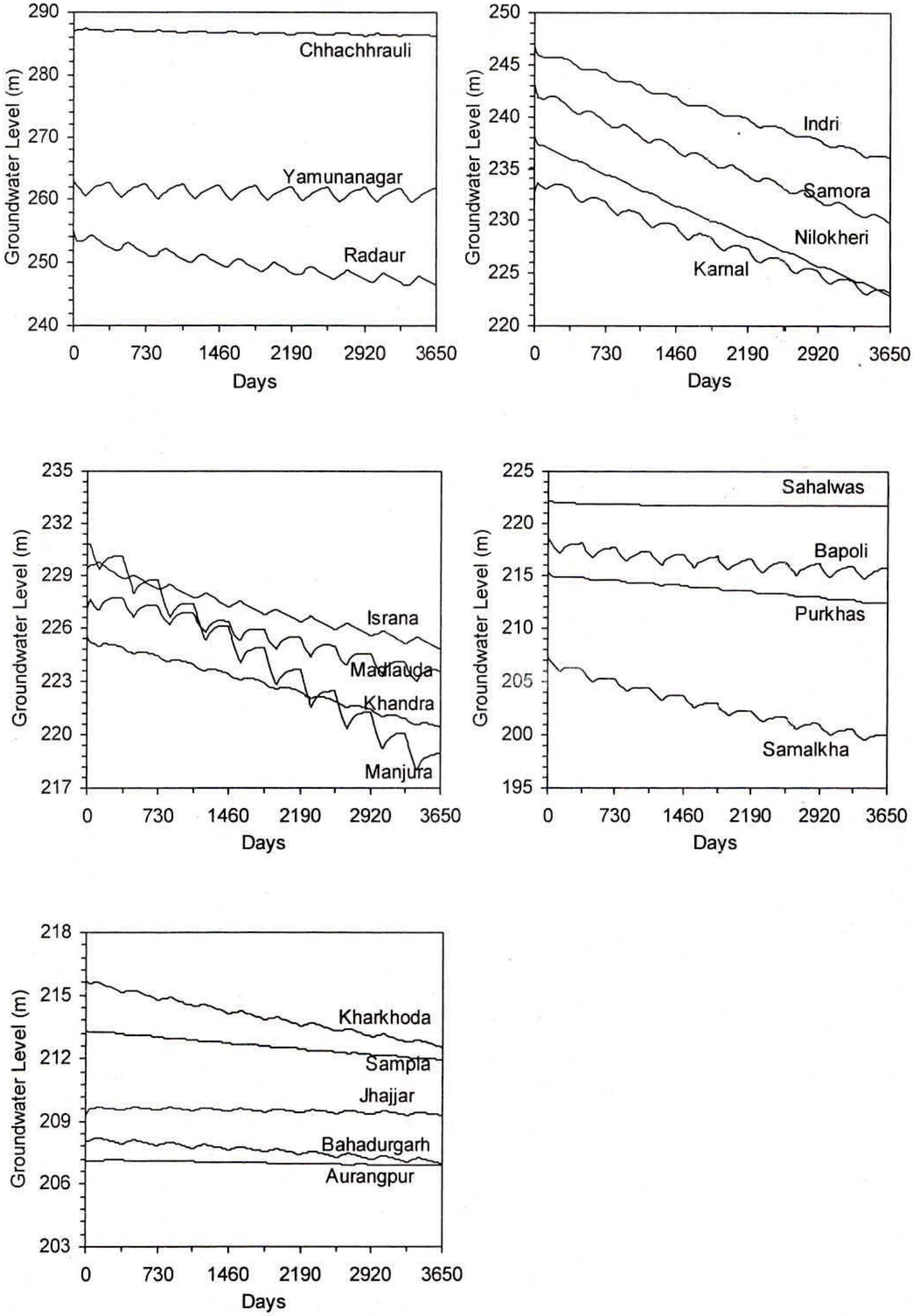


Fig. 29(a). Predicted groundwater level hydrographs for Aquifer I (Scenario III-A)

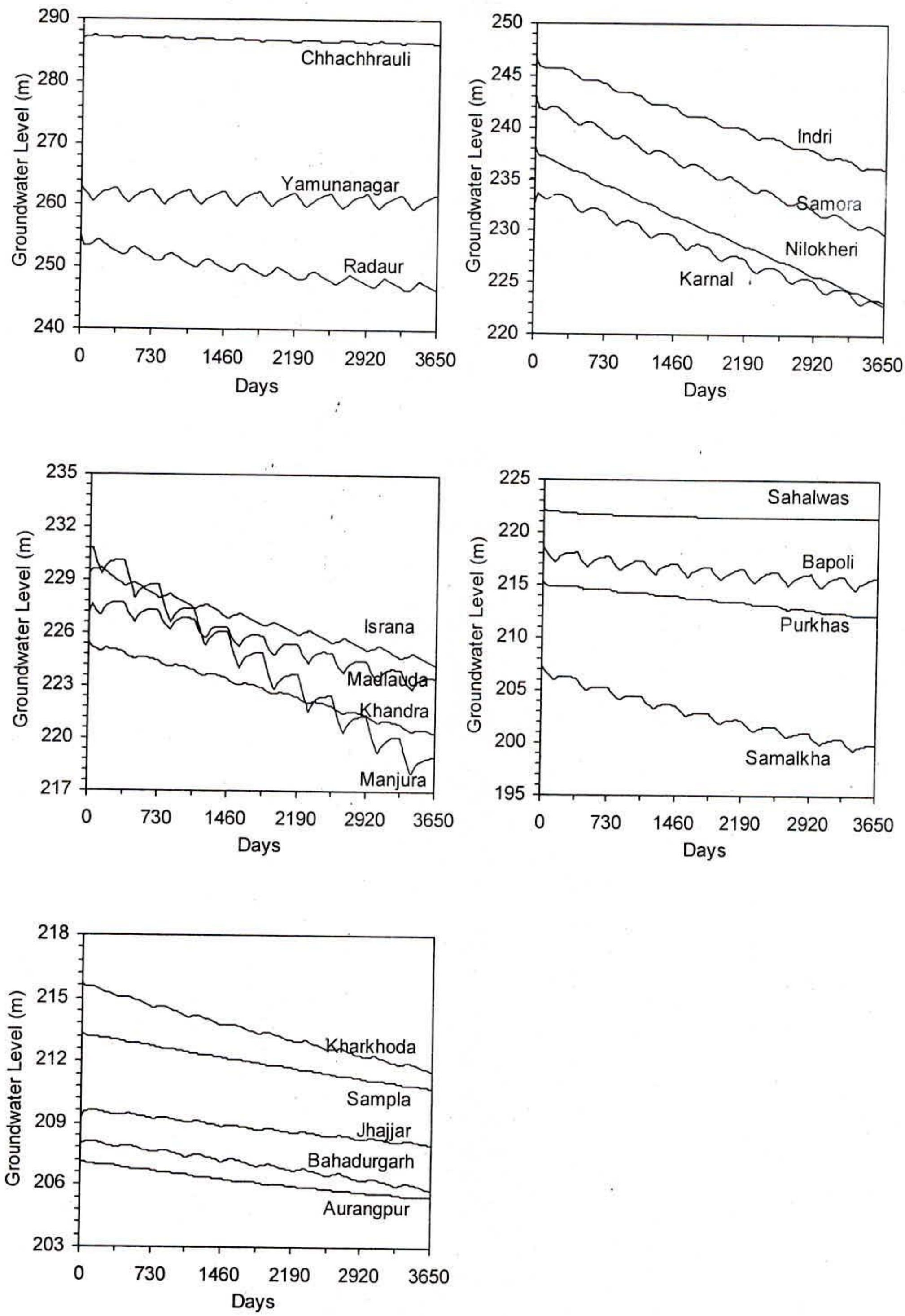


Fig. 29(b). Predicted groundwater level hydrographs for Aquifer I (Scenario III-B)

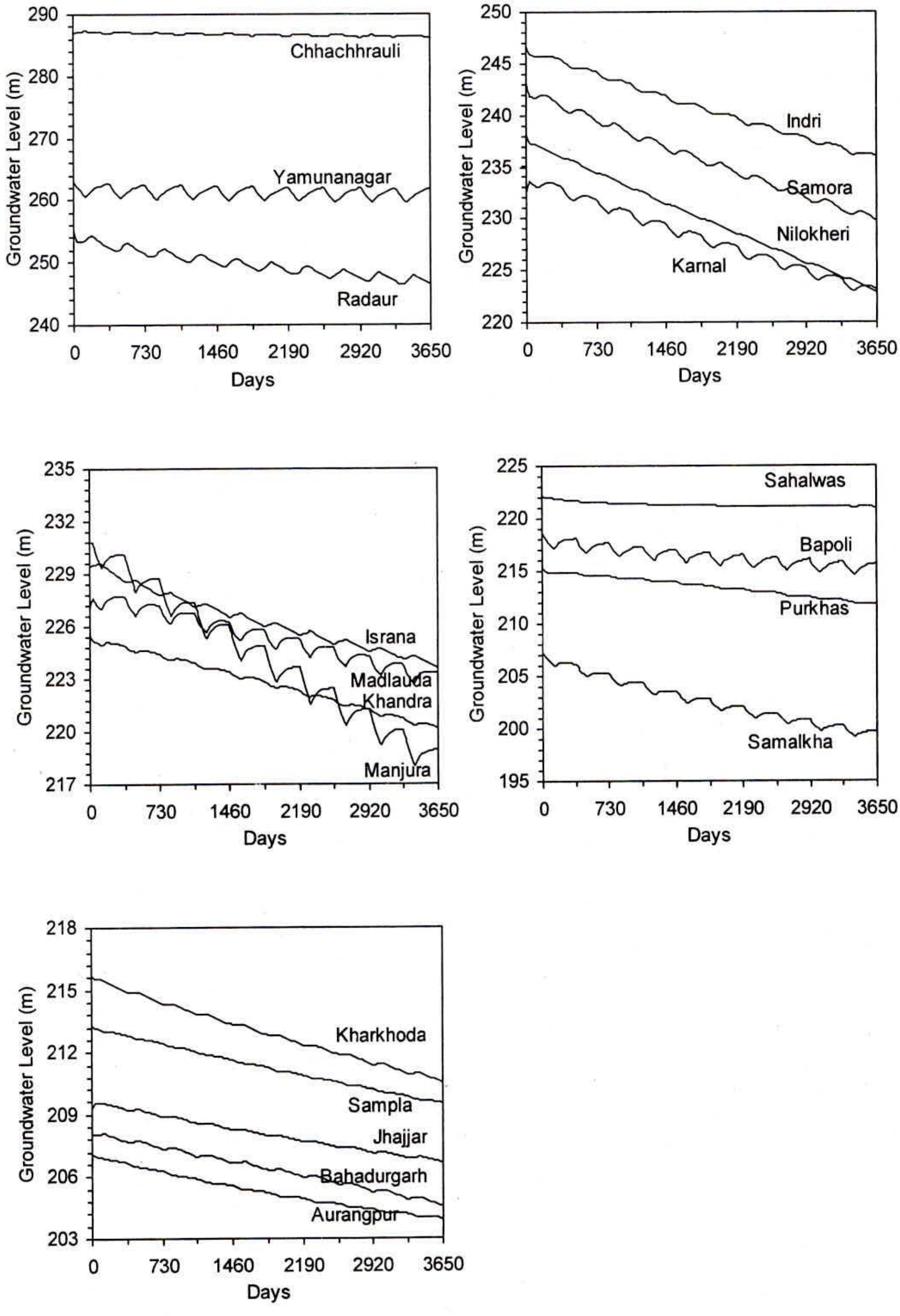


Fig. 29(c). Predicted groundwater level hydrographs for Aquifer I (Scenario III-C)

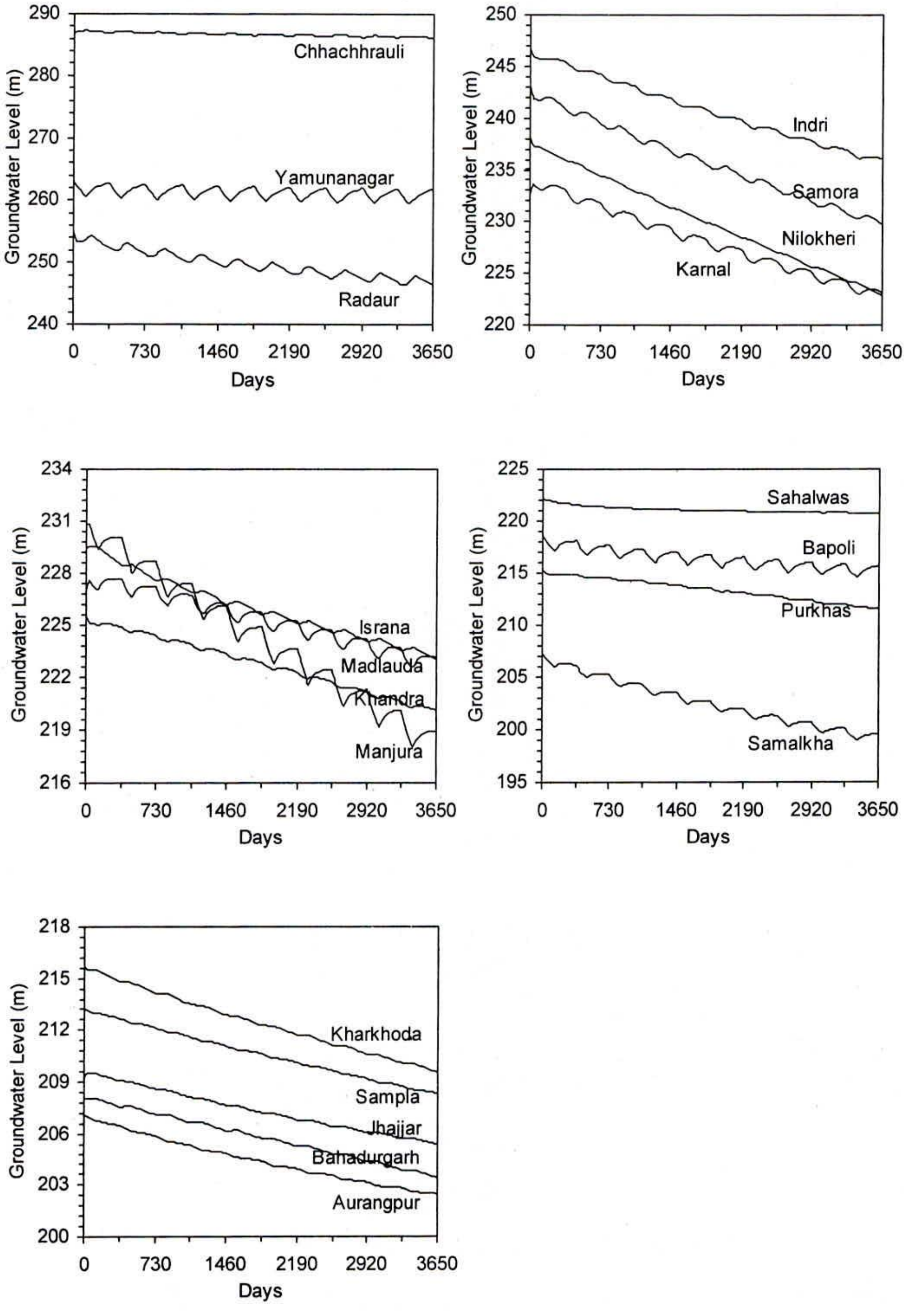


Fig. 29(d). Predicted groundwater level hydrographs for AquiferI (Scenario III-D)

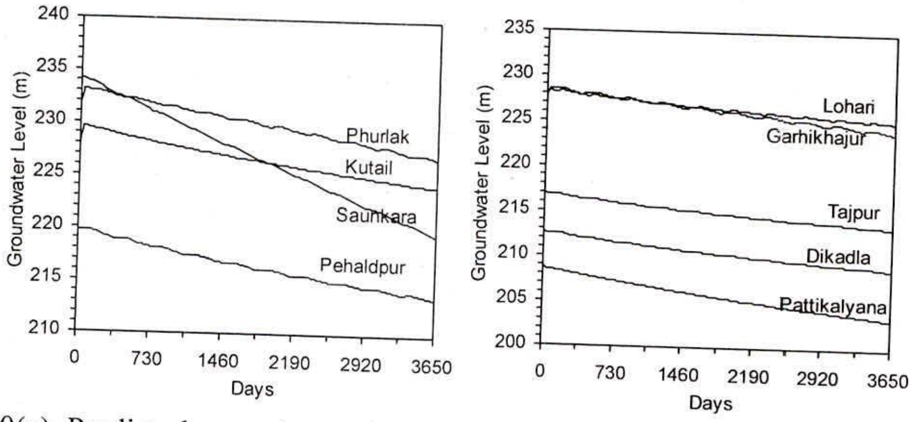


Fig. 30(a). Predicted groundwater level hydrographs for Aquifer II(ScenarioIII-A)

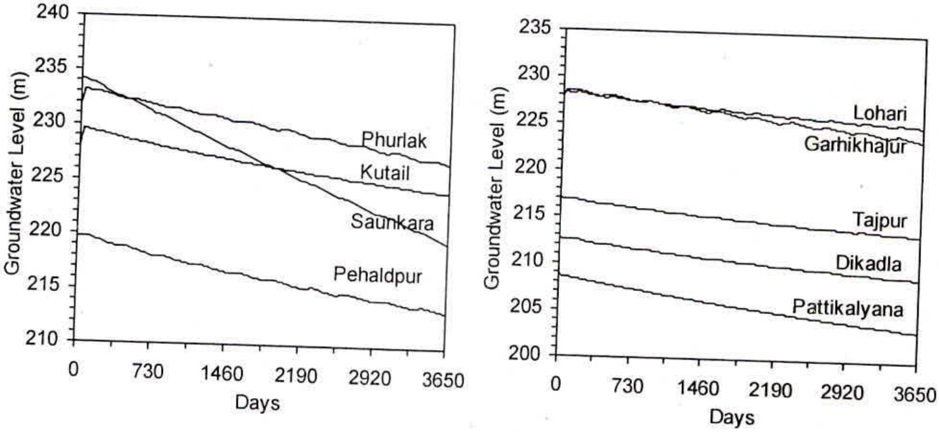


Fig. 30(b). Predicted groundwater level hydrographs for Aquifer II(ScenarioIII-B)

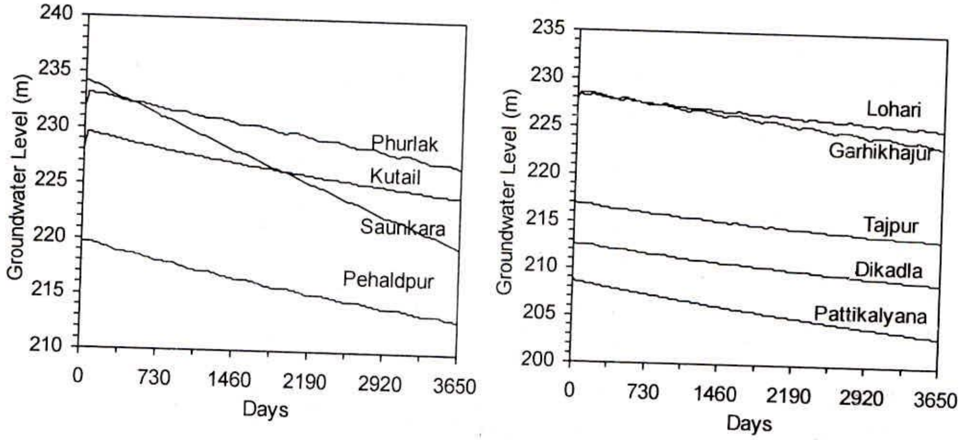


Fig. 30(c). Predicted groundwater level hydrographs for Aquifer II(Scenario III-C)

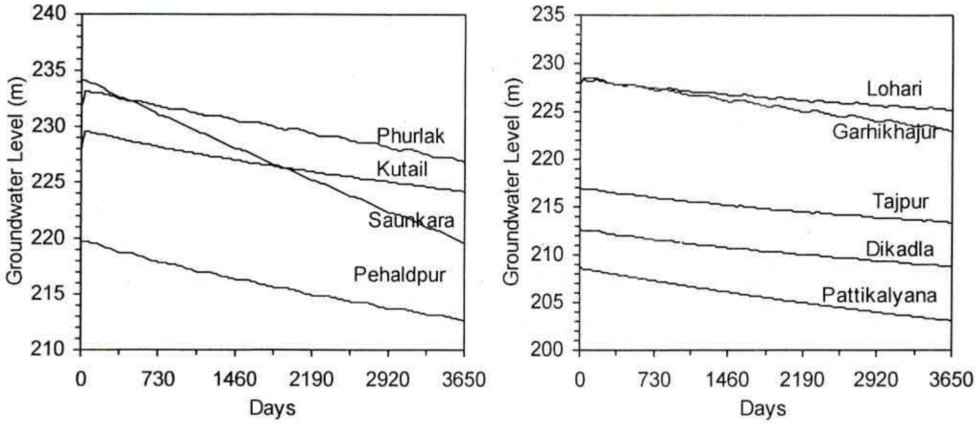
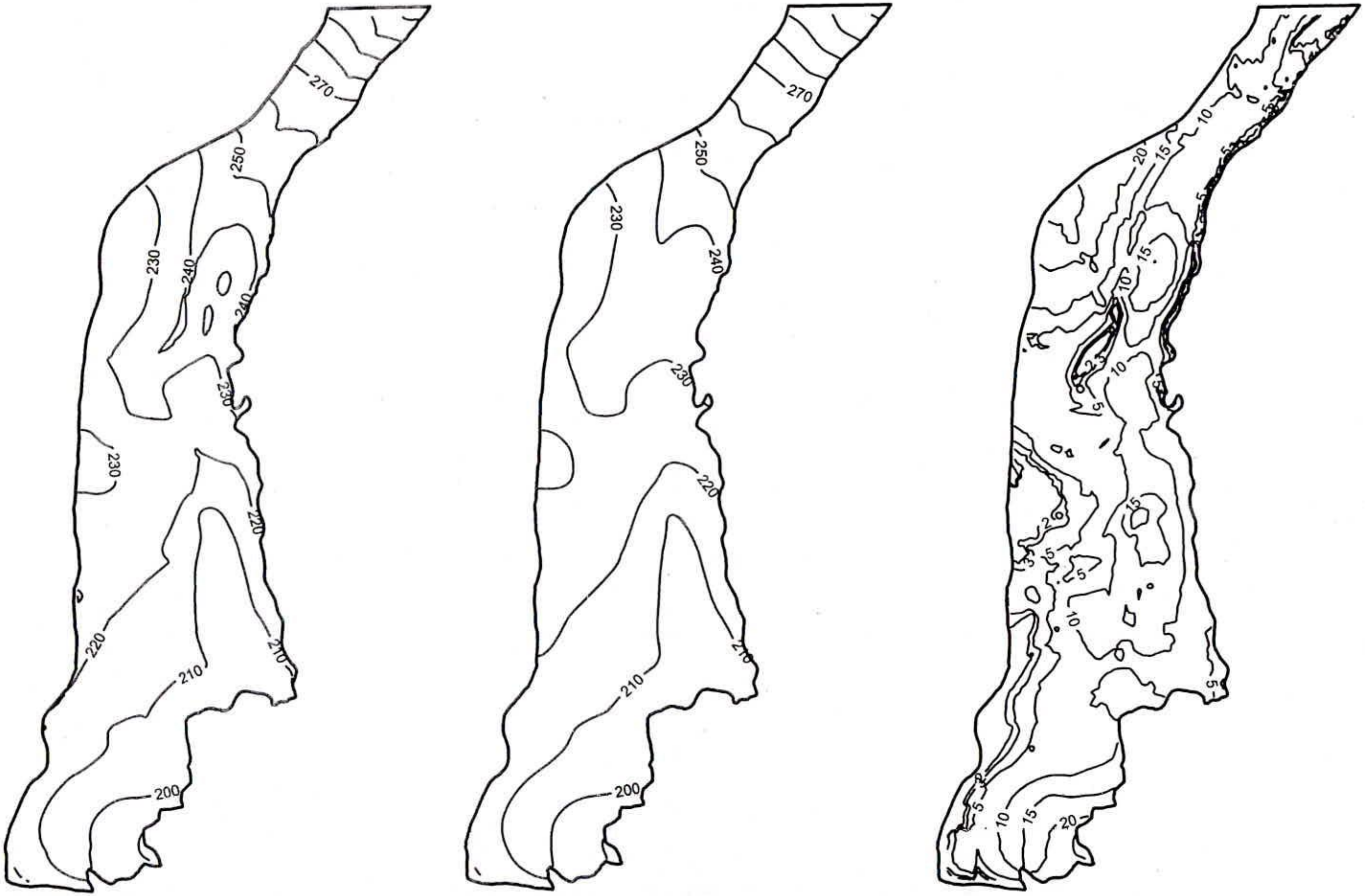


Fig. 30(d). Predicted groundwater level hydrographs for AquiferII(Scenario III-D)

9.7.4 Scenario IV

Reduction in recharge and Increase in pumping by 20% in blocks having waterlogging/rising water level problem and reduction in pumping by 20% in all other blocks. This is rather a combination of scenario II (B) and Scenario III (C) and the effect is also seen accordingly. The results of this scenario in terms of water table contour maps of both the aquifers and depth to water level map of phreatic aquifer are presented in Fig. 31. The area falling under different depths to water level below ground level is presented in Table 20.

There is improvement in the situation by way of reduction in the water logged area due to increase of pumping by 20% in water logged areas along with reduction in the water level decline due to reduction in pumping in other areas. The groundwater hydrographs shown in Fig. 32 and 33 also support the above results.



Groundwater table (Aquifer I) Groundwater table (Aquifer II) Depth to groundwater level (Aquifer I)

Fig. 31 Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario IV)

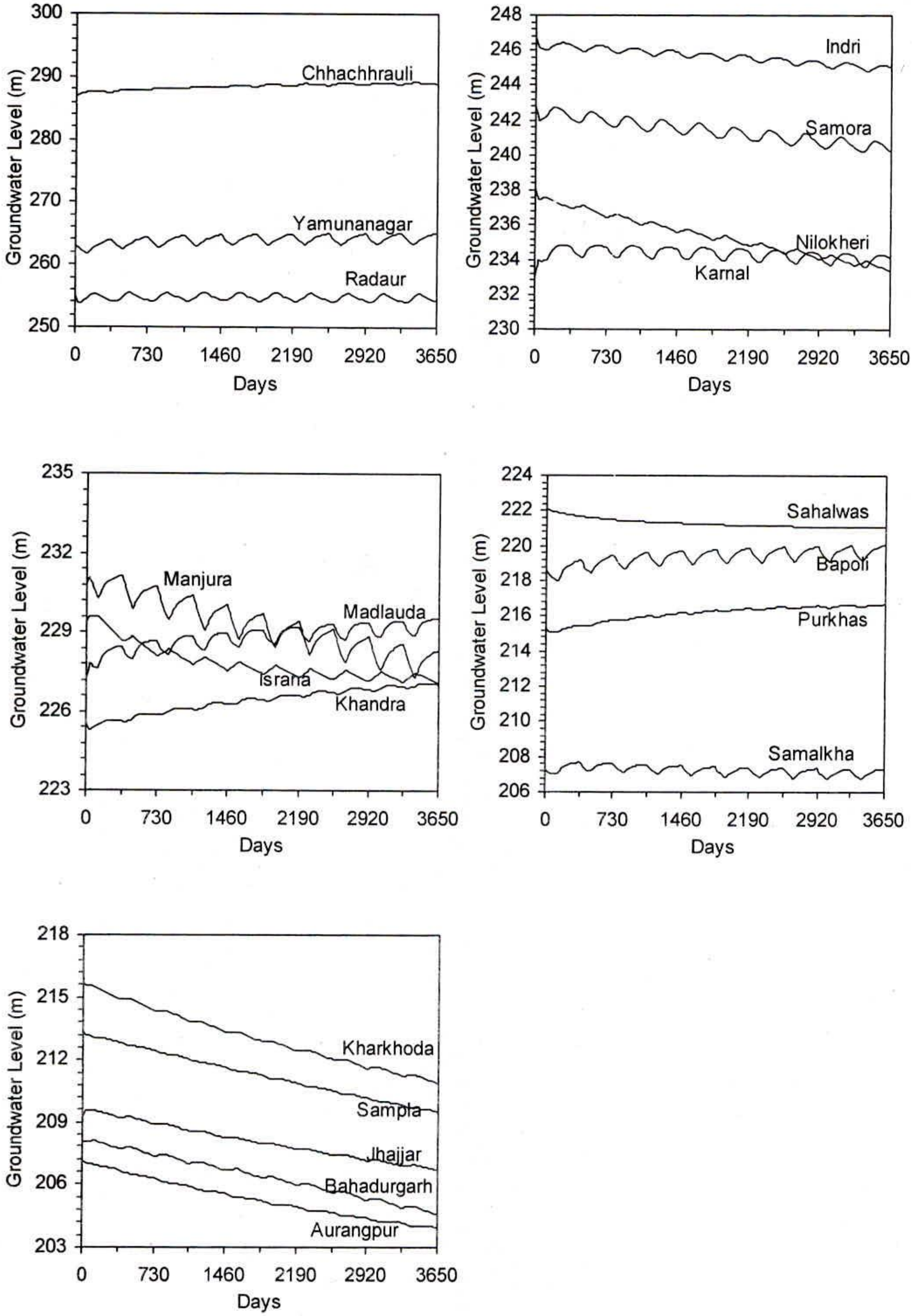


Fig. 32. Predicted groundwater level hydrographs for Aquifer I (Scenario IV)

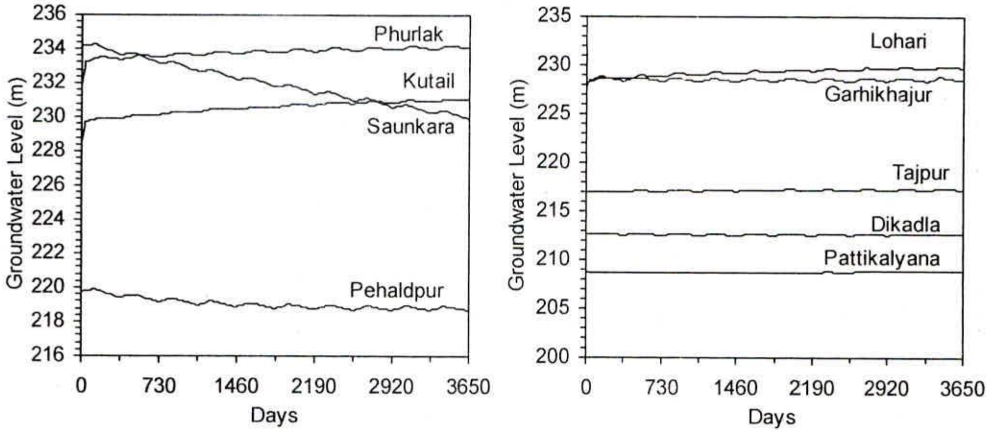


Fig. 33. Predicted groundwater level hydrographs for Aquifer II (Scenario IV)

Table 20. Area (%) falling under different groundwater depths (Scenario IV)

Groundwater Depth below Ground Level	2005	2015
2 m	12.8	6.5
3 m	18.2	10.0
5 m	28.6	20.4
10 m	61.1	59.8
15 m	87.0	84.7
20 m	98.5	94.3
25 m	100.0	99.2
30 m		100.0

The Scenarios V and VI are created to test the sustainability of the semi-confined aquifer if the ground water is to be withdrawn from this aquifer.

9.7.5 Scenario V

In this scenario, the pumping from the phreatic aquifer was reduced as in scenario II and the same amount of water was withdrawn from the semi-confined (third layer) aquifer. Under this scenario, three sub-scenarios were simulated as

(A) 10% reduction in pumping from phreatic aquifer and increasing the same volume from the semi-confined aquifer

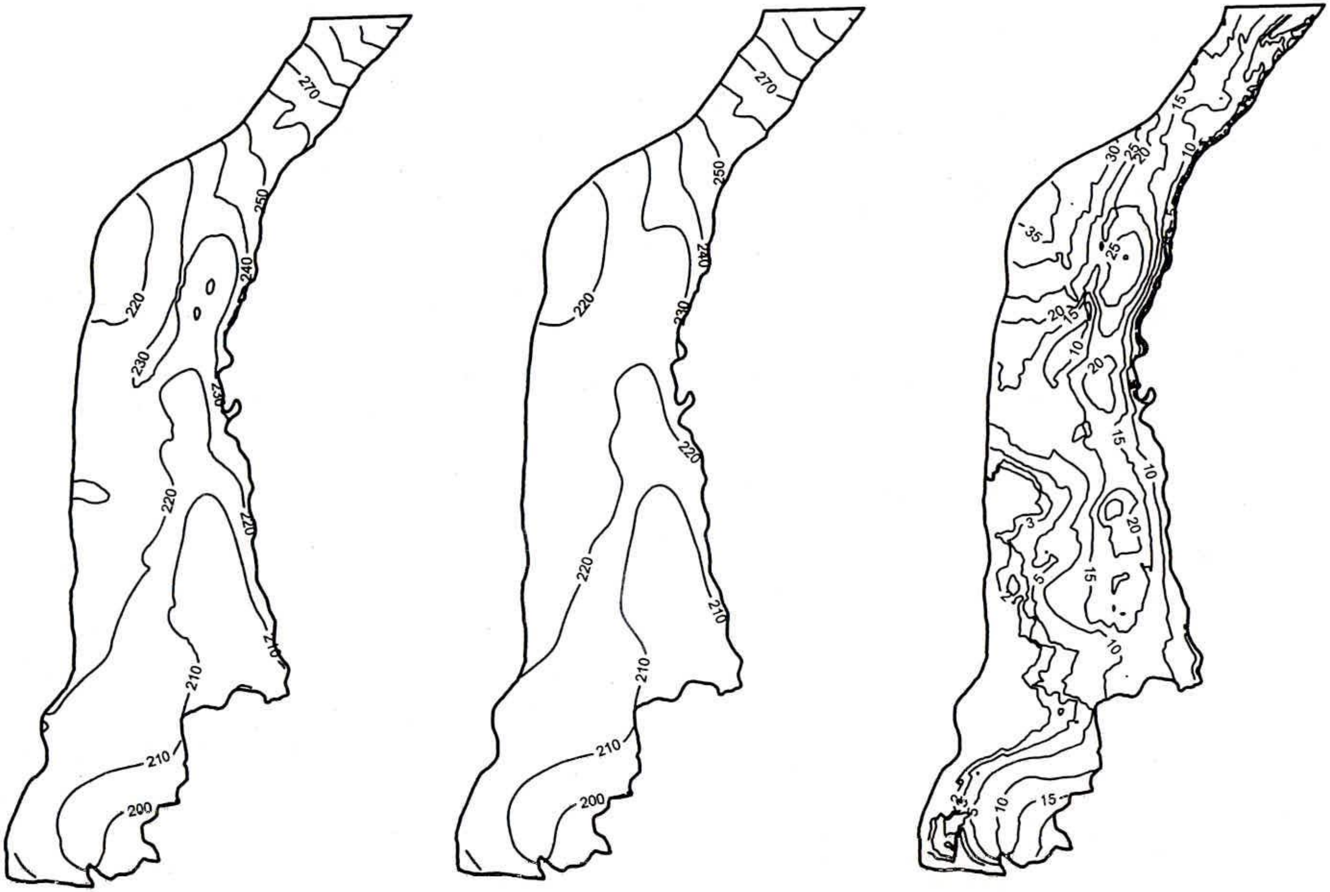
(B) 20% reduction in pumping from phreatic aquifer and increasing the same volume from the semi-confined aquifer

(C) 30% reduction in pumping from phreatic aquifer and increasing the same volume from the semi-confined aquifer

The results of this scenario in terms of contour maps, groundwater level hydrographs and percentage area under different depths is provided in Fig.34 to 36 and Table 21. The results indicate that there is no marked change in the groundwater level situation of aquifer I as compared to Scenario I by pumping from the IInd aquifer. The water table contour maps of IInd aquifer in Scenario I and current scenario are almost similar. The extent of waterlogged/prone to waterlogging area is also similar in all the sub-scenario to that of scenario I. The groundwater hydrographs of wells in aquifer I of this scenario are also similar to corresponding hydrographs in Scenario I. There is declining trend with time in the water level of IInd aquifer and the groundwater hydrographs of this aquifer shows the effect of pumping in every year. This may be indicative of connectivity of aquifer I and II and thereby pumping in the semi-confined aquifer indicates vertical downward movement of water. The important observation of this scenario is that the reduction in pumping from the phreatic aquifer and withdrawing the same volume of water from the IInd aquifer does not show any positive effect on water level in phreatic aquifer.

Table 21. Area (%) falling under different groundwater depths (Scenario V)

Groundwater Depth below Ground Level	2005	2015		
		V-A	V-B	V-C
2 m	12.8	11.8	11.7	11.7
3 m	18.2	16.7	16.5	16.5
5 m	28.6	[illegible]	24.9	24.9
10 m	61.1	[illegible]	42.7	42.7
15 m	87.0	66.2	65.4	65.6
20 m	98.5	82.3	82.1	82.2
25 m	100.0	90.3	90.4	90.5
30 m		95.5	95.6	95.6
35 m		99.0	99.0	99.0
40 m		100.0	100.0	100.0

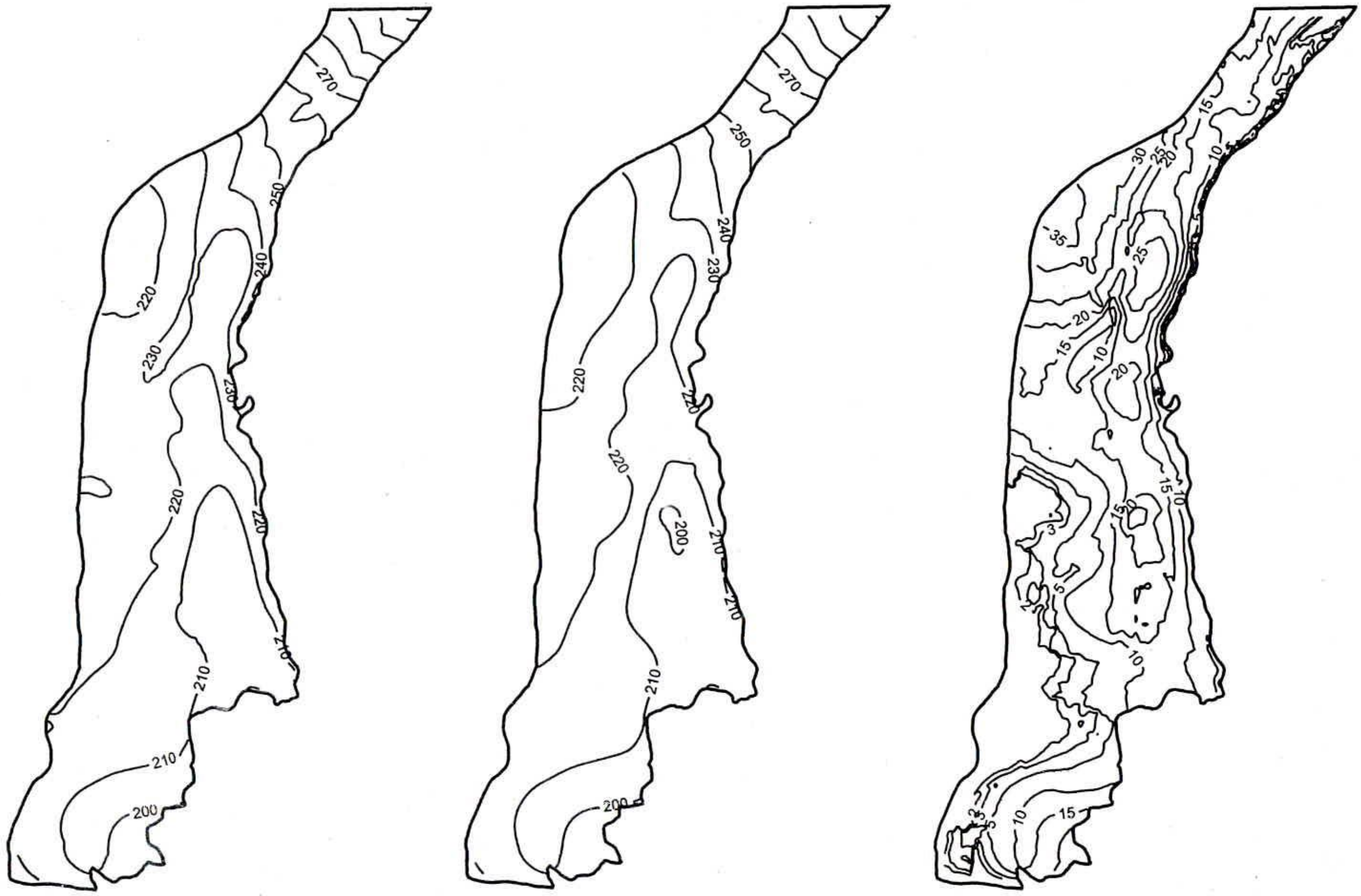


Groundwater table (Aquifer I) Groundwater table (Aquifer II) Depth to Groundwater level (Aquifer I)

Fig. 34(a) Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario V-A)

Groundwater table (Aquifer I) Groundwater table (Aquifer II) Depth to groundwater level (Aquifer I)

Fig. 34(b) Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario V-B)



Groundwater table (Aquifer I) Groundwater table (Aquifer II) Depth to groundwater level (Aquifer I)

Fig. 34(c) Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario V-C)

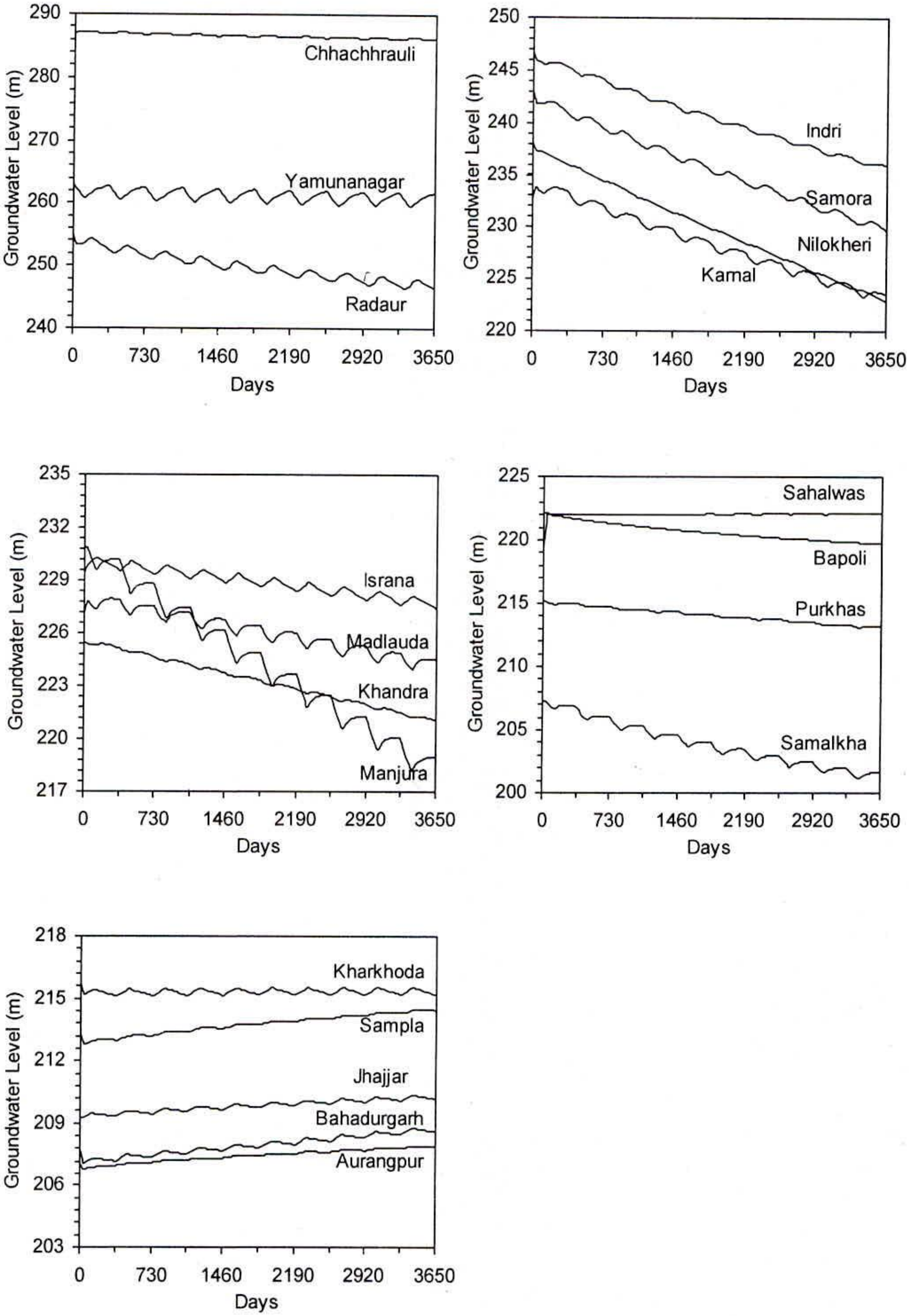


Fig. 35(a). Predicted groundwater level hydrographs for Aquifer I (Scenario V-A)

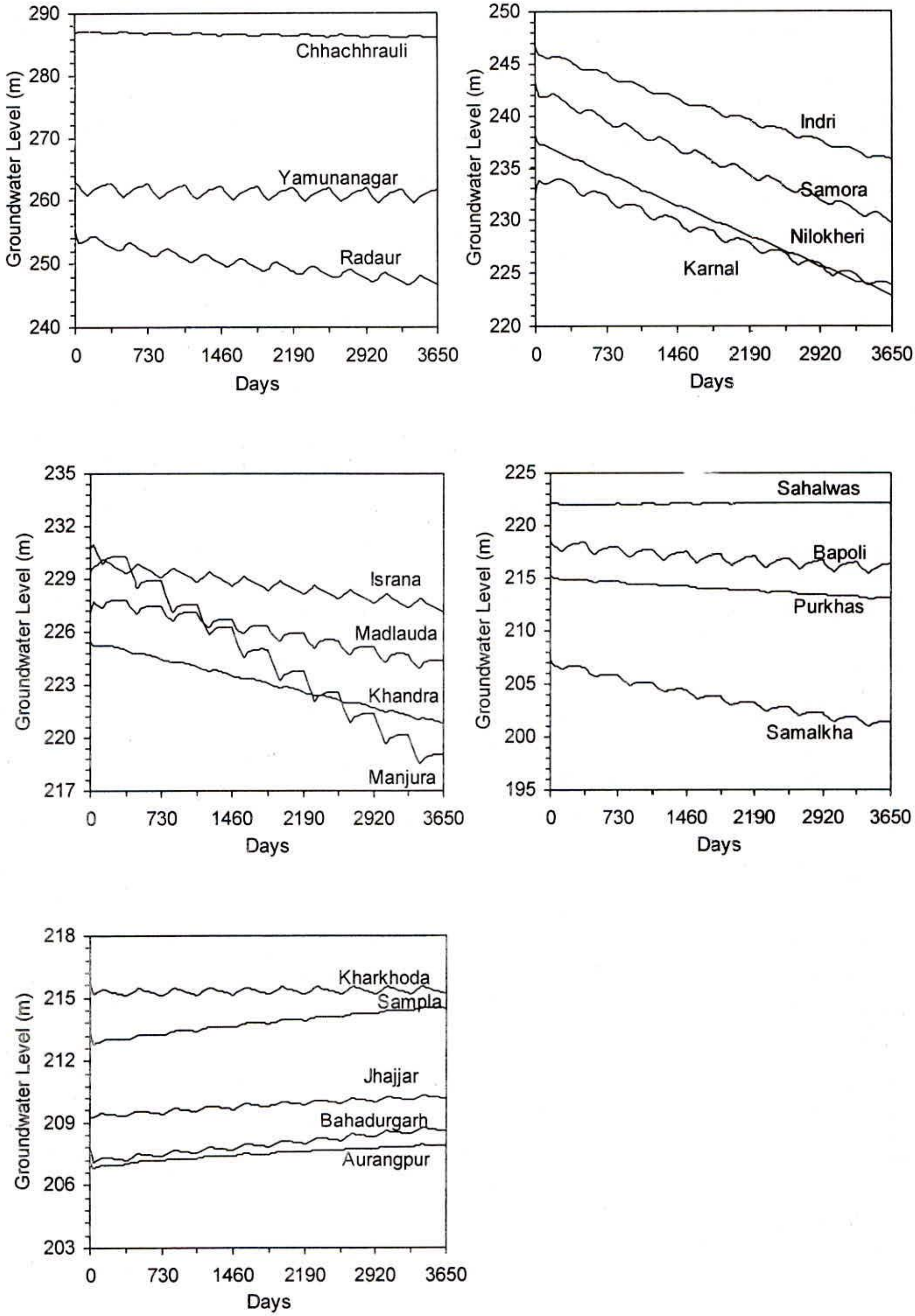


Fig. 35(b). Predicted groundwater level hydrographs for Aquifer I (Scenario V-B)

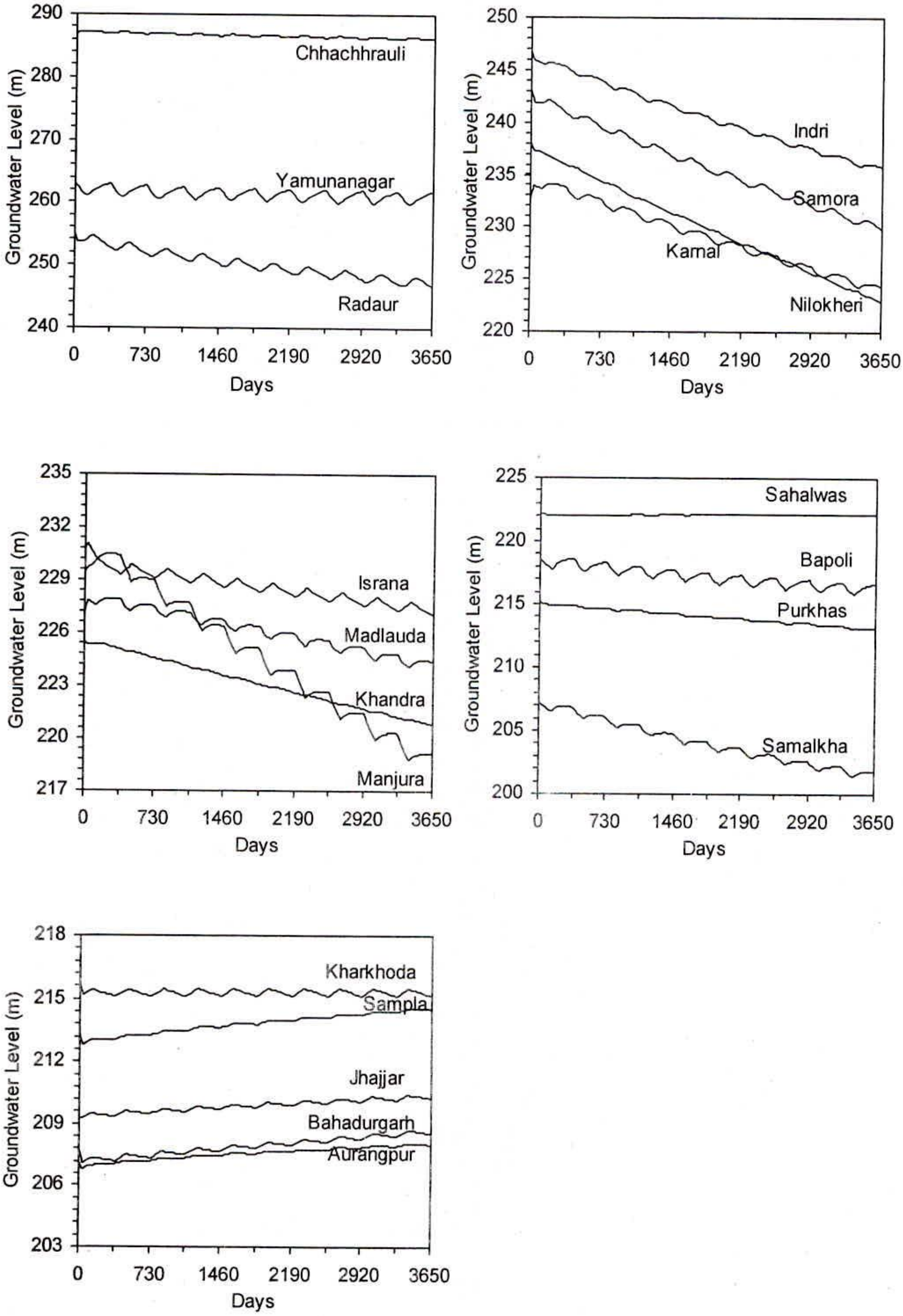


Fig. 35(c). Predicted groundwater level hydrographs for Aquifer I (Scenario V-C)

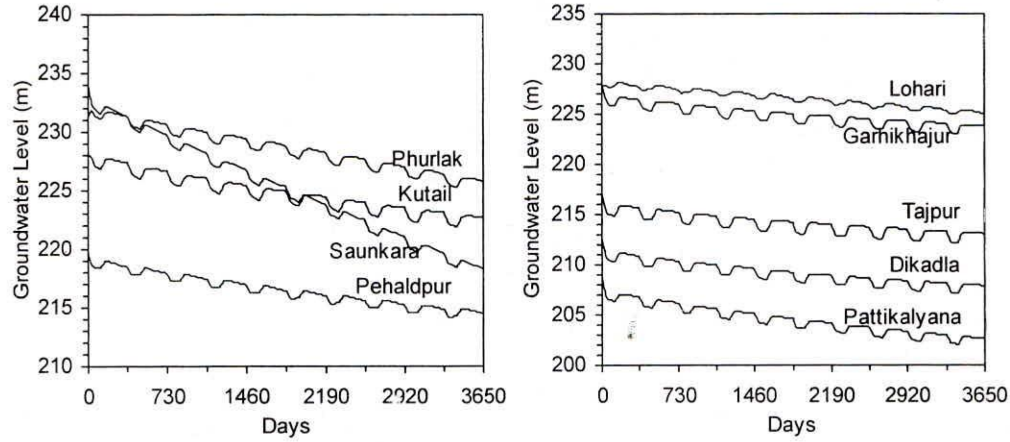


Fig. 36(a). Predicted groundwater level hydrographs for Aquifer II(Scenario V-A)

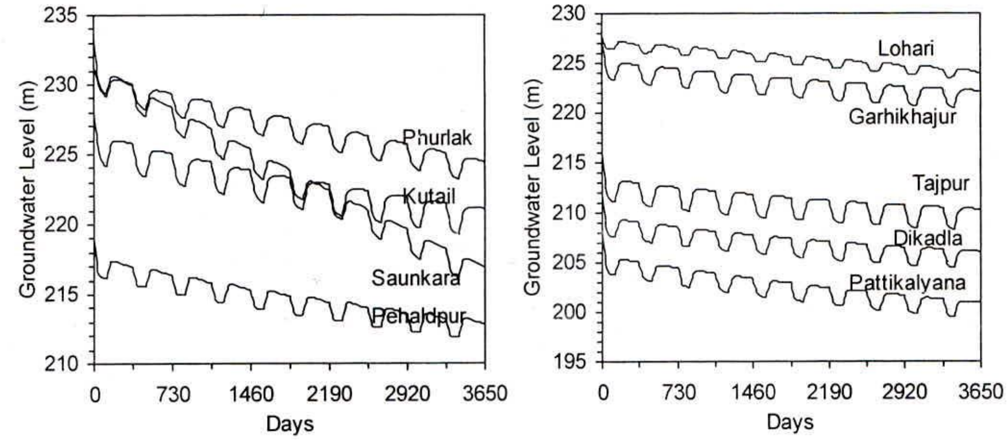


Fig. 36(b). Predicted groundwater level hydrographs for Aquifer II(Scenario V-B)

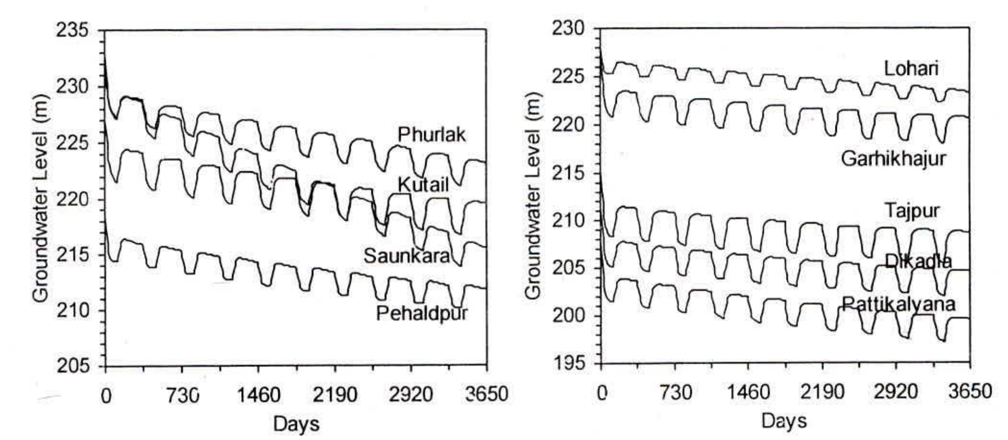


Fig. 36(c). Predicted groundwater level hydrographs for Aquifer II (Scenario V-C)

9.7.6 Scenario VI

In this scenario, increase in pumping by 20% in waterlogged blocks and reduction in pumping by 20% in all other blocks from the phreatic aquifer and withdrawing the same volume of water from the IInd aquifer is modeled. This is an extension of Scenario IV by withdrawing water from IInd aquifer.

The results of this scenario in terms of water table contour map of both the aquifers and depth to water level map of phreatic aquifer are presented in Fig.37 and the area falling in different zones of depth to water level below ground level is depicted in Table 22. In this Scenario, as seen in Scenario V, there is no marked change in the groundwater levels of phreatic aquifer and the water table contour of semi-confined aquifer shows decline of water table in areas other than waterlogged. The groundwater hydrographs of Ist aquifer (Fig. 38) are similar to Scenario IV and of of IInd aquifer (Fig. 39) shows declining trend with time and effect of pumping in every year as in Scenario V.

Table 22. Area (%) falling under different groundwater depths (Scenario VI)

Groundwater Depth below Ground Level	2005	2015
2 m	12.8	3.3
3 m	18.2	5.6
5 m	28.6	12.2
10 m	61.1	35.1
15 m	87.0	61.1
20 m	98.5	80.7
25 m	100.0	90.0
30 m		95.5
35 m		99.0
40 m		100.0

Groundwater table (Aquifer I) Groundwater table (Aquifer II) Depth to groundwater level (Aquifer I)

Fig. 37 Predicted groundwater heads for aquifer I and II and depth to groundwater level for aquifer I for May 2015 (Scenario VI)

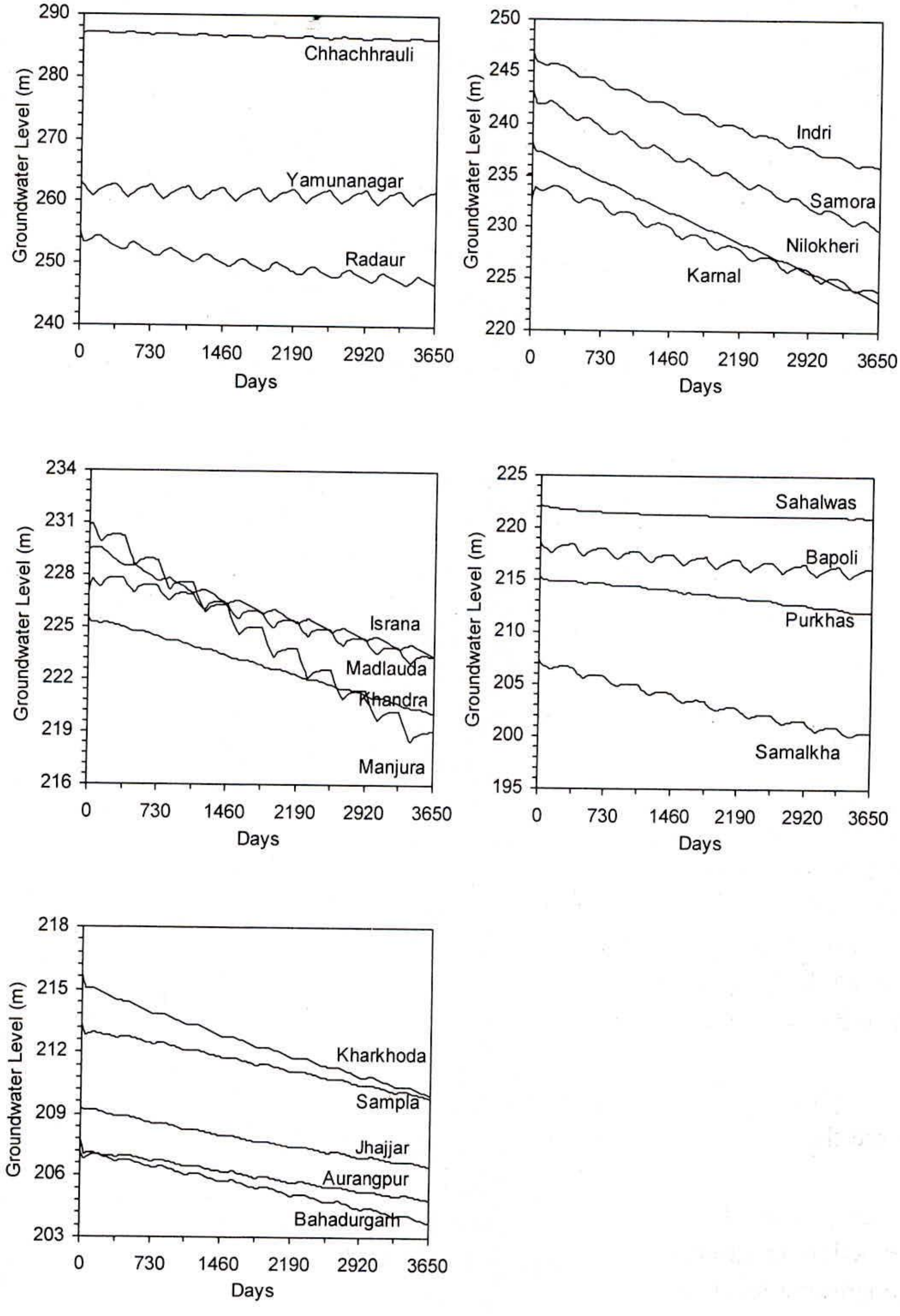


Fig. 38. Predicted groundwater level hydrographs for Aquifer I (Scenario VI)

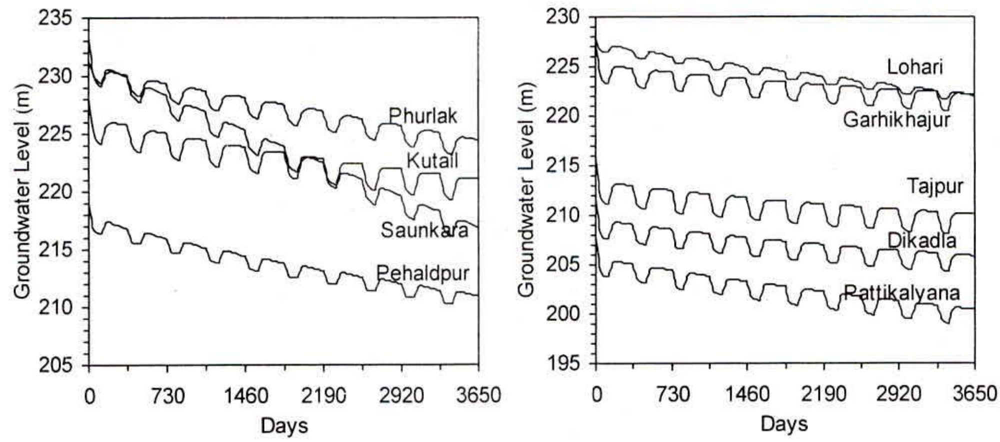


Fig. 39. Predicted groundwater level hydrographs for Aquifer II (Scenario VI)

9.8 Discussion and Conclusions

A mathematical model has been set-up to simulate the hydrogeological conditions and groundwater flow in the model area. Various inputs like hydrogeological parameters, areal recharge and groundwater abstraction was assigned to the model based on the data available in Upper Yamuna Basin reports and groundwater estimation report of Haryana state. Although the model has been calibrated to the extent possible, the area simulated is comparatively large (more than 7500 sq. km.) with the limitation in data availability in space and time. Further, limited data was available for the semi-confined aquifer. For this aquifer, the aquifer parameters were known at only 8 points out of which only four points were inside the model area. These four points are located in the central part of the study area and no data was available in the northern and southern part of the study area. Further, limited data on recharge/discharge to/from this layer was used in the model development. Consequently, the calibration results for this layer were not so good. Keeping this in view, the results of this modelling are only indicative and are to be used with caution.

The calibrated model was run further for a period of ten years (2005-2015) to see the impact of various pumping scenarios on the groundwater conditions. The results of modelling study indicate that the present rate of groundwater pumping may lead to further deterioration in the ground water situation. Reduction in groundwater pumping from all blocks will arrest the declining groundwater levels from the blocks facing this problem but will further deteriorate the situation in blocks where groundwater levels are rising.

The reduction in surface water irrigation and stepped up pumping from the blocks facing rising groundwater levels will alleviate this problem in such blocks. A combination of reduced pumping from the blocks facing declining groundwater levels and stepped up pumping from the blocks facing rising groundwater levels is likely to alleviate the rising/declining groundwater level problem in the area. This strategy can be tried in the field after a detailed pilot study of a small area.

The pumping from the second aquifer is to be tried after detailed field tests as very less data for this aquifer was available for calibration of the model. The behavior of the available piezometric data suggests that this aquifer is almost phreatic to semi-confined in nature. If this fact is confirmed from the field tests then the water withdrawal from second aquifer will be more sustainable. If the second aquifer is semi-confined to confined, then its sustainability of groundwater use may have to be confirmed for enormous withdrawal of water for irrigation as per the views expressed by field hydrogeologists who have worked in this area.

The reduction in pumping as suggested in some scenarios can be achieved by way of improving water use efficiency and changing cropping pattern (by growing crops which have lesser water requirement than the existing ones). There is enough scope to reduce the recharge by way of lining the canals in the water logged blocks, thereby saving surface water as well as recovering the area from the water logged conditions.

9.9 Limitations of the Modelling Study

1. There was limitation of data in space and time for both aquifers, particularly for second aquifer. The aquifer characteristics were known at very limited points (only 14 points in first aquifer and 8 points in second aquifer), due to which the exact spatial distribution of these parameters in the model was not possible. Also, the monitoring of the groundwater levels in second aquifer was limited both in space and time. Further, the data regarding the confining layer (Layer II) was also very limited, restricting the knowledge of this layer.

2. No data on the groundwater withdrawal from the second aquifer and limited availability of ground water withdrawal data (only monsoon

and non-monsoon) from the phreatic aquifer was a constraint in the calibrated model.

10.0 RECOMMENDATIONS

1. The analysis clearly brings out the deteriorating situation of groundwater in the study area both in terms of declining ground water level in part of the area and rising ground water level in other parts of the area. Groundwater development in most of the blocks falls under critical/over-exploited category. So there is a need to regulate the ground water development in the study area for sustainability of the ground water regime.

2. Stoppage of surface irrigation and increase in pumping by 20% of the present pumping in the blocks facing rising water level and reducing groundwater draft by 20% for all other blocks will alleviate the problem of rising/declining groundwater levels in the study area.

3. The run off generated from the precipitation in this area, can be harnessed by various means to increase the utilizable surface water resources, thereby arresting the declining ground water level.

4. There is need to change the cropping pattern in the area to reduce the crop water requirement and to reduce the stress on the groundwater resources.

5. A pilot project on a small area may be taken up to test the recommended scenario in the field.

6. The second aquifer and other confined aquifers (aquifer 3 and 4) below the phreatic aquifer have to be further studied in detail for the aquifer characteristics and monitored through dedicated piezometers for scientific management of water resources of the area. Such study will also be helpful for water resources management in areas having similar hydrogeological set up, especially in the whole of Indo-Gangetic alluvial plain.

11.0 FURTHER STUDIES RECOMMENDED

1. It is recommended to study the quality aspect of ground water in various aquifers by developing a solute transport model for the area to determine the possible spread of the salinity.

2. The surface water modelling in the study area can also be taken up and the results may be combined with groundwater modelling.

3. Optimization techniques can be combined with the simulation model to arrive at the optimal allocation plan for the study area.

4. It is also recommended to set-up a groundwater simulation model for whole of the WYC command to plan for sustainable groundwater development.

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यस्था समुद्र उत सिन्धुरापो यस्यामत्न कृष्टयः संवभूवुः ।
यस्थामिंद जिन्वति प्राषदेजत सा नो भूमिः पूर्व पेयें दधातु ।।

(अथर्व वेद)

Those who use rainwater wisely by means of rivers, wells, canals etc. for the purposes of navigation, recreation, agriculture etc. prosper all the time.

(Atharva Veda)

शंत आपो हेमवतीः शमु ते सन्तु वर्ष्याः ।
शं ते सनिष्पक्ष आपः शमु ते सन्तु वर्ष्याः ।।

(अथर्व वेद)

One should take managerial action to use and conserve the water from mountains, wells, rivers and also rainwater for use in drinking, agriculture, industries etc.

(Atharva Veda)

Conserve Water - Save Life

WYC near Hathni Kund Barrage

WYC near Yamuna Nagar

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