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DEVELOPMENT OF CONJUNCTIVE USE MODEL FOR LOWER GANDAK BASIN
(PART-I)

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PREFACE

Integrated use of surface and groundwater is termed as conjunctive use. Presently it is recognized as a significant strategy for the optimum utilization of regional water resources, especially when demands of water are increasing and available resources are limited. The National Water Policy, 1987 also recommends planning for conjunctive use right at the formulation stage of the project itself. Even in the existing irrigation projects, the conjunctive use planning has a great scope as it would not only reduce the ill-effects of waterlogging but also helps in optimum utilization of both the resources. Although conjunctive use is in practice in the country in some form or the other, it may not have been done in a planned manner. The present report attempts a conjunctive use study in the Habibpur region of lower Gandak command.

The area has the usual characteristic of having insufficient surface water during Rabi and Garam seasons and excess surface water condition in Kharif season. This inequitable distribution of water leads not only to waterlogging condition for large extent of agricultural area but also affects the agricultural productivity of the region. The area has considerable potential for groundwater development. The groundwater can effectively be used in conjunction with surface water to improve agricultural output and to reduce surface waterlogging conditions. A conjunctive model (groundwater flow model) for the region has been developed to simulate the groundwater behaviour when surface water and groundwater are interacting. The model has been used to predict different scenarios of the extent of waterlogging in the area subject to different stresses.

The study titled "Development of conjunctive use model for lower Gandak Basin (Part-I)" has been carried out by Sri Biswajit. Chakravorty, Scientist `C', Sri N. G. Pandey, Scientist `B' and Dr. Sanjay Kumar, Scientist `B' as per work program for the year 1999-2000 of Ganga Plains North Regional Centre, Patna.

DIRECTOR

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ABSTRACT

A conjunctive use problem involving judicious use of surface and groundwater in the Habibpur region of Gandak command has been attempted in the study. The area is characterized with insufficient surface water during Rabi and Garam seasons and excess surface water condition in Kharif season. The study area falls in the Gandak command and lies between the river Gandak and Vaishali Branch Canal (VBC), one of the branches of the Gandak canal system. The Habibpur sub-distributary from VBC conducts water to the study area. The canal system provides water during Kharif season and only 35-45 days during Rabi season and no flow during summer season when it is extremely needed for irrigation. This uneven availability of surface water in different seasons results in waterlogging and poor agricultural output from the region.

As groundwater potential in the area is yet to be fully explored, it is proposed to use groundwater resources in the region. This can provide two fold advantages for the region. (i) to increase the irrigation water availability for Garam and Rabi crops and (ii) subsequent replenishing of groundwater in Kharif season. This would not only improve the waterlogging conditions but also bring more cultivable area under agricultural practices. Increasing the cropped area in different seasons would also improve waterlogging conditions in addition to increasing agricultural productivity of the area.

A groundwater flow model has been developed for the region to simulate the groundwater behaviour taking into account the surface water groundwater interaction under various external stresses. The calibrated model has been used to predict the waterlogging conditions under increased crop area coverage. The model has also been used to forecast the extent of waterlogged areas on utilizing the groundwater resources of the area.

1.0 INTRODUCTION

Integrated use of surface and groundwater – commonly termed as *conjunctive use* – is now recognized as a significant strategy for the optimum utilization of regional water resources, especially when demands are increasing and available resources are limited. It is estimated that even on full exploitation, the available water resources could cover only half the cultivated area for irrigation (CWC, 1995). It is therefore important that both the surface and groundwater resources have to be used in an integrated manner, by planning conjunctive use as rightly recommended by the National Water Policy. The National Water Policy, recognizes the need for conjunctive use and recommends that the conjunctive use of surface and groundwater should be ensured right from the project planning stage and should form an essential part of the project. The earlier practice of planning of surface and groundwater independently does not permit optimum utilization of water resources in the command and prevents flexibility of system operation.

Recent estimate (1991) of the Working Group set up by Govt. of India on Water logging and salinity indicates that in all irrigation commands, the total extent of waterlogged area is 2.46 mha. Also, 3.06 mha area suffers from salinity problems. In this context, the conjunctive use of surface and groundwater sources in irrigation projects assumes importance as one of the means of achieving sustainable irrigation. In areas of eastern U.P., Bihar etc. where groundwater development in surface irrigation commands has not taken place extensively, the possibility of waterlogging and salinity continues. Thus, planned development of the conjunctive use of surface and groundwater is necessary.

In the present study, a conjunctive use of surface and groundwater has been suggested in the lower part of Gandak basin which may possibly reduce waterlogging condition in the region. Gandak river basin in alluvial plains of North Bihar has a network of canals for surface irrigation. The diversion of Gandak river flow at Valmikinagar is the main source of water for this canal system. The flow in Gandak river is dominantly seasonal and non-uniform. The river has high flows during the monsoon period and low flows during summer and winter season. Consequently, Gandak canal system, which is based on diversion of river flows is incapable to meet surface irrigation requirement in different seasons of the year. Therefore, the irrigation requirement in different seasons and availability of flow in the river have high negative correlation. This situation often leads to waterlogging and drainage congestion during monsoon in the tail reaches of Gandak command. The situation becomes further unsuitable because of shallow water table in the area. This leads to a gross under utilization of agricultural potential of the area and at the same time leads to counterproductive situations due to poor agricultural drainage.

These adverse features of exclusive surface irrigation in Gandak command area can be effectively taken care of by conjunctively utilizing the groundwater for irrigation. Adequate availability of groundwater at relatively low lifts and their hydrologic interaction with river makes such utilization highly prospective. This additional source of water serves two purposes: (i) to increase the water availability for irrigation and (ii) to mitigate the undesirable fluctuations in surface water supply, thus increasing the irrigation intensities in the command area. This would give greater flexibility and better control to farmers in supply and application of water. This on one hand would satisfy the crop water requirement in a more assured way and at the same time help in crop diversification, adopting more remunerative crops and increasing yield. Also, by depressing the water table/piezometric head will improve waterlogging condition, rendering irrigation both hydrologically sustainable and agriculturally productive.

It is therefore essential to know the groundwater potential and surface water potential so that a balanced use of both the resources can be made to maximize the agricultural production throughout the year during all three seasons i.e Kharif, Rabi and Garam (summer) season. *Evolving practically feasible strategy for conjunctive utilization of groundwater and surface water resources in Gandak command area is the main objective of the present study.* The study area falls in the Gandak command and lies between Gandak river and Vaishali Branch Canal (VBC) where there is more probable interaction between the surface and groundwater. A modeling approach involving canal water supply, groundwater resources, interaction between surface and groundwater (stream aquifer interaction), withdrawl from aquifer, recharge, evapotranspiration would perhaps provide an integrated solution.

Generally, the conjunctive use of ground and surface water sources is practiced in order to attain one or more of the following objectives:

i. To increase the total amount of water supply.

ii. The aquifers can be used as sub-surface reservoirs to store excess water and its subsequent withdrawal.

iii. To attain a higher flexibility in supply according to the demand.

iv. To reduce salinity by mixing of different quality of water.

Utilization of aquifer storage in conjunction with surface reservoir has been thought of since 1940. A number of development took place in U.P, Punjab, Maharashtra, Tamilnadu and other states in the forties with respect to utilization of groundwater. However, the optimal utilization of surface and groundwater to meet specific requirement was absent. From 1960 onwards increased attention of central and state governments was focussed on optimal utilization of surface and groundwater resources conjunctively. In Bihar, the command of Sone project has been using groundwater with canal supplies. There is scope of further conjunctive development of surface and groundwater resources in other commands too. In general, groundwater has been developed to a limited extent in private sector in rural Bihar. It has been found to be haphazard and unplanned. Problem of waterlogging has been experienced in irrigation projects of North Bihar. Waterlogging problem can be avoided if the conjunctive use is envisaged in the command area during project planning stage itself.

The conjunctive use may involve different levels of time and space integration. For example, if one parcel of land is irrigated with surface water and if the excess irrigation results in additional groundwater recharge and if this recharge is allowed to flow to another adjoining parcel of land where it is extracted and used as groundwater, it is one way to meet conjunctive use. Another form would be to use surface water in one season (say, in wet season) and to use groundwater in another season (say, in dry season) on the same parcel of land. Yet another form would consist of physical mixing of the water in a common distribution network. A lot of literature is available on how surface and groundwater can be used conjunctively. A brief review of literature is given in the next section.

2.0 LITERATURE REVIEW

Surface water in conjunction with groundwater has been the subject of extensive study. Most of these studies were carried out in a dynamic framework, seeking a rule for allocating the groundwater over time when demand for groundwater varies according to availability of surface water.

Young et.al.(1972) studied the problem of groundwater withdrawal and its impact on streamflow. Their model consists of a hydrologic model and an economic model for studying the stream aquifer relation in the South Platte Valley of eastern Colorado.

Maddock (1974) developed operating rules for the conjunctive use of surface water and groundwater when demand and supply sources are stochastic. These rules allow the quantities of water pumped from wells, diverted from streams, spread and returned to the stream after use to be determined for a given time period even if the required needs and availability of supply are uncertain at the beginning of the time period. These rules are dependent on a technological function relating streamflow interaction with well pumping and with the statistics of the demands, streamflow, pumping, and drawdowns.

Flores et.al.(1978) examined a stream connected aquifer system for optimal water management wherein a physical system is represented by a linear reservoir model and a conditional probability approach is used to estimate the effect of parameter variability. In the study operating rules that minimize the cost of meeting water demands over several periods of time with a single aquifer hydraulically connected to a stream was established.

Bredhoeft et.al.(1983) examined the South Platte system in Colorodo where surface and groundwater are used for irrigation. In the study the extent of groundwater being developed as insurance against period of low streamflow was studied. The result suggests that under prevalent economic conditions the most reasonable groundwater pumping capacity is the total capacity capable of irrigating the available acreage with groundwater thus maximizing the expected net annual benefits and also minimizes the variation in annual income.

O'Mara et.al.(1984) examined alternative policies for achieving more efficient conjunctive use in the Indus basin of Pakistan. In the study, a simulation model is used to link the hydrology of a conjunctive stream aquifer system to an economic model of agricultural production. The result suggests that large gains in agricultural production and employment are possible with efficient alternative policies.

Tsur (1990) studied the stabilization role of groundwater when surface water supplies are uncertain. The economic benefit associated with this stabilization role is analyzed. The methodology is established by taking a case study in Negev desert in South Israel

Paudyal et.al.(1990) used a multi-level optimization technique for solving the complex problem of irrigation management in a large heterogeneous basin. The solution strategy is based on the physical decomposition of a large system into inter-connected sub-systems. In the study various alternative activities such as surface water diversion and pumpage, groundwater withdrawal and recharge, and alternative future operational scenarios are analyzed in an integrated way. The method is illustrated through a case study.

Onta et.al.(1991) suggests a three step modeling approach for comprehensive analysis of the planning problem involving integrated use of surface and groundwater in irrigation. Applicability of the approach is illustrated through a case study of Baghmati river basin in Nepal. The first step involves a stochastic dynamic programming model used to derive the long term operation policy guideline for alternative plans. In the second step, a lumped simulation model is used to evaluate the alternative plans and policies. Finally, a multiple-criteria decision making method is used to select the most satisfactory alternative plan for indicating the system design capacities and water allocation policies.

Georgakakos et.al.(1991) addressed the problem of imprecise parameter and boundary condition in groundwater management. In the study the authors have formulated a stochastic groundwater management problem and subsequently proposed an appropriate solution approach. In the approach, equations of groundwater flow are converted to dynamical state-space system using finite difference and finite element techniques. Parameter and boundary condition uncertainty is incorporated using the small perturbation method. The approach is applied to the management of a two-layer aquifer system with various boundary conditions and uncertainty levels. The results provide useful insight of the system response under uncertainty.

Matsukawa et.al.(1992) applied conjunctive use management model in Mad river basin, California for planning and operational strategies. In this context a conjunctive use model has been extended for developing a planning model that can also be used for short term and long term planning.

Provencher et.al.(1994) presented two methods for approximating the optimal groundwater pumping policy for several interrelated aquifers in a stochastic setting that also involves conjunctive use of surface water. In the first method the value function is estimated by Monte Carlo simulation combined with curve fitting techniques, whereas the second method uses Taylor series approximation for solving a system of equations equal to the number of aquifers. The two methods yield nearly identical estimates of the optimal pumping policy as well as a steady state pumping depth. A case study has been done for Madera County, California to explain the two methods.

Reichard (1995) identifies efficient strategies for meeting water demands using a simulated optimization model for ground and surface water management. In the methodology, three objective functions are considered: (i) minimizing the need for supplemental water, (ii) minimizing imposed water use reductions, and (iii) minimizing the changes from current pumping pattern. The methodology is applied to Santa Clara-Calleguas Basin in South California.

Lall (1995) used a hybrid simulation-optimization strategy for monthly operation of reservoir and aquifer system using historical hydrological data. To demonstrate the utility of the model a case study in Jordan river basin, Utah was taken.

Philbrick et.al.(1998) questioned the intuitive rules based on experiences for management of surface and sub-surface storage. The authors demonstrates the way to incorporate the different capabilities of surface and sub-surface storage for long term application to conjunctive use plan. In the study authors also evaluate the benefits of adding ground water supplies to an existing surface water supply system.

Haken et.al.(1998) developed a management model to determine optimal water allocation policies for time variant surface and groundwater supplies in a hypothetical system. The model minimizes deviation from a set of rule curves defined for storage in the reservoir and along the stream course, so as to consider possibilities for storage of excess water during wet periods and its distribution in subsequent dry periods. The management model is formulated and solved for monthly time steps. The impact on operating policies of groundwater supplies has been analyzed through sensitivity

McCarl et.al.(1999) investigated a combined hydrologic-economic model for the Edwards Aquifer near San Antonio, Texas to take care of water markets, to protect agricultural rights and the species habitat. The results indicate that proposed pumping limits have adverse consequences on agriculture uses and decreases the welfare of current aquifer pumping users but at the same time gains regional economical welfare from protection of species habitat.

In the present study, the groundwater fluctuations for each season i.e Garam, Kharif and Rabi have been modelled using MODFLOW package. At present MODFLOW is most widely used groundwater flow modelling package in the world. The package is capable to simulate steady and non-steady flow in three dimensions for an irregularly shaped flow system in which aquifer layer can be confined, unconfined, or a combination of confined and unconfined. Flow from external sources, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river, can be simulated. The study area in lower Gandak command has all these complexities. Thus considering these complexities and the objective of the present study MODFLOW package has been thought to be most suitable to deal with such field problem. The sensitivity of water table due to increase in the percentage of cultivated area in different cropping seasons and its effect on waterlogging conditions have been demonstrated. The detailed description of the study area and analysis has been given in subsequent sections.

3.0 DESCRIPTION OF THE STUDY AREA

The study area is a part of the alluvial plains of the Indo-Gangetic basin. Based on the surface water network system, the area is described as a part of the lower Gandak basin. The index map and the model boundaries of the study area are shown in figures 1(a) and 1(b) respectively. The area falls mainly in Vaishali and south of Muzaffarpur districts. The river Gandak forms the western boundary of the area. Vaishali Branch Canal (VBC) bounds its eastern side. Habibpur sub-distributory is an off take of VBC and is in the middle of the study area. The area is measured between the latitudes of 25°56′ and 26°05′ N and longitudes of 84°57′ and 85°08′ E and is estimated to be 181.6 sq km.

The area comprises of an extensive plain formed by the alluvium brought by river Gandak. It falls in the southern part of Gandak basin sloping towards SSE. The land slope varies from 1 in 5,000 to 1 in 20,000. The maximum ground elevation is 56.27m above MSL in the north east part and minimum is 50.90m above MSL. The topography of the study area is shown in figure 2. The river Gandak flows towards south east direction and meets Ganga river near Hajipur. Full channel flow generally lasts only for some weeks during the peak rainy season. The erosional and depositional process of the basin have been mainly controlled by Gandak river The Gandak valley has more or less established itself and the various drainage channels in this valley have steady courses with no marked shifting tendency. The area is plain with few shallow depressions and marshes locally known as *`Chaurs'* having no outlets to river. During high floods in the rivers of the area and/or when the level of Ganga is high, these *`Chaurs'* form a sparawling sheet of water, rendering kharif cultivation impossible. Occasionally, these condition continue till late in the month of December or January, rendering the land unfit for `Rabi' cultivation.

3.1 SOIL CHARACTERISTICS AND LANDUSE PATTERN

The soil of the area is capable of retaining moisture and is very fertile. The top soil is characterized by more percentage of silt and classified as silty loam. Soil samples were collected from two places at different depths in Habibpur area and textural classifications were done by ASTM sieve analysis. The result is shown in table 1. Agricultural activity is done in most part of the area and the bulk of its population is engaged in agriculture.

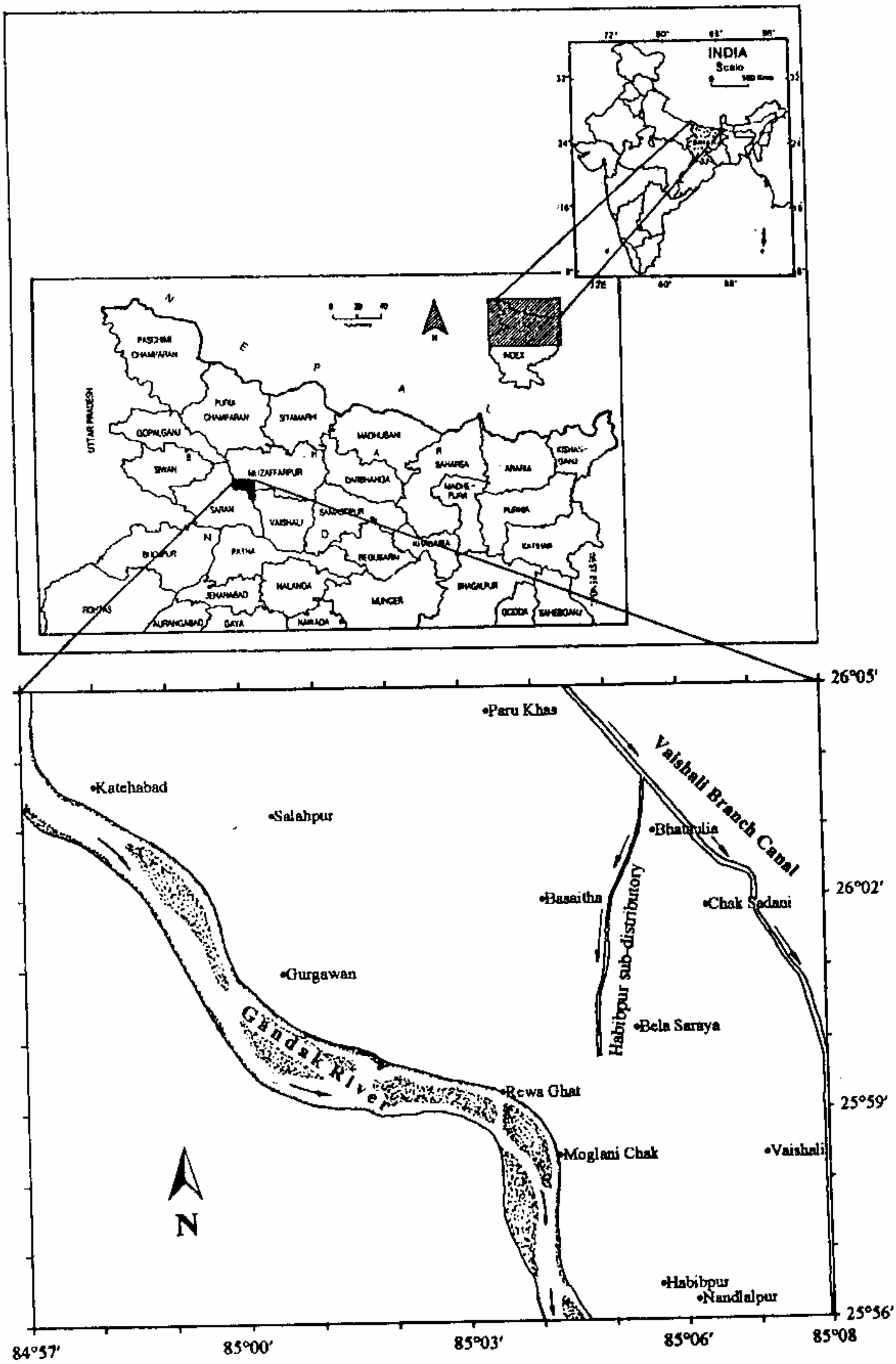


Figure 1(a) : Index map of the study area.

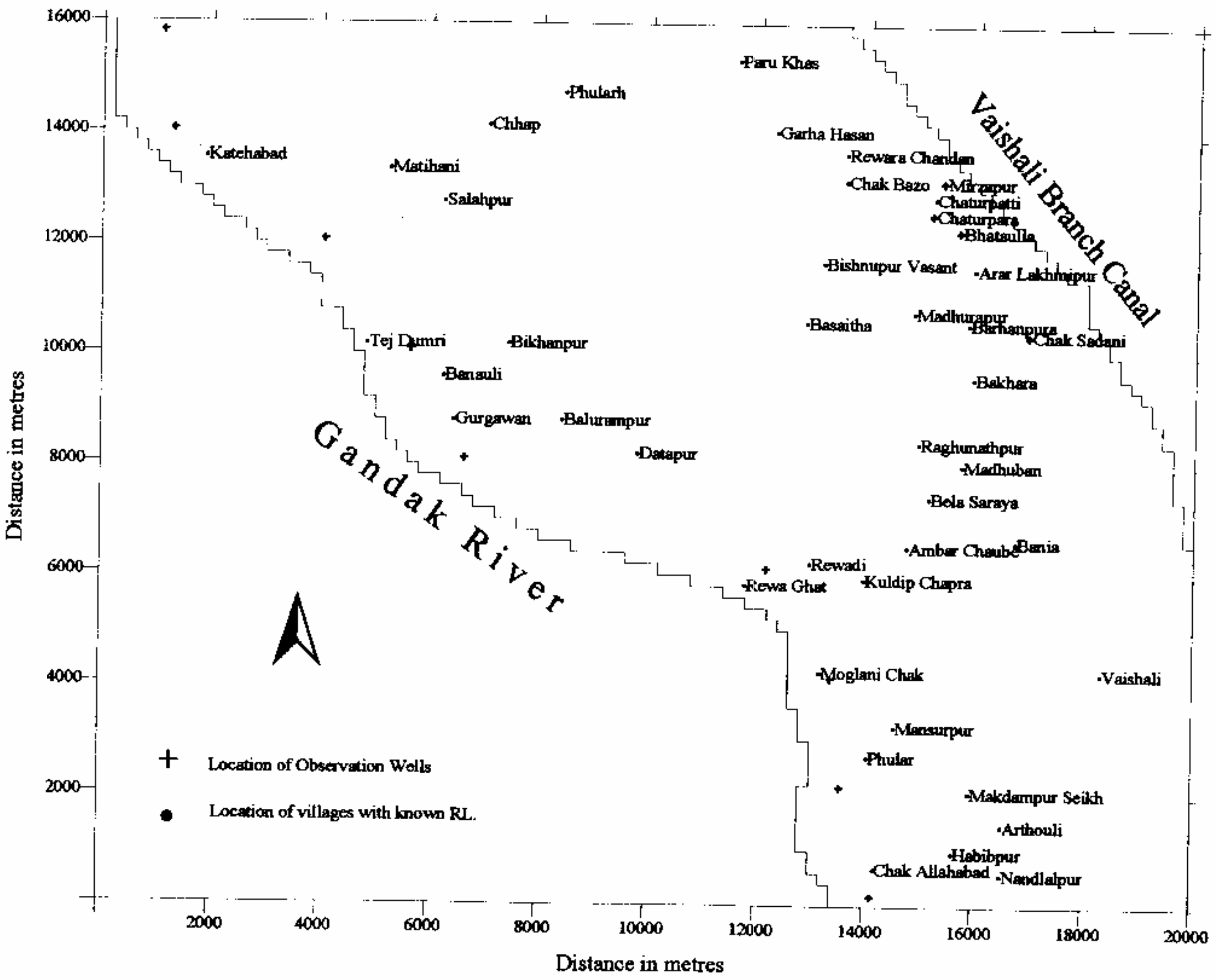
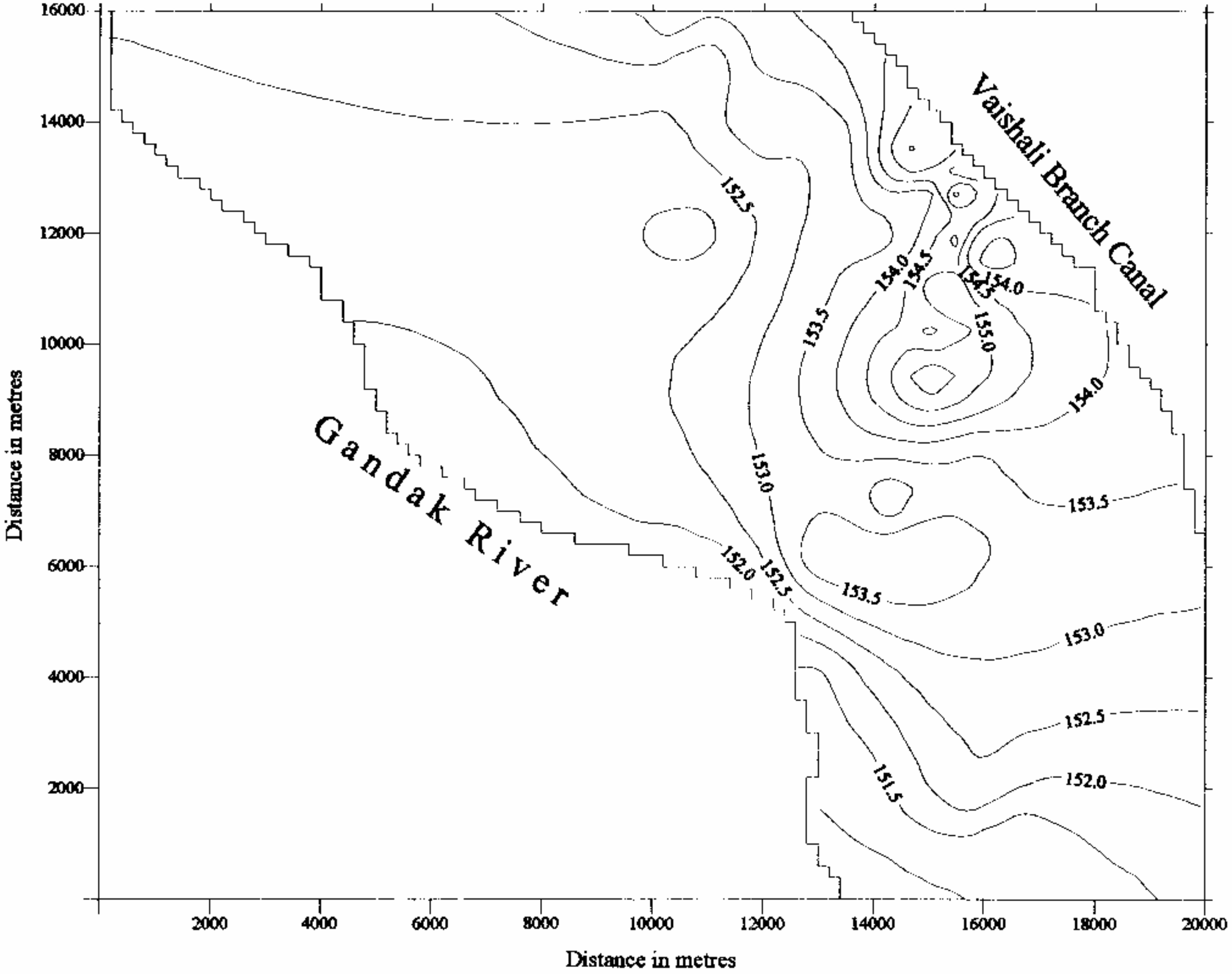


Figure 1(b) : The study area with model boundaries.



* 100m is the arbitrary datum above MSL

Figure 2 : Topography of the model domain.

The area is highly fertile and well suited for both food and cash crops. The density of population in the area is 1053 persons/km^2 as per 1991 census.

Table 1: Textural classification of soils in the study area (near Habibpur sub-distributery).

Chainage	Depth (cm)	% Sand	% Silt and Clay	Av. Classification by USDA	Remarks
`0' RD	30	42.0	58.0	Silt loam	Clay contents are 10-15%. The top layer root zone depth (upto 2.0m) is predominantly of silt and fine sand.
`0' RD	60	62.0	38.0	Sandy loam	
`10' RD	30	45.0	55.0	Silt loam	
`10' RD	60	32.0	68.0	Silt loam	

* 1 RD = 1000 feet.

It has been reported (CGWB, 1993) that as a whole in Vaishali district, about 68% of the cultivable area remains unirrigated while groundwater contributes about 26.7% of the total irrigation and the rest by surface irrigation (5.3%). In groundwater irrigation, tube well plays a major role.

Land use and its changing pattern in the study area is similar to those in the entire Gandak command. As per the Directorate of Statistics, Govt. of Bihar, the land use for different classes of land in 1982-83 i.e after a decade of operation of the Gandak project for the portion of the command lying in Bihar (24,133 sq km) is given in table 2:

Table 2: Land use pattern and percentage of different classes of land over total land.

Sl. No.	Classes of Land Use	Area in '000 ha	% of total area
1.	Total area as per village record	2413.29	
2.	Forest land	91.92	3.81
3.	Uncultivable waste land	79.08	3.28
4.	Land put under non-agricultural use	337.00	13.96
5.	Land under permanent pasture	5.59	0.23
6.	Land under misc. trees and groves	71.86	2.90
7.	Cultivable waste land	14.15	0.59
8.	Current fellow	170.36	7.07
9.	Other fellow	30.22	1.25
10.	Net area sawn	1613.11	66.83
11.	Area sawn more than once	678.33	
12.	Gross cropped area	2291.44	

(Source: WALMI, CWRS and IIMI report, 1993)

During 1990-91 land use classifications were done from satellite imageries by Bihar Remote Sensing Application Centre for two major crop seasons (Kharif and Rabi) in and near the study area. Their findings are given in table 3. The table shows that Kharif and Rabi crops are grown in approximately 60% and 36% of the area and the fellow land during Kharif and Rabi season on an average is 12% and 36% respectively. These figures have implication and significance for cultivation of major crops in different cropping seasons in the area.

3.2 CROPPING PATTERN

As far as cropping pattern of the study area is concerned, it is predominantly a paddy growing area. Maize and wheat are other important cereal crops. `Arhar', Gram, `Moong' and `Masoor' are the principal pulses grown in the area. Rapeseed and Mustard are major oil seed crops. Sugarcane, Chilly and Tobacco are the main cash crops.

As in most parts of North Bihar, there are three distinct crop seasons; Garam or Summer (March to June), Kharif (July to October) and Rabi (November to February). The most common Kharif crops are paddy and maize and during Rabi, wheat, winter maize, gram, mustard and tobacco are taken. In Garam, lands are either kept fellow or certain summer crops like maize and vegetables are grown. In addition to these crops, perennial crops like sugarcane are also grown. Apart from these crops grown in various seasons, mixed cropping, i.e. growing more than one crop in a given crop season is also practiced.

3.3 SURFACE WATER HYDROLOGY

3.3.1 Gandak River

The river Gandak which is in the western side of the study area is perennial in nature flowing towards south eastern direction before meeting the river Ganga near Hajipur. During monsoon season the river carries high discharge inundating its flood plains and leaves many patches in the adjoining areas under surface waterlogging condition for a considerable length of time. During lean period the river width narrows down to an extent about 100 m at many places. A close look at the 21 years discharge data (1970-91) of Gandak river at Valmikinagar reveals maximum discharge of 15,540cumec occurring

Table 3: Land use pattern of the study area during Kharif and Rabi season 1990-91.

Sl.	Block	Season	Percentage area under						
			Cultivation	Forest	Fellow	Waterlogged*	Marshy	Water Bodies	Settlements
Vaishali District									
1.	Hajipur	Kharif	55.19	6.65	9.36	2.82	0.10	7.88	18.00
		Rabi	34.77	6.65	29.20	3.50		7.88	18.00
2.	Mahua	Kharif	60.19	2.47	11.19	7.22	0.75	0.18	18.00
		Rabi	41.25	2.47	33.45	4.65		0.18	18.00
3.	Goraul	Kharif	60.60	0.43	12.93	7.39	0.63		18.00
		Rabi	34.40	0.43	41.44	5.73			18.00
4.	Lalganj	Kharif	64.45	1.67	6.42	4.95	1.08	0.43	18.00
		Rabi	30.50	1.67	42.83	3.15		0.43	18.00
5.	Vaishali	Kharif	64.76	2.93	11.00	2.86		0.45	18.00
		Rabi	39.55	2.93	35.38	1.88	1.82	0.45	18.00
Muzaffarpur District									
6.	Saraiya	Kharif	56.12	0.64	17.69	5.34	0.73	1.48	18.00
		Rabi	38.35	0.64	37.51	2.46	1.56	1.48	18.00
7.	Paroo	Kharif	65.36	0.35	7.49	8.18	0.30		18.00
		Rabi	38.00	0.35	34.62	3.21	0.21		18.00

(Source: WALMI, CWRS and IIMI report, 1993)

*The Waterlogged coverage shown in the table has been estimated from satellite map and thus is surface waterlogging.

sometimes during July to September and minimum of 305cumec sometimes during February/March (Water year book 1991).

The contour plot of water table apparently shows that the river Gandak is mostly an influent river during monsoon season and effluent during lean period. The river stage data of Gandak measured at Rewaghat and Lalganj falling in the study domain show that during monsoon months the water level go as high as 55.41m (above MSL) at Rewaghat and 51.43m (above MSL) at Lalganj. The bed slope of the river on an average is between 1:15,000 to 1:20,000. The width of the river varies from section to section. The spread of the river during monsoon month goes as high as 1.00 km at some places.

3.3.2 Gandak Canal System

The Gandak irrigation project was taken up to ensure irrigation facilities to about 17.894 lac ha of land of the eight adjoining districts of North Bihar. These districts include Gopalganj, Muzaffarpur, Vaishali, Samastipur, West Champaran, East Champaran, Siwan and Saran. Three main canals have been constructed to receive water from the 739.33 m long Gandak main barrage at Valmikinagar. These canals are the *West main canal (Saran main canal), the East main canal (Tirhut main canal)* and the *Nepal west canal.* The Tirhut main canal provides irrigation to about 6.772 lac ha of land in different districts of Bihar including Vaishali district.

The discharge in the river is diverted to Main Western Canal (MWC) and Nepal Western Canal (NWC) on the right having a design discharge of 544.5 cumecs and to Eastern Main Canal (EMC) with a design discharge of 443.4 cumecs. Vaishali Branch canal (VBC) takes off at 554RD of Tirhut Main Canal. It is an unlined canal. A schematic diagram of EMC and TMC showing the off take of VBC is shown in figure 3.

The VBC forms the eastern boundary of the study domain having an average bed slope of 1:7000 with side slopes 1:1.5. The bottom width of the canal is more at the off take point of TMC (at '0' RD of VBC) and it is 17.5m having a design discharge of 36.95 cumec. The bottom width and the design discharge is less at the downstream side. The bottom width and design discharge of VBC at 138.2 RD from where the Habibpur sub distributory takes off is 10 m and 15.9 cumec respectively.

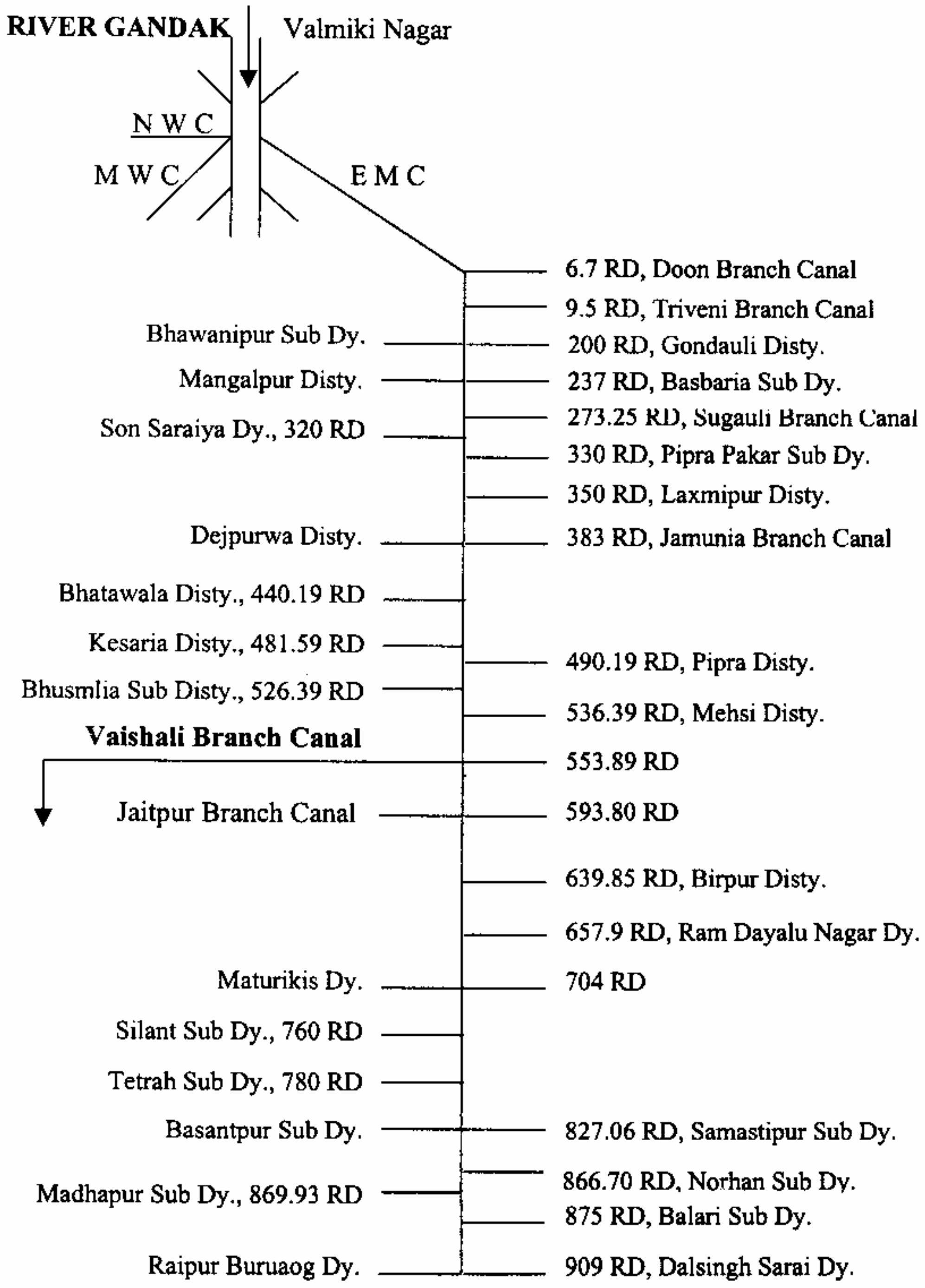


Figure 3: Schematic Diagram of Eastern Main Canal of Gandak Irrigation Project

Habibpur sub-distributory – an unlined canal takes off at 138.2 RD of VBC planned to serve CCA of 4062 ha with a design discharge of 2.264 cumecs in a length of 43.8 RD. The slope of the canal has been kept at 1:4500 having bottom width of 3.5m. A schematic diagram of VBC is given in figure 4. Habibpur sub-distributory provides irrigation facility through 18 number of outlets of 0.025cumec average discharge each. There are five state tube wells and more than 900 private tube wells in the command.

3.4 GROUNDWATER HYDROLOGY

Groundwater is available in water table condition at shallow depths. Depth to water table is influenced by topography, distribution of drainage channels, surface water bodies and rainfall. The depth to water table is minimum during post monsoon period. The maximum depth to water table is observed in the north- east part where the topography is high (3.0-3.5m bgl) and reduces towards the river Gandak to the extent that surface waterlogging condition prevails in an of 40-45 sqkm during monsoon season in the study area. During the pre monsoon period, the water table declines and the depth to water table increases to 5.0-5.5m in the north east part and 0.6m near Gandak river. The depth to water table at the end of the post monsoon and pre monsoon periods are depicted in figures 5 and 6.

It was difficult to ascertain the number of tubewells in the category of shallow (0-15m), medium (15-30m) and deep (>30m) operating in the area. Tubewells operating in the area are mostly privately owned and there are only a few numbers of state tubewells operating in the area. From tubewell census of the area, shallow privately owned tubewells are 957, out of which irrigation figures are available for 345. (WALMI Report, 1993). Generally, these private shallow tubewells have irrigation capacity of 2-5 ha each (CWC, 1995) with a discharge of 10-20 m^3/hr (CGWB, 1993).

3.4.1 Sub-Surface Geology

The sub surface formations consist of a thick pile of unconsolidated alluvial sediments having different textures, alongwith their admixtures. They form the aquifers of the area. Thick and promising aquifers are fine to medium sands available at different depths. If these aquifers are tapped, they can meet the demand for irrigation to a considerable extent.

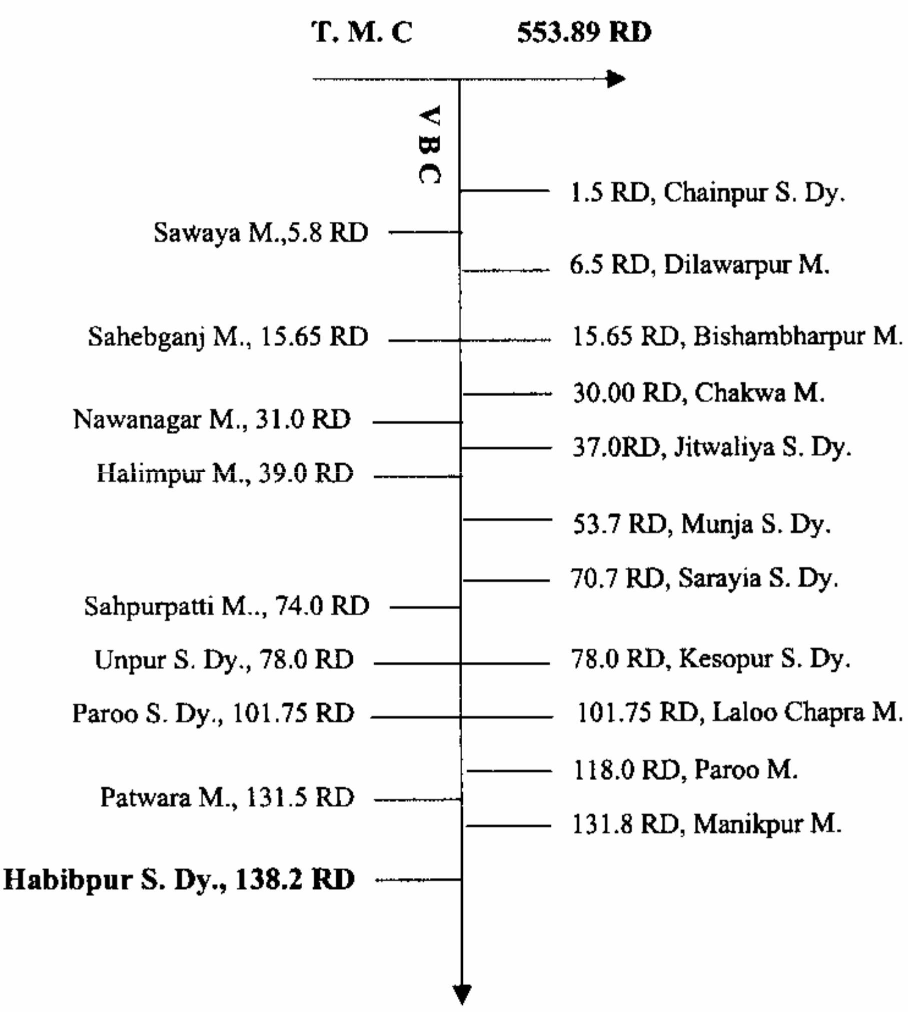


Figure 4 : Schematic Diagram of Vaishali Branch Canal (VBC).

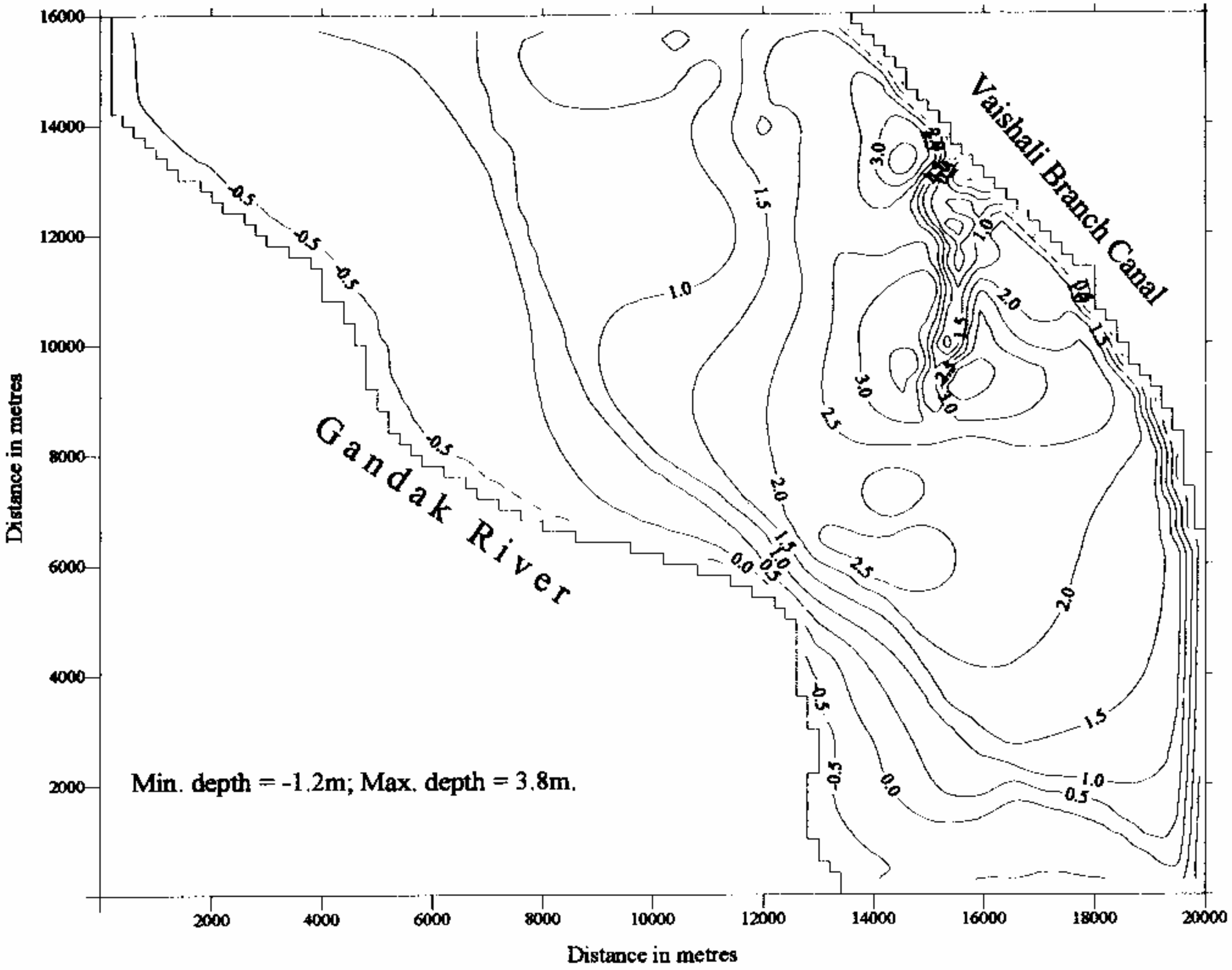


Figure 5 : Depth to water table contours (m) in post-monsoon season.

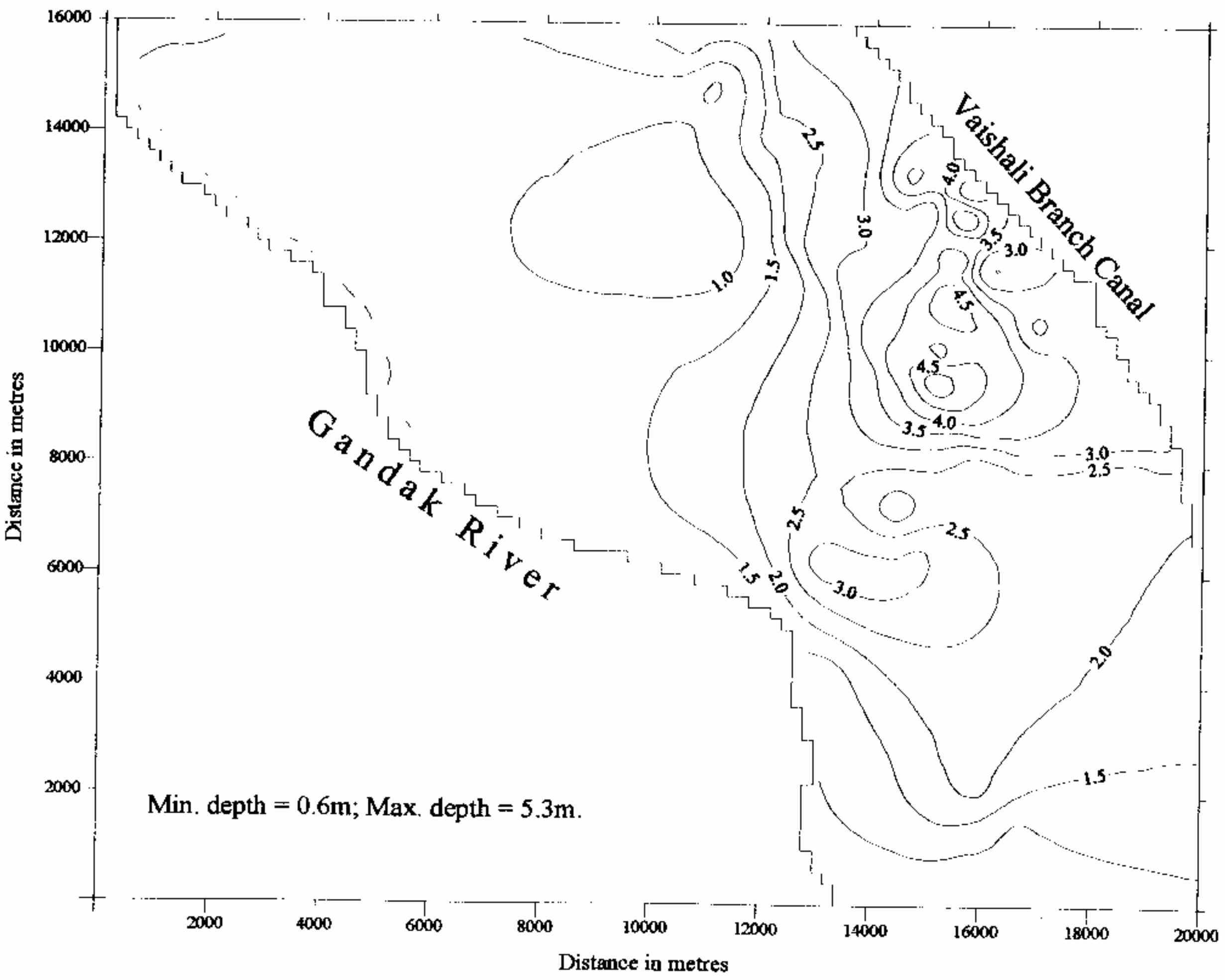


Figure 6 : Depth to water table contours (m) in pre-monsoon season.

The top surface is mostly patched with formation of fine sand mixed with silt. On an average the thickness of this layer is 15 to 20m. Lithological informations of seven VASFA (Vaishali Small Farmers Association) boreholes in the study area (table A-1 in appendix A) indicate a complex sub-surface geological formation with changing lithological units. The sub-surface formation consists of sand of various grades, silt, clay, gravel and their admixtures. This can be seen from the lithologs of seven boreholes of VASFA (appendix -A). From the table a general trend of different sub surface formations is difficult to establish. Therefore, similar lithological units were combined which indicate that formations can be grouped into three categories namely fine sand, clay mixed with fine sand and sand for all the seven boreholes. These reclassifications have been done to approximate the number of layers required as an input to the Conjunctive use model.

The reclassified formations of seven boreholes can be seen in table A-2 (in appendix A). From the table, the trend of the formations are; top layer consisting of fine sand, second layer of clay mixed with fine sand and the third layer consisting of sand and then followed by clay or sandstone. The average thickness of these formations are: 15m, 15m, and 50m respectively. Most of the wells are shallow wells tapping the first layer unconfined in nature and a few deep tubewells (state tubewells) tapping the deeper zones in the third layer semi-confined in nature. The aquifer in the study area can thus be considered as *unconfined to semi confined aquifer system*.

3.5 AGROCLIMATE

The study area is in monsoon sub-tropical zone. The average annual precipitation is in the range of 1168 mm out of which 10% occurs during *Garma* (hot weather) season from March to June, 85% occurs during *Kharif* season from July to October and the rest i.e only 5% occurs during *Rabi* season from November to February.

The temperature of the study area is high during April to June. The highest temperature is recorded in the later part of May or early June when it may go up to 40°C. With the onset of monsoon temperature begins to drop. The coldest temperature is recorded in January at a mean of about 13.5°C. In February, temperature rises slowly and from March onwards, the rise is more rapid.

The study area as most of the Gandak command is a humid area. Humidity is highest in the monsoon months (maximum around 90%) and lowest in March to May (minimum around 35%). Humidity is also high in November-December.

3.5.1 Evapotranspiration (ET)

The potential evapotranspiration (ET_0) of reference crop is defined as the rate of ET from an extensive surface of 8-15 cm tall, disease free, green grass cover of uniform height, actively growing, completely shading the ground and not short of water (FAO-24).

Hargreaves (1985) published crop water evaluation manual for India in which ET_0 at different locations throughout the country in map (point data) as well as in tabular form for different months of the year for different locations of the country are available. Ambient air temperature and solar radiation are two important weather parameters influencing potential water use. Hargreaves calculated ET_0 considering the above two parameters. ET_0 values pertaining to the study area were taken from the average ET_0 values available for two nearby locations viz. Muzaffarpur and Patna (table 4). The crop water requirements were calculated taking the average rate of ET_0 of above two districts.

Table 4: Monthly ET_0 (mm) of Muzaffarpur and Patna

Place	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Muzaffarpur	98	114	173	206	243	195	154	146	146	162	119	96
Patna	98	116	176	209	238	202	151	143	162	161	123	99

(Source: Hargreaves, 1985).

3.6 CROP WATER REQUIREMENT

Crop Water Requirements (CWR) for a particular crop is defined as the depth of water needed to meet the water loss through evapotranspiration (ET_{crop}). In addition, water needed for land preparation and special needs viz. to account for seepage and percolation loss to maintain the submergence (in case of paddy) and at the time of harvest (in case of groundnut) etc. are added. Mathematically CWR can be written as:

$$CWR = ET_{crop} + \text{Added water requirements.}$$

ET_{crop} is the actual evapotranspiration of a particular crop (Consumptive use). It depends on the crop coefficient (K_c) and is given by the relation:

$$ET_{crop} = ET_o * K_c$$

Crop coefficient is a function of type of crop, its rate and growth stage, growing season and the prevailing weather conditions. The value of K_c have been used from FAO-33 (table 18).

Net Irrigation Requirement (NIR) is the depth of water required for meeting evapotranspiration (ET_{crop}) minus contribution by precipitation, groundwater, stored soil water and does not include operational losses and leaching requirements.

$$NIR = ET_{crop} - \text{Effective rainfall etc.}$$

or, $$NIR = ET_o * K_c + \text{special need if any} - \text{Effective rainfall etc.}$$

The effective rainfall is a function of monthly ET_{crop}, mean monthly rainfall and effective root zone storage *excepting paddy*. The mean monthly rainfall has been taken from Bihar irrigation commission report for 70 years Normal Monthly Rainfall (mm) pertaining to Vaisali District given in table 5. The effective rainfall has been estimated from FAO-24 (table 34) given in appendix-B. For Paddy, the calculations of effective rainfall is done by:

$$\begin{aligned} P_e &= 0.8P - 25 \quad (\text{when } P>75 \text{ mm/month}) \\ &= 0.6P - 10 \quad (\text{when } P<75 \text{ mm/month}) \end{aligned}$$

Where, P_e is the effective rainfall (mm) and P is the mean monthly normal rainfall.

Table 5 : 70 years normal monthly rainfall (mm) of Vaisali District.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22.4	14.8	8.7	7.8	27.9	151.2	263.3	284.1	200.7	51.8	9.9	3.4

(Source: Bihar Irrigation Commission Report, pp 53)

Net irrigation requirement of each crop in the study area was calculated for the entire growing period of different crops separately in different seasons (details of calculations given in Appendix-B). The summery of different crops grown in different seasons and their NIR is given in the following table:

Table 6: Net irrigation requirement of crops in different seasons.

Sl.	Crop	NIR (mm)	Sl.	Crop	NIR (mm)
Garam season			*Rabi season*		
1.	Vegetables	555.35	1.	Wheat	522.88
2.	Maize	546.81	2.	Maize	314.15
			3.	Potato	413.96
Kharif season			4.	Mustard	487.17
1.	Paddy	423.88	5.	Tobacco	414.95
2.	Maize	97.44	6.	Gram	431.93

While taking care of the NIR in the Conjunctive use model, the maximum value of NIR in a particular season will be considered as an input to the model for the net cropped area.

4.0 METHODOLOGY

Based on intended objectives and nature of study, different concepts can be applied to formulate a model particularly for solving real-life situations confronted with a number of questions. The effectiveness of model's output depends on how accurately one conceptualizes the problem, and strength of the input database. In case of groundwater flow modeling, selection of the flow domain and its initial and boundary conditions besides the system parameters, such as; transmissivity and storativity values are important.

For an one-dimensional straight forward simple boundary condition problem, solutions can be given by an analytical model. However, for problems of complex boundaries and varying hydrological conditions as usually observed in most of the real-life situations, analytical solutions of the equation of flow are not available. The method suitable for solving a real-life flow problem is a numerical modelling due to its capacity in solving large and complex groundwater problems having spatial heterogeneities and anisotropy.

In numerical modelling, a continuous aquifer system is replaced by an equivalent set of discrete elements. Second, the equations governing the flow of groundwater in the discretized model are written in finite-difference (or finite element) form. Both the space and time are treated as discrete parameters. Finally, a set of finite difference equations are solved numerically.

Many things can be done with a groundwater model, but model's value is *limited* where the aquifer and overall groundwater system is poorly understood. The model demands that the aquifer characteristics be well known as far as possible, the water table has been carefully monitored, rainfall figures are reliable and the recharge mechanism is carefully considered.

4.1 MODELLING TOOLS

4.1.1 Flow Model - MODFLOW

MODFLOW is a MODular 3-dimensional finite difference groundwater FLOW model developed by McDonald and Harbough of the USGS, USA in 1988. It simulates steady and non-steady flow in three dimensions for an irregularly shaped flow system in which aquifer layer can be confined, unconfined, or a combination of confined and unconfined. Flow from external sources, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and stream-aquifer interaction can be simulated

MODFLOW uses a modular structure wherein similar program functions are grouped together. The modular structure consists of a main program and a large number of independent subroutines called `modules'. The modules, in turn, have been grouped into `packages'. A package is a group of modules that deals with a single aspect of simulation. For example, the option `Well package' simulates the effect of wells, the `River package' simulate the effect of river etc.

MODFLOW discretizes the model domain with a mesh of blocks called cells, the location of which are described in terms of rows, columns, and layers.

The period of simulation is divided into a series of 'stress period' within which stress parameters are constant. Each stress period, in turn, is divided into a series of time steps. The user specifies the length of the stress period, the number of time steps at each stress period, and the time step multiplier. Using these terms, the program calculates the length of each time step in the stress period. Thus, within a simulation, there are three nested loops: a stress-period loop, within which there is time-step loop, which in turn contains iteration loop.

Discretization of a system describing by a partial differential equation in space and time, forms a number of simultaneous linear algebraic equations. MODFLOW has the option of a number of iterative methods, such as Strongly Implicit Procedure (SIP), Slice Over Relaxation Method (SSOR) and Pre Conjugate Gradient Method (PCG) to obtain the solution of linear algebraic equations.

4.1.2 Mathematical Background of MODFLOW

The three dimensional unsteady movement of groundwater of constant density through porous earth material under equilibrium condition in a heterogenous anisotropic medium can be described by the following partial differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad (1)$$

Where,

K_{xx}, K_{yy}, K_{zz} : hydraulic conductivity along major axes $[LT^{-1}]$,
h : potentiometric head [L],
W : volumetric flux per unit volume and represents sources and/or sinks of water $[T^{-1}]$,
S_s : specific storage of the porous material $[L^{-1}]$ and,
t : time [T].

In general, S_s, K_{xx}, K_{yy} and K_{zz} are function of space and are aquifer parameters, whereas W and h are functions of space and time and are variables. This equation for flow together with specification of flow conditions at the boundaries of an aquifer system and specification of initial head conditions, constitutes a mathematical model of groundwater flow.

4.1.3 Discretization of the Study Area

The east and west boundaries of the study area are governed by the layout of Vaishali Branch Canal and Gandak rivers respectively with varying distances between them as they flow from north to south. The distance between the extreme point of the river Gandak in the western side, and the extreme point of the VBC in the eastern side is 20 km. North and south sides do not have any conventional boundaries. The modelling area has been chosen as 20 km. in length in the east-west direction, and 16 km. in width in the north-south direction. The area outside the river and the canal boundaries are beyond the interest and has been considered as inactive.

There are no standard procedures for fixing the grid size. It is the choice of the modeler to decide and select the grid size(s). Smaller the size of grid, more the number of gridal cells and larger the computational burden. Finer grids provide detailed scenarios in the local scale and preferred when representative database are available. Requirement of output results and the field conditions can be a guideline to select the grid size. The study area of 20 km X 16 km has been divided into 100 X 80 equal sizes gridal network i.e 8,000 cells having a cell dimension of 200 m X 200 m. The discretized area is shown in figure 7.

Thus, the number of active cells in the model domain is 4540 having an area of **181.6** sqkm. Three layers have been considered in the model based on the sub-surface geology of the area as explained in section 3.4.1. Accordingly the average thickness of three layers from top are 15m, 15m and 50m respectively.

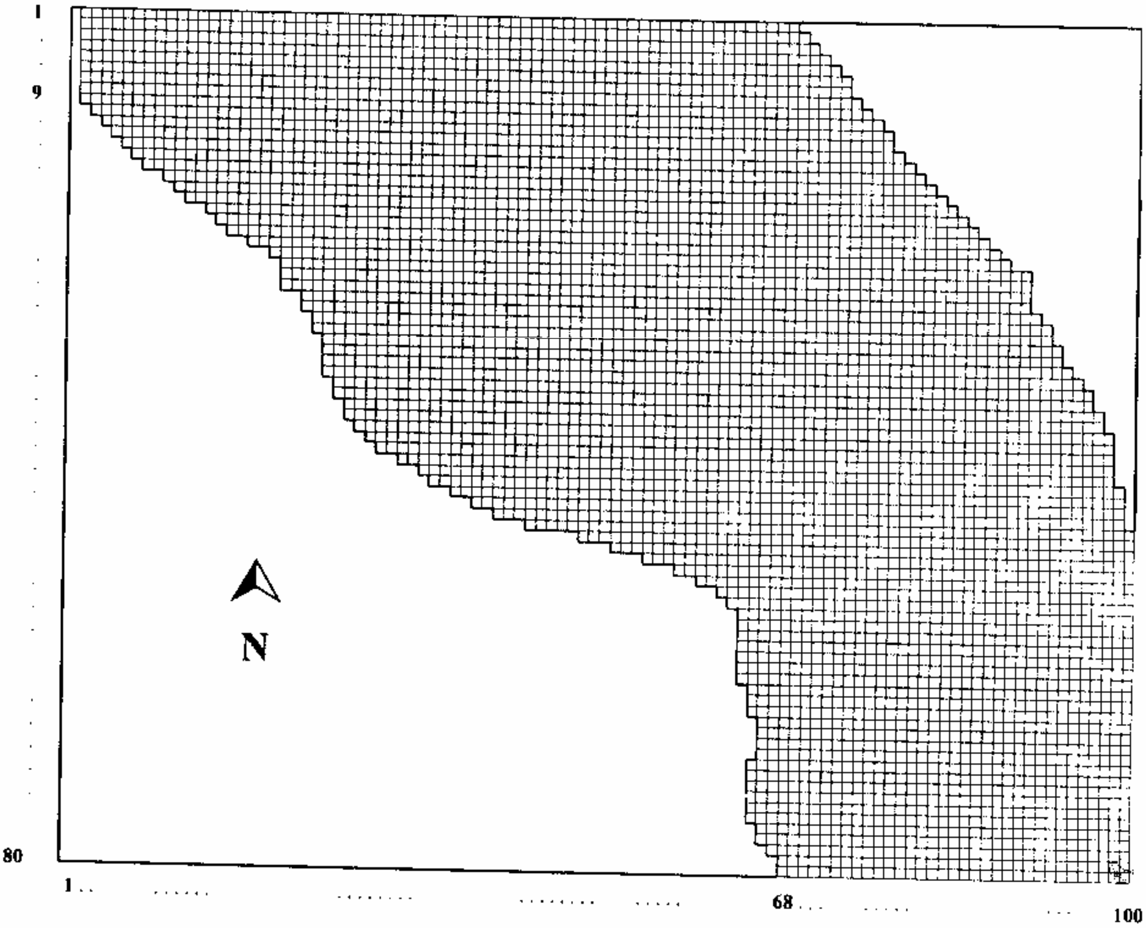


Figure 7: Discretization of the study area - Gandak on west and VBC in the east. (Grid size: 200m X 200m, 80 rows and 100 columns).

5.0 FLOW MODELLING

A groundwater flow model computes piezometric head and water table elevation under different hydrologic conditions and external stresses with respect to space and time. The groundwater flow equation (1) indicates various input requirements for the model. Basically, the input requirements are aquifer parameters (hydraulic conductivity and specific storage) and time varying inflow-outflow terms (recharge from rainfalls, evapotranspiration losses, recharge from river/canals, inflow-outflow across a boundary etc.).

5.1 INPUT DATA PREPARATION

5.1.1 Hydraulic Properties

For a 3-D flow model, hydraulic conductivity (K) and specific storage (S_s) are the model parameters. These parameters are usually estimated from pump test data. Vaisali district report (CGWB, 1993) indicates that the transmissivity (T) of the aquifer increases towards north east direction and decreases towards south west direction. The range of transmissivity values have been given in the range of 400-700 m^2/day with specific yield and coefficient of storage (S) as 12-20% and 0.15 respectively and has been termed as good aquifer. Since location specific input parameter values were not available the representative value of hydraulic conductivity and specific storage were taken from the standard literature (Krusman, 1991 and Boonstra, 1989) for different aquifer materials for three layer aquifer system (although not very distinct) in the study area as described and reclassified earlier. The input value of K for first, second and third layers vertically downwards have been taken as 10.0 m/day, 1.0 m/day and 25.0 m/day. Similarly, specific storage values are 0.01, 0.002 and 0.0001 for three layers (re-classified). These values will be modified during the process of calibration of the model, if needed.

The vertical hydraulic conductivity which is also an input parameter to the model has been taken to be 1/20 times the horizontal hydraulic conductivity uniformly distributed over the area. The porosity has been assumed to be 0.20 for all the three layers.

5.1.2 Initial Conditions

The initial condition was taken in Garam season. One year observed daily watertable data (10-05-91 to 12-05-92) for four locations at Mirzapur, Chaturpara, Bhataulia and Chak Sadani were available. Since observed water table data were scanty, additional 9 wells were assumed adjacent to the river Gandak having fluctuation of water table elevation same as that of the stage of Gandak river. The highest water table elevation is observed in the north east part of the area and gradually decreases towards Gandak river (figure 8). For the sake of convenience all the water table data were transformed and elevated with respect to a reference level of 100m above msl.

5.1.3 Boundary Conditions

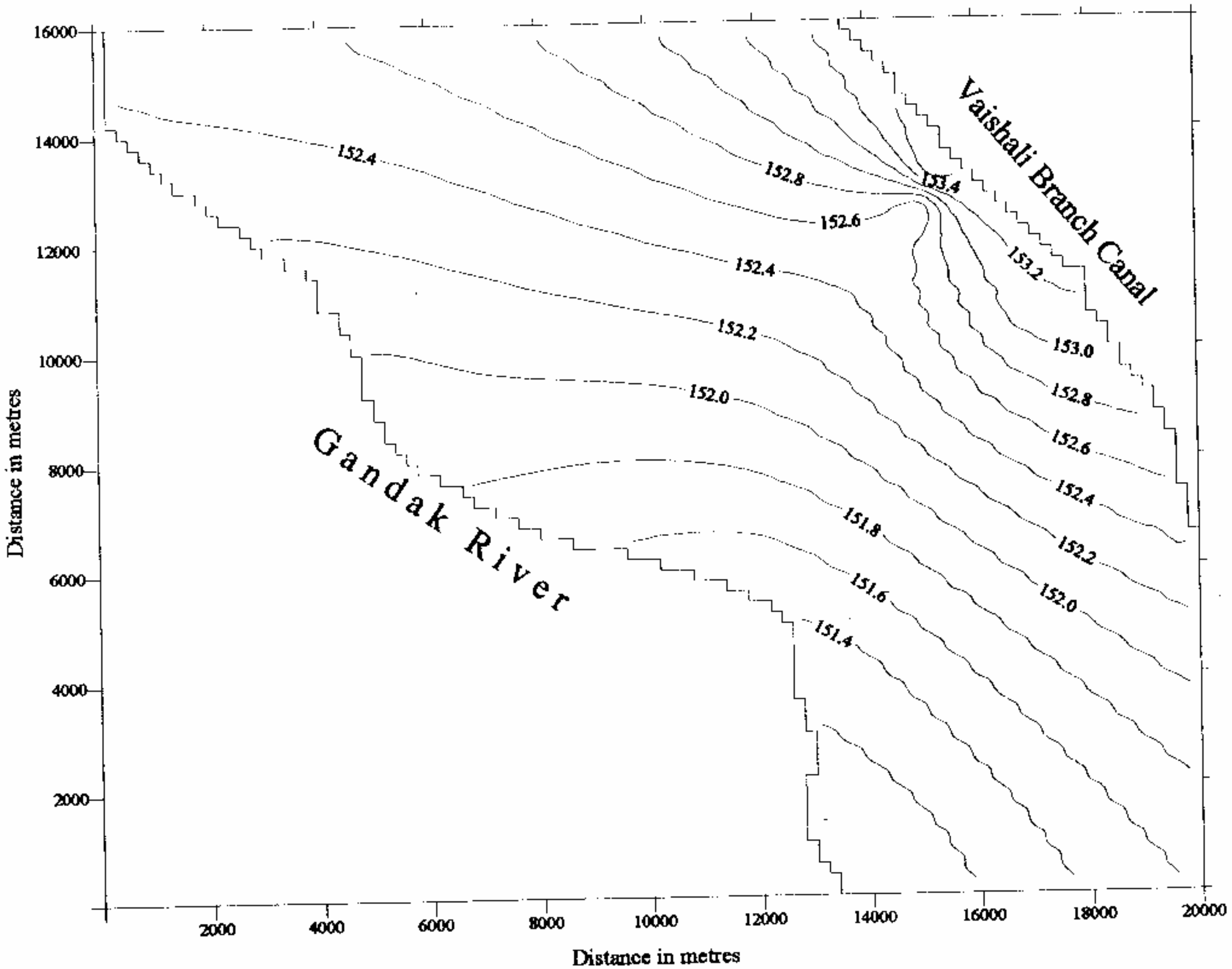
Ideally, a groundwater basin boundary should form the boundary condition to solve the flow equation. In the absence of natural ground water basin boundaries, it is appropriate to select some surface water hydrological features like rivers etc.

In the study area, west and east side is bounded by Gandak river and Vaishali Branch Canal (VBC) flowing from north to south. So, river and canal boundaries (taking it as a stream) have been taken in the western and eastern side of the study domain. Habibpur sub-distributary takes off at 138.2RD of VBC near Chaturpatti entering the study domain has also been taken as a stream. Rivers contributes water to the groundwater system or drain water from the flow domain depending on the head gradient between the stream and the groundwater regime. The effect of the river taken care of by the 'River package' in the MODFLOW, simulates the flow between surface water features and the groundwater system. To simulate the effect of river/stream data types required for each river cell are: hydraulic conductance of the river bed $[L^2 T^{-1}]$, elevation of the river bed bottom [L], and head in the river [L]. These data for different seasons were used as input variables for different stress periods in the model.

Flow between the stream and the groundwater system is estimated from the following formula:

$$QRIV = CRIV\left(HRIV - h_{i,j,k}\right)$$

$$CRIV = \frac{k.L.W}{M}$$



* 100 is the arbitrary datum above MSL.

Figure 8 : Contour plot of initial water table elevation (May '91).

where,

QRIV = flow between the stream and the aquifer $[L^3T^{-1}]$,
CRIV = hydraulic conductance of the stream-aquifer interaction $[L^2T^{-1}]$,
HRIV = head in the river [L],
$h_{i,j,k}$ = head at the node in the cell underlying the stream reach [L],
k = hydraulic conductance of river bed $[L\ T^{-1}]$
L = length of the reach contained in the river cell [L]
W = width of the river [L]
M = thickness of the river bed material [L]

Hydraulic conductance value of river/stream bed material has been assumed as 0.04m/day. This assumption is based on the available exit resistance of water through streambed of rivers. Thickness of the bed material has been taken as 2.0 m for river and 0.25m for canals. The average width of Gandak river in the model domain, VBC and Habibpur sub-distributary are 750m, 10m and 4m respectively based on the available informations. The cell length is 200m. Values of `QRIV' for other cells have been calculated by linear interpolation method from the slope of the river bed and canal. Detail of calculations of different data types used as input to the `river package' is given in the following table:

Table 7: Details of river parameters considered in the `River package' in the model.

Stress Period	**Entry (North)**		**Exit (South)**		**CRIV (m^2/d)**
	RL of water surface (m)	**RL of river or stream bed (m)**	**RL of water surface (m)**	**RL of river or stream bed (m)**	
Gandak River					CRIV value for: Gandak = 3000 m^2/d; VBC = 320 m^2/d and HSD = 117 m^2/d. Gradient of: Gandak = 1:15000; VBC = 1:8000 and HSD = 1:4500.
Garam	151.50	148.00	150.00	146.50	
Kharif	153.50		152.00		
Rabi	152.50		151.00		
Vaishali Branch Canal (VBC)					
Garam	155.31	155.31	152.20	152.20	
Kharif	156.65		153.54		
Rabi	155.72		152.61		
Habibpur Sub-distributary (HSD)					
Garam	155.24	155.24	154.42	154.42 (Last point)	
Kharif	156.33		155.41		
Rabi	155.40		154.63		

North and south side of the study domain did not have any conventional hydrological boundaries. These two sides were considered as General Head Boundaries (GHB) or flux boundaries or open boundaries. The GHB in the flow model simulates flow into or out of a cell from an external source. Two data types are required for each GHB cells namely; hydraulic conductance [$L^2 T^{-1}$] of the interface between the aquifer cell and the boundary and the head on the boundary. The hydraulic conductance values of GHB are calculated by multiplying `K' by the layer thickness while heads on the boundaries are estimated from the information of observation wells near the boundary.

Since river stage vary from season to season, and so is the GHB. The setup of the model boundary thus represents *unsteady condition*.

5.1.4 Estimation of Stresses

Stresses in a groundwater system are usually due to outflow from the aquifer or inflow into the aquifer. In the present model domain, the components of outflow consist of pumpage from aquifer, evapotranspiration, rivers and boundaries. The inflow components consist of recharge through rainfall, irrigation return flow and due to boundaries etc. The outflow from the aquifer is defined as discharge and inflow is termed as recharge.

Estimation of Discharge

Withdrawal from aquifer and the evapotranspiration have been considered as discharge components. Withdrawl from aquifer has been assumed from the first layer and the third layer. The exact number of tubewells which are functioning in the area and their discharge values were not available. However, from tubewell census of Bihar, shallow private tubewells are 957 in number out of which irrigation figures available are of 345 nos. Thus, in the model a conservative estimate of 800 tubewells distributed in first and third layer with discharge of 25 m^3/day for each well were inserted as input during Garam and Rabi seasons only.

Evapotranspiration values for the *cropped area* in the model domain in Garam (16%), Kharif (60%) and Rabi (60%) seasons have been taken as 5.31mm/day, 3.66mm/day and 3.02mm/day respectively. These values have been arrived at by dividing the consumptive use by the base period of the crop in different seasons. The details and calculations have already been discussed in sections 3.5.1 and 3.6 in Chapter-3. The ET value for the dominant crop in the particular season has been taken for the purpose of calculation. The root zone depth has been assumed to be 2.0 m. For the *uncropped area* the input `ET' values were taken as 50% of the ET of the *cropped area*. This is simply a rational assumption which may require to be modified marginally during calibration.

The outflow or inflow through boundaries (river/canal or general head) would be automatically taken care of by the model while simulating the flow depending upon the river/canal stages and the head on the boundary.

Estimation of Recharge

Areal recharge through rainfall and irrigation return flow due to spreading of water on the field through 18 nos of outlets of the Habibpur sub-distributary have been considered as external recharge to the model domain. Recharge/inflow from river/canal and the head dependent boundaries are taken care of by the model automatically depending upon the heads in the boundaries.

The distribution of total average annual rainfall of 1168mm in Garam, Kharif and Rabi seasons are 10%, 85% and 5% respectively in the study area. The recharge during all the three seasons have been taken as 20% of rainfall occurring in a particular season. This value of recharge will be modified during calibration process if needed.

Each outlet of Habibpur sub-distributary has an average discharge of 0.025cumec and irrigates approximately 10 ha. Assuming 70% of total discharge through outlets going as recharge, the recharge due to irrigation return flow during ***kharif season*** comes to 0.015 m/day when the canal is operational throughout the season. In Rabi season the canal operates only for 45 days. Thus, the recharge due to irrigation return flow during Rabi season (taking 50% of release through outlets as recharge) comes to 0.004m/day.

5.2 CALIBRATION OF THE MODEL

For a system with reliable input parameters and stresses, the response of the model generally come in close agreement with the observed field data. Disagreement in model output with the observed values would reflect unreliable input data with respect to either the stresses or the system's parameters. Such disagreements were experienced in the present modelling exercise on initially simulating the model. This eventually seeks the requirement to calibrate the model parameters and to look into the uncertainty part of the stresses. For example, the total number of wells operating in the area and their discharges were not known apriori. Underestimation of pumpage will lead to overestimation of water table elevation and vice versa. Similarly, potential evapotranspiration values arrived at by following the *Hargreaves* based on only two climatological parameters (solar radiation and ambient air temperature) may not lead to actual estimation of evapotranspiration. Incorrect assignment of aquifer parameters would also lead to distortion of estimated value of water table elevations. Calibration of model parameters and reliable magnitude of stresses were thus necessary.

In order to calibrate the model, initially the model was simulated with the input values of aquifer parameters and external stresses to/from the model domain. The output i.e the computed water table elevations were compared with the observed data of observation wells in the study area for the three stress periods. In case of mismatch, the aquifer parameters and/or stresses were modified. During the initial run, the difference between the observed and computed water table elevation for three stress periods were noticeable and thus minor calibrations became necessary.

Subsequently, the model parameter namely the hydraulic conductivity `K' was modified and the outputs were again compared. Finally, the evapotranspiration and the recharge values were also modified marginally considering the conditions prevailing in the area. Final calibrated values of hydraulic conductivity `K', evapotranspiration `ET' and rainfall recharge are given in tables 8, 9 and 10. Tables of comparisons of observed and computed water table elevations for three stress periods are also given in tables 11, 12 and 13.

Table 8: Calibrated value of Hydraulic conductivity

Layer	**Hydraulic conductivity**	
	Initial value (m/day)	*Calibrated value (m/day)*
For first layer	10	5
For second layer	1	1
For third layer	25	20

Table 9: Calibrated value of Rainfall recharge

Stress periods	Rainfall recharge	
	Initial value (mm/day) (20% of rainfall)	*Calibrated value (mm/day)*
First stress period *(Garam)*	0.195	0.243
Second stress period *(Kharif)*	1.655	4.137
Third stress period *(Rabi)*	0.097	0.122

Table 10: Calibrated value of Evapotranspiration

Stress periods	Initial value (mm/day)		Calibrated value (mm/day)	
	Cropped area	*Uncropped area*	*Cropped area*	*Uncropped area*
1st stress period *(Garam)*	5.31	2.65	6.37	2.65
2nd stress period *(Kharif)*	3.66	1.83	4.39	1.46
3rd stress period *(Rabi)*	3.02	1.51	3.02	1.51

Table 11: Observed and computed water table elevation at the end of Garam season after calibration.

Cell	Observed WT (m)	Computed WT (m)
(5,1)	151.50	151.72
(6,10)	151.37	151.33
(20,20)	151.20	151.13
(28,30)	151.00	150.94
(33,40)	150.86	150.80
(61,50)	150.51	150.53
(67,60)	150.29	150.30
(68,70)	150.14	150.11
(71,80)	150.00	150.25
(77,14)	150.82	150.95
(76,17)	150.18	150.58
(77,20)	151.05	150.59
(85,28)	152.65	152.32

Table 12: Observed and computed water table elevation at the end of Kharif season after calibration.

Cell	Observed WT (m)	Computed WT (m)
(5,1)	153.50	153.24
(6,10)	153.37	153.36
(20,20)	153.20	153.12
(28,30)	153.00	152.89
(33,40)	152.86	152.84
(61,50)	152.51	152.46
(67,60)	152.29	152.30
(68,70)	152.14	152.13
(71,80)	152.00	151.79
(77,14)	154.02	154.14
(76,17)	152.88	153.29
(77,20)	153.33	153.39
(85,28)	154.10	153.92

Table 13: Observed and computed water table elevation at the end of Rabi season after calibration.

Cell	Observed WT (m)	Computed WT (m)
(5,1)	152.50	152.63
(6,10)	152.37	152.25
(20,20)	152.20	151.98
(28,30)	152.00	151.77
(33,40)	151.86	151.70
(61,50)	151.51	151.28
(67,60)	151.29	151.22
(68,70)	151.14	151.01
(71,80)	151.00	151.18
(77,14)	153.75	153.62
(76,17)	152.21	152.26
(77,20)	152.68	152.30
(85,28)	153.25	153.33

From above tables it is observed that the difference between the observed and computed water table elevation is marginal and thus the calibration process was terminated at this stage.

6.0 ANALYSIS OF RESULTS

6.1 CALIBRATED RESULTS

In the present study, the observed water table data were available during the period 1991-92 for all three cropping seasons namely Garam, Kharif and Rabi. These observed water table data has been used to calibrate the groundwater flow model. Simulations were performed by taking the initial condition of Garam season (March). The output of the first stress period (Garam season) becomes the input or the initial condition for the second stress period (Kharif season) and so on. The main driving force for external stresses were due to evapotranspiration, areal recharge and the stage of Gandak river. The cropping areas in existence at that period of time (1991-92) indicated that 16% of the model domain was cultivated during Garam, 60% in Kharif and 60% in Rabi season. However, the cropping areas and agricultural practices in the region have changed over the years.

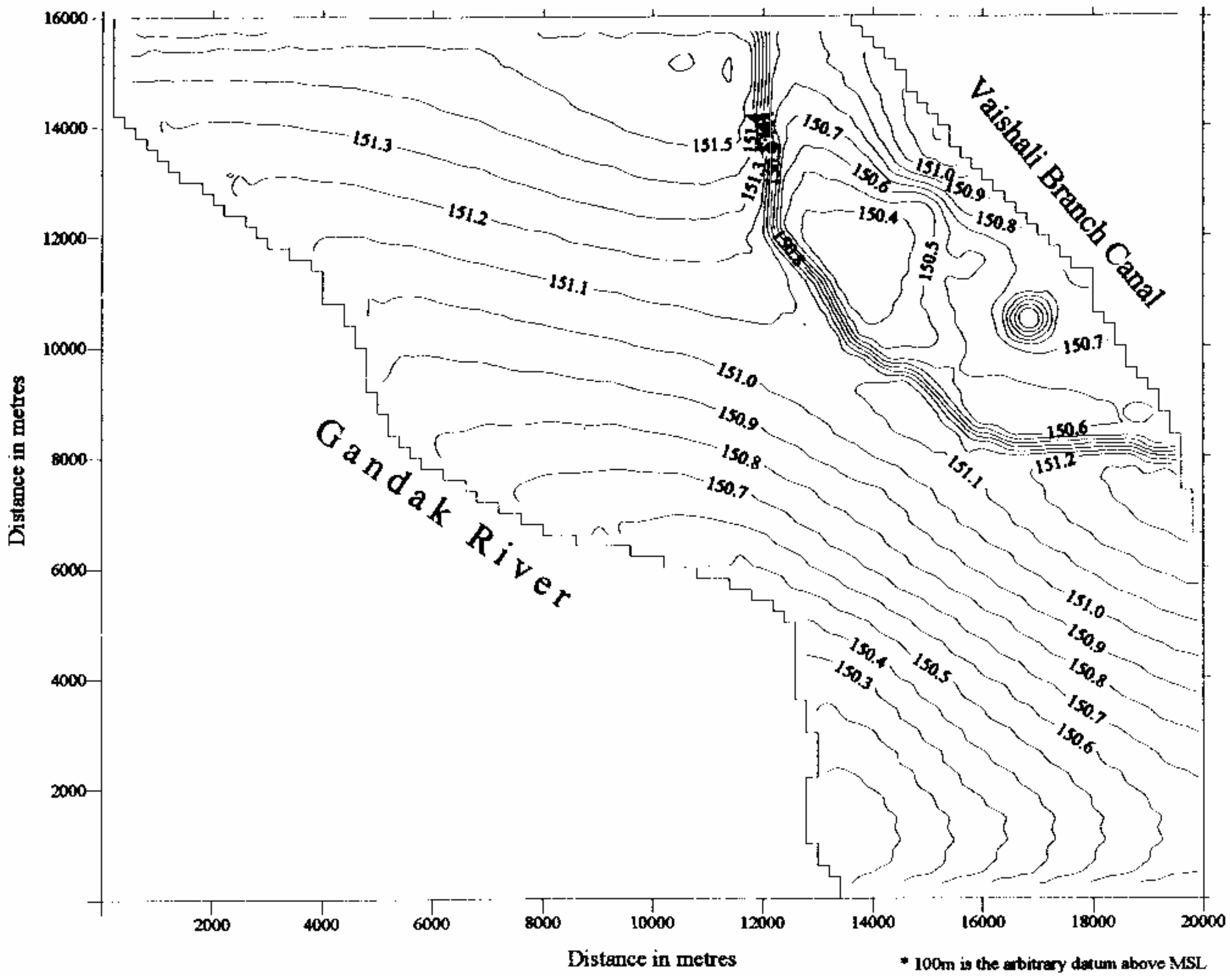
6.1.1 Garam Season

The initial condition of Garam season has already been discussed in section 5.1.2. The water balance analysis computed by the model at the end of this season indicates the inflow and outflow for following components of stresses considered:

Table 14: Water balance of various terms (m^3/d) at the end of Garam season.

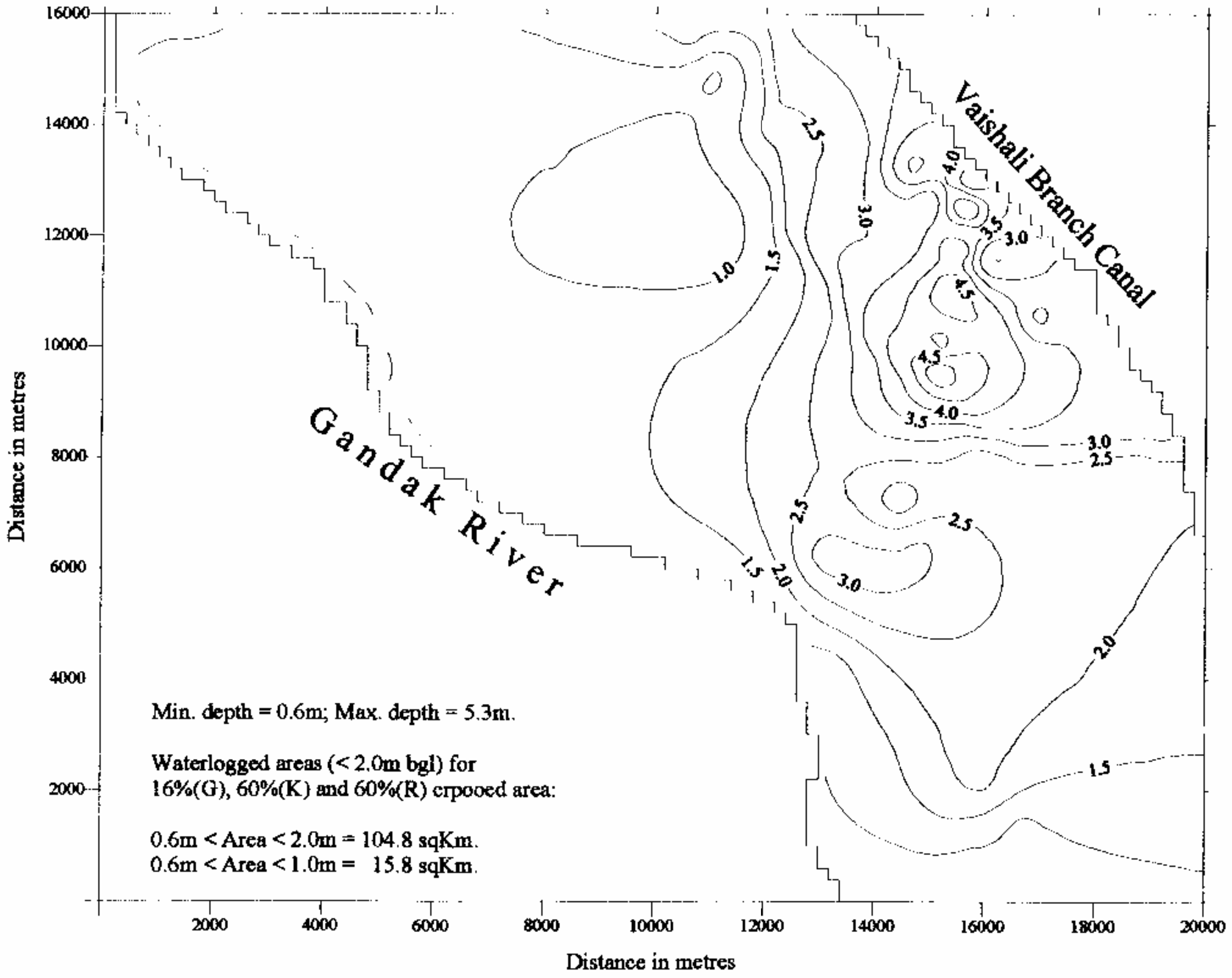
Water balance components	River leakage	E T	Recharge	G H B
Inflow to the model domain	1,300	--	44,182	6,588
Outflow from the model domain	301	505,253	--	3,375

The above table shows that during Garam season, the river Gandak feeds to the aquifer as well as gains marginally. The inflow and outflow through GHB is also indicated. The evapotranspiration is quite high which can only be met out of the aquifer storage. Thus, there is net depletion in water table. The computed water table elevations are shown in figure 9. These water table elevations were substracted from the ground elevation of the area and the depth to water table were computed and shown in figure 10. These contours demarcate the waterlogged (< 2.0m bgl) and non-waterlogged (> 2.0m bgl). The maximum and minimum depth to water table in the area comes to 5.3m and 0.6m bgl



* 100m is the arbitrary datum above MSL

Figure 9 : Computed water table elevation (m) at the end of 1st stress period (Garam season).



Min. depth = 0.6m; Max. depth = 5.3m.

Waterlogged areas (< 2.0m bgl) for
16%(G), 60%(K) and 60%(R) crpooed area:

0.6m < Area < 2.0m = 104.8 sqKm.
0.6m < Area < 1.0m = 15.8 sqKm.

Figure 10 : Depth to water table contours (m) at the end of 1st stress period (Garam season).

respectively. Although extent of waterlogged area is 104.8 sqkm, but the areas for which depth to water table is < 1.0m bgl is only 15.8 sqkm with no surface waterlogging. It means, considerable area in the model domain has shallow water table. These are the perspective areas which can be brought under suitable cropping pattern within an acceptable limit.

6.1.2 Kharif Season

The initial condition of Kharif season is the calibrated groundwater table elevation at the end of Garam season. The model computed water balance at the end of this season for following components of stresses of inflow and outflow are:

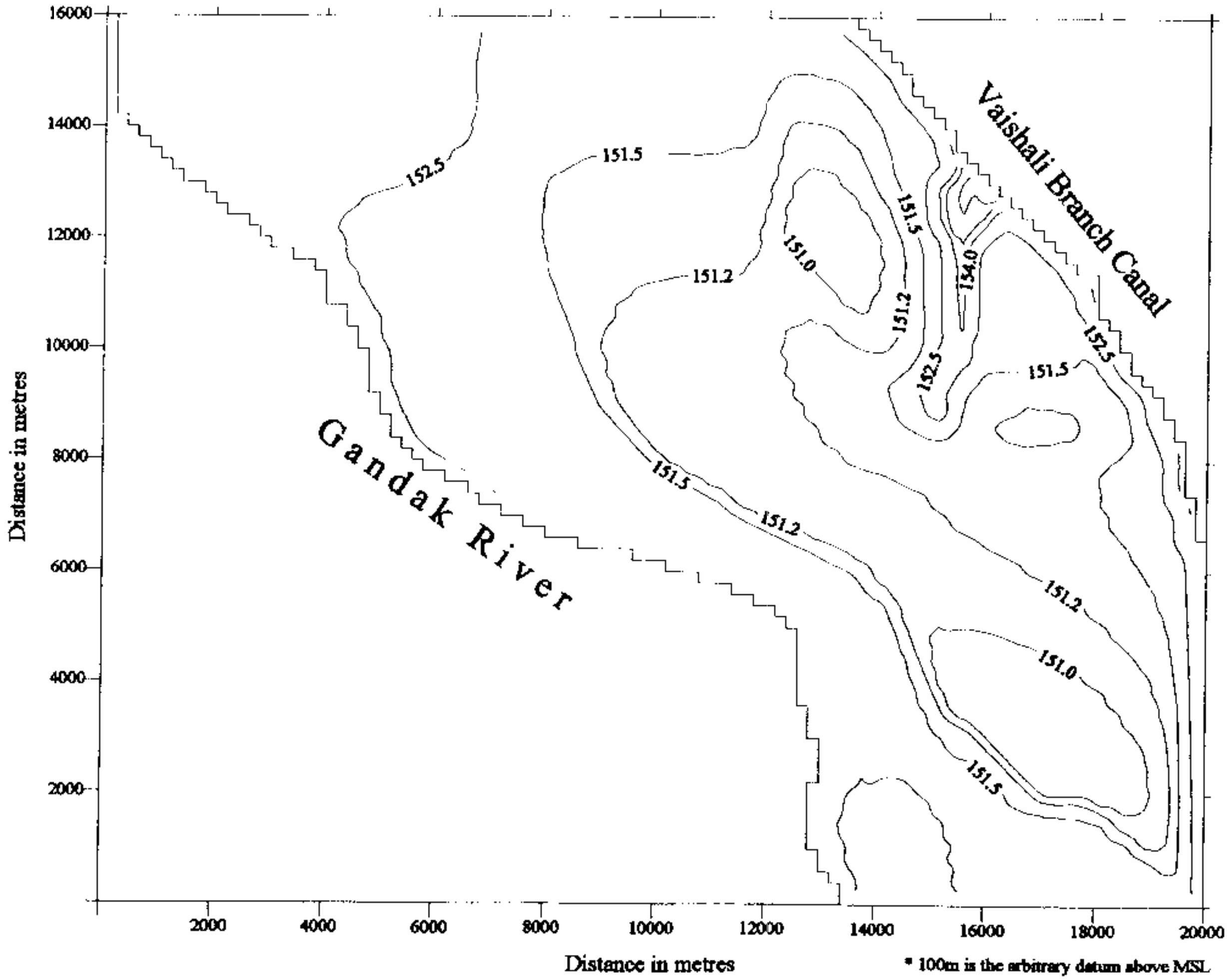
Table 15: Water balance of various terms (m^3/d) at the end of Kharif season.

Water balance components	River leakage	E T	Recharge	G H B
Inflow to the model domain	55,018	--	781,493	10,523
Outflow from the model domain	0	528,620	--	3,420

The above table shows that during Kharif season, the river Gandak feeds to the aquifer totally. The inflow due to flux boundary is quite considerable. The recharge component is more than the ET component indicating increase in storage. The water table elevation would rise. The computed water table elevations of the domain have been plotted figure 11. The depth to water tables have also been shown in figure 12. The maximum and minimum depth to water table in the area comes to 3.8m bgl and –1.2m (i.e surface ponding) respectively. The extent of waterlogged area (< 2.0m bgl) is 128.2 sqkm. The areas for which the depth to water table is < 1.0m bgl is 83.8 sqkm with surface waterlogging (< 0.0m) areas of 45.6 sqkm. It means, considerable area in the model domain has remains under surface waterlogging condition.

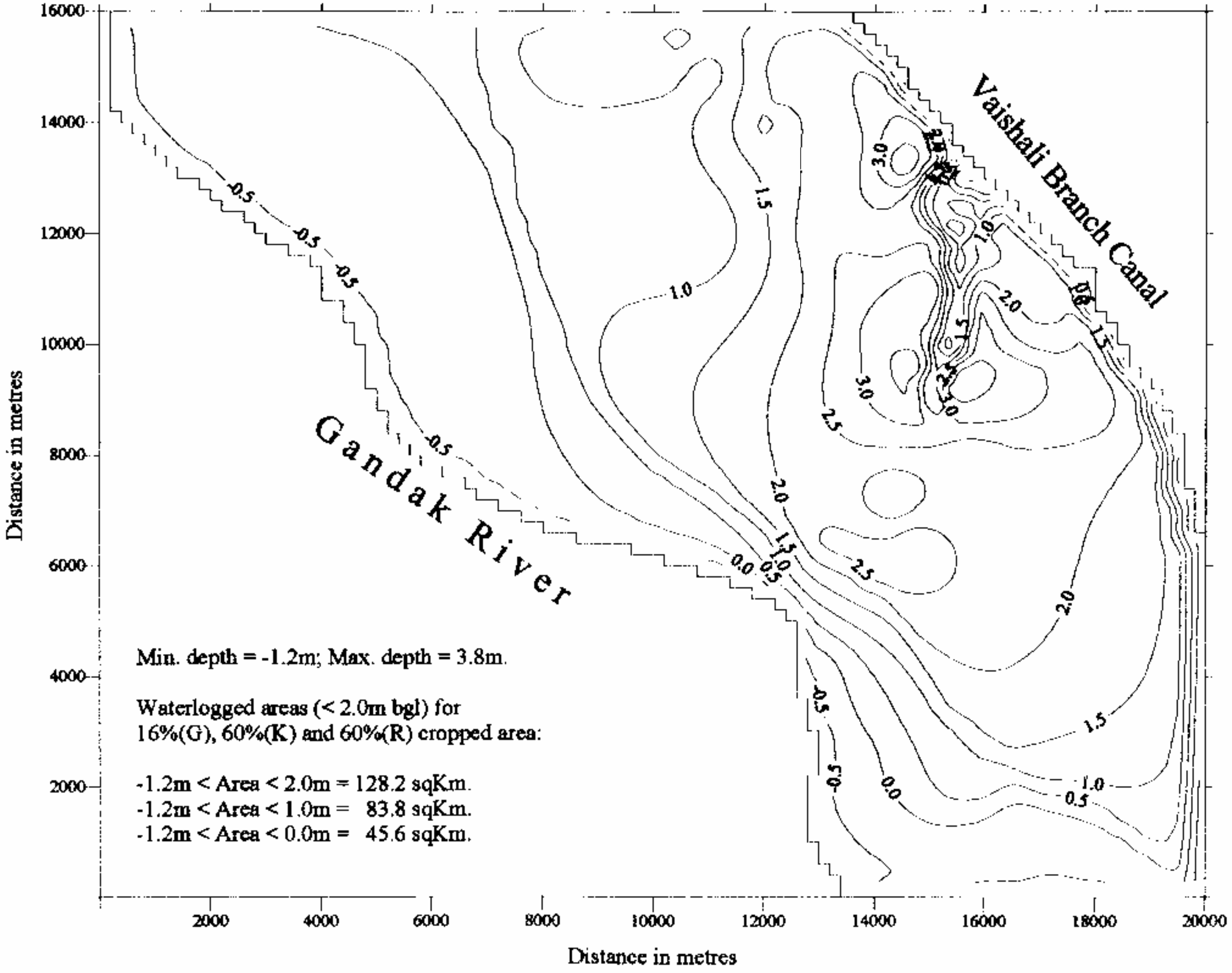
6.1.3 Rabi Season

The initial condition of Rabi season is the calibrated groundwater table elevation at the end of Kharif season. The water balance analysis computed by the model at the end of this season indicates the inflow and outflow for following components of stresses considered:



* 100m is the arbitrary datum above MSL

Figure 11 : Computed water table elevation (m) at the end of 2nd stress period (Kharif season).



Min. depth = -1.2m; Max. depth = 3.8m.

Waterlogged areas (< 2.0m bgl) for
16%(G), 60%(K) and 60%(R) cropped area:

-1.2m < Area < 2.0m = 128.2 sqKm.
-1.2m < Area < 1.0m = 83.8 sqKm.
-1.2m < Area < 0.0m = 45.6 sqKm.

Figure 12 : Depth to water table contours (m) at the end of 2nd stress period (Kharif season).

Table 16: Water balance of various terms (m^3/d) at the end of Rabi season.

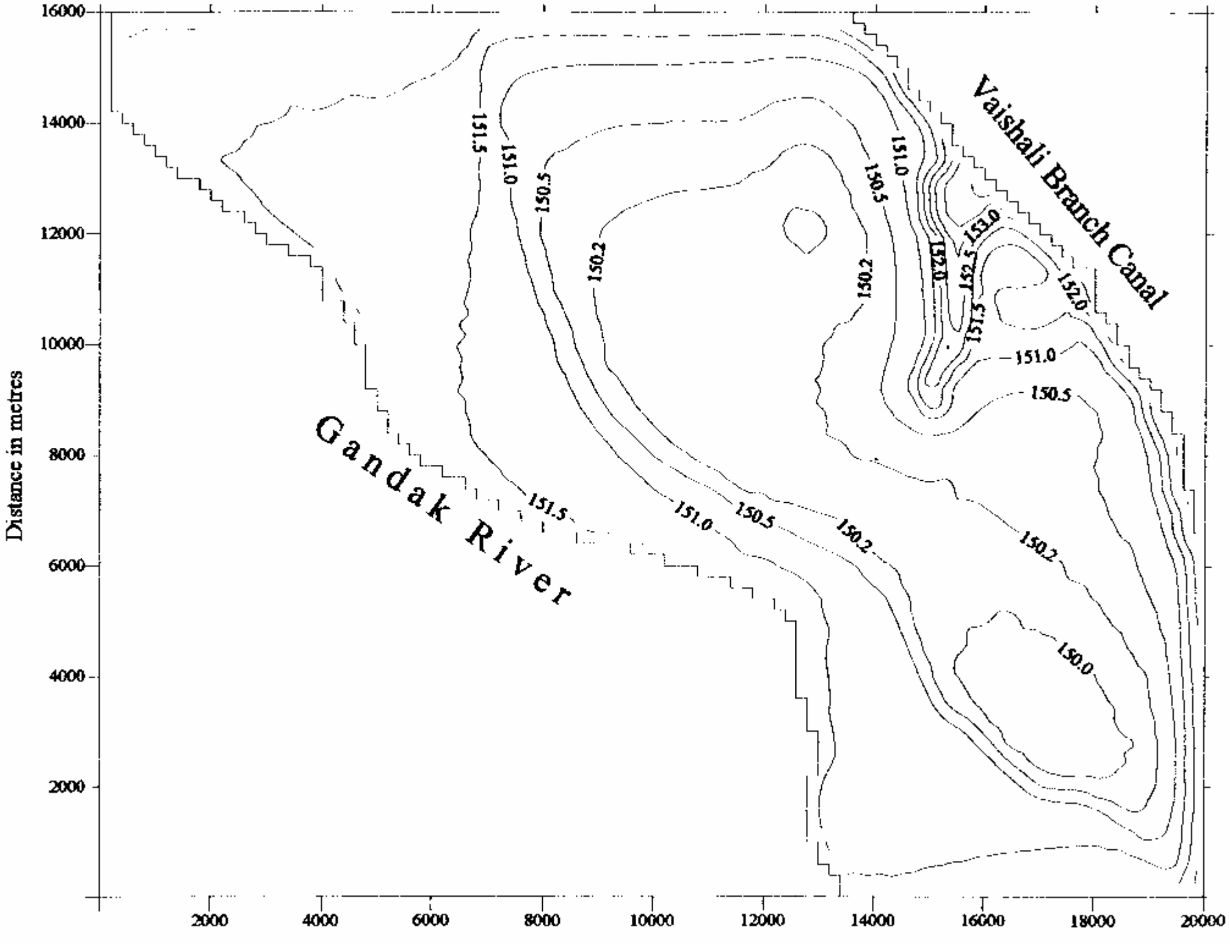
Water balance components	River leakage	E T	Recharge	G H B
Inflow to the model domain	15,164	--	32,938	27,704
Outflow from the model domain	339	375,688	--	6

The above table shows that during Rabi season too, the river Gandak feeds to the aquifer as well as gains although negligibly. There is also inflow through flux boundary. Since the ET is quite high, there would be net loss from the storage and the water table would go down. The computed water table elevations of the domain has been shown in figure 13 and the depth to water table contours in figure 14. The maximum and minimum depth to water table in the area comes to 4.5m bgl and –0.4m (i.e surface ponding) respectively. The extent of waterlogged area (< 2.0m bgl) is 86.4 sqkm. The areas for which the depth to water table is < 1.0m bgl is 52.2 sqkm with surface waterlogging (< 0.0m) areas of 1.5 sqkm only.

The depth to water table contours for three seasons clearly suggests that due to maximum rainfall occuring during Kharif season (85% of the annual rainfall) and inflow from Gandak, surface waterlogging condition prevails on an area of 45.6 sqkm. During Rabi season, the conditions improve and the surface waterlogging conditions become marginal (1.5 sqkm only). This would however be reduced considerably if cropping area is increased. These maps also show emergence of waterlogging areas near Vaishali Branch Canal and Habibpur sub-distributary during Kharif season since the canal operates for all 120 days. The farmers also showed their resentments when the site was visited because of submergence of their cultivable fields due to canal release and its seepage to the adjoining areas.

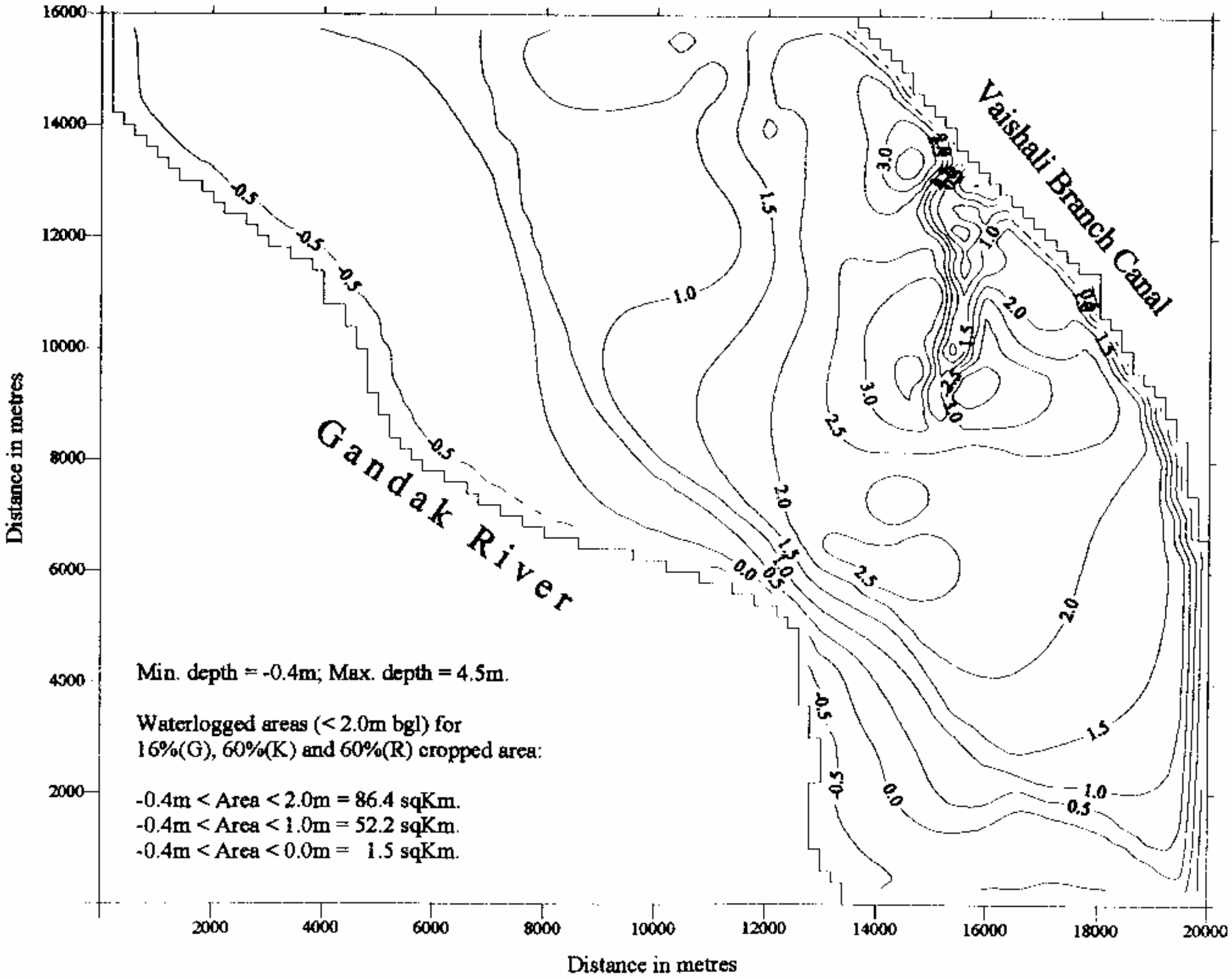
The output of the model given in these figures give fairly an idea about the areas where attention need to be diverted, means to the areas where the depth to groundwater table is less than 2.0m bgl (defined as waterlogged areas). These areas can easily be demarcated. These areas can be taken up for minimizing waterlogged areas by exercising various remedial options, which have been discussed in section 6.2.

The CGWB report of Vaishali district (1993) indicates overall groundwater resources utilization less than 50%. Thus, lot of irrigation potential in the area still remains to be explored. The model would help in planning futuristic groundwater surface water



* 100m is the arbitrary datum above MSL

Figure 13 : Computed water table elevations (m) at the end of 3rd stress period (Rabi season).



Min. depth = -0.4m; Max. depth = 4.5m.

Waterlogged areas (< 2.0m bgl) for
16%(G), 60%(K) and 60%(R) cropped area:

-0.4m < Area < 2.0m = 86.4 sqKm.
-0.4m < Area < 1.0m = 52.2 sqKm.
-0.4m < Area < 0.0m = 1.5 sqKm.

Figure 14 : Depth to water table contours (m) at the end of 3rd stress period (Rabi season).

developmental activity in the area and its impact on the overall groundwater regime. The model can conveniently be used for any kind of water resources developmental activity which would incorporate change in cropped area, cropping pattern, change in rainfall and change in the stages of Gandak river, canal.

It has been observed (GADA, 1999) that the crop coverage in different seasons have changed over the years. Farmers are also flexible to change of cropping pattern and adopting improved agricultural practices. The cropped area in all three seasons has increased considerably. There is also an inclination to utilize the groundwater potential in the area. Thus, these changes are to be incorporated in the model so that its effect can be seen through the output in regards to future scenarios. This has been dealt in subsequent section.

6.2 SCENARIOS

The main objective of the conjunctive use model is to utilize water resources available in the area (surface water and groundwater) optimally, so as to increase the water availability for irrigation requirements. In this study an additional objective of reducing waterlogged areas through increased water use during dry period and subsequent recharging in wet season is suggested. The calibrated model gives the scenario of waterlogged areas for the year 1991-92. Waterlogged areas can be reduced either by i) increasing the cropped area in different seasons to an acceptable limit and/or ii) utilizing groundwater potential to the maximum so as to meet the net irrigation requirement of crops in different seasons of the year for the cropped area. Increasing the cropped area would mean more evapotranspiration which would result in lowering of water table. Utilizing groundwater potential would also help in lowering of water table.

Thus, two scenarios would be predicted through the use of the present model i.e i) by increasing the cropped area and ii) utilizing groundwater potential to meet the net irrigation requirements (NIR).

Present trend in the area shows that the tendency for changing of cropping pattern and the cropped area has already started in the Gandak command. This is reflected in Gandak Area Development Authority report (GADA, 1999). The groundwater utilization and groundwater development in the area for irrigation has also started. Farmers have formed a cooperative society named Vaisali Area Small Farmer's Association (VASFA) in Vaishali and Saraiya block in Vaishali and Muzaffarpur districts respectively for the development and utilization of groundwater potential in the area. The effect of increased cropped area on waterlogging is analyzed in the next section.

6.2.1 Increasing the Cropped Area

The cropping area in terms of percentage in existence during 1991-92 and the increased cropped area in different season for which the model has been used as a predictive tool is given in the following table:

Table 17: Existing and projected cropped area for different seasons.

Season	Existing cropped area (1991-92)	Projected area				
1	2	3	4	5	6	7
Garam	16%	25%	35%	25%	35%	35%
Kharif	60%	60%	60%	80%	80%	80%
Rabi	60%	60%	60%	60%	60%	80%

Initially, the cropped area in Garam season was increased to 25% and 35% keeping the cropped area in kharif and Rabi the same since there is a possibility to bring more areas under vegetables and summer maize in summer season. Subsequently, the cropped areas during Kharif and Rabi was also increased alongwith the Garam season. The cropped area of 25%, 80% and 60% during Garam, Kharif and Rabi respectively as mentioned in column no. 5 of above table is the present status as reflected in GADA report 1999.

In the model, these changes would be taken care of through evapotranspiration taking place from the increased cropped area. The model was simulated for these changes separately for three stress periods. The computed water table elevations were subtracted from the topography of the area and the depth to water table contours for each and every cell of the domain was computed and is depicted in the form of contours (Figures C-1 to C-15 in appendix-C). These figures fairly demarcate waterlogged (< 2.0m bgl) and non-waterlogged areas for these changes. The areas under different categories namely: i) < 2.0m bgl, ii) < 1.0m bgl and iii) < 0.0m bgl (i.e surface water logging) have also been estimated and depicted in these figures. The maximum and the minimum depth to water table in the area in different seasons can also be seen in these figures.

A summery of above figures for different cropping areas is depicted in figures 15, 16 and 17 in the form of bar graph. These figures clearly indicate that increase of crop area in a particular season would not only lead to decrease in waterlogged areas in that season, but also in subsequent seasons.

Thus, if farmers are motivated to bring more areas under cultivation, this would definitely have positive impact in reducing waterlogged areas.

6.2.2 Utilizing Groundwater Potential to meet the Net Irrigation Requirement (NIR) of Crops

The calculation of NIR incorporates crop type, growth stage, prevailing climatic conditions, special need of crop (if any) and effective rainfall. So, NIR indicates the amount of water need to be supplemented to the crops in terms of depths.

In exercising this option for the area, NIR is supplied by pumping groundwater after subtracting the canal recharge and existing withdrawl (1991) pattern of the area. This was done during Garam and Rabi seasons for the following cropped areas:

i. 25% in Garam, 80% in Kharif and 60% in Rabi which is also the condition of 1999 (GADA report).

ii. 35% in Garam, 80% in Kharif and 80% in Rabi as future scenario predicted.

The reduction in waterlogged areas in three seasons for i) < 2.0m bgl, ii) < 1.0m bgl and iii) 0.0m bgl (i.e surface waterlogging) are shown in figures D-1 to D-6 in appendix-D. For easy comparison, the inference of these figures are also depicted in the form of bar graphs for the above cropped areas (figures 18,19 and 20).

It is clear from these figures that utilization of groundwater resources would considerably reduce waterlogged areas in the model domain.

Figure 15: Effect of crop coverage on waterlogged areas (< 2.0m bgl).

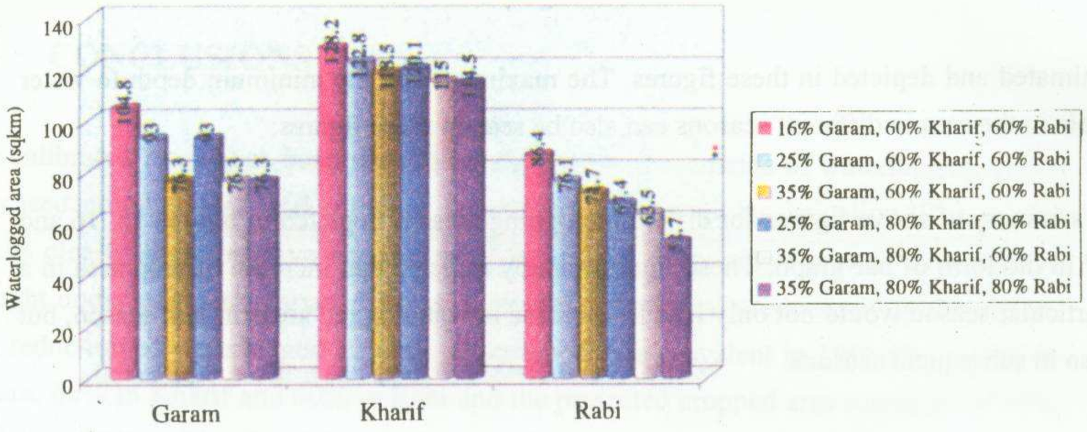


Figure 16: Effect of crop coverage on waterlogged areas (< 1.0m bgl).

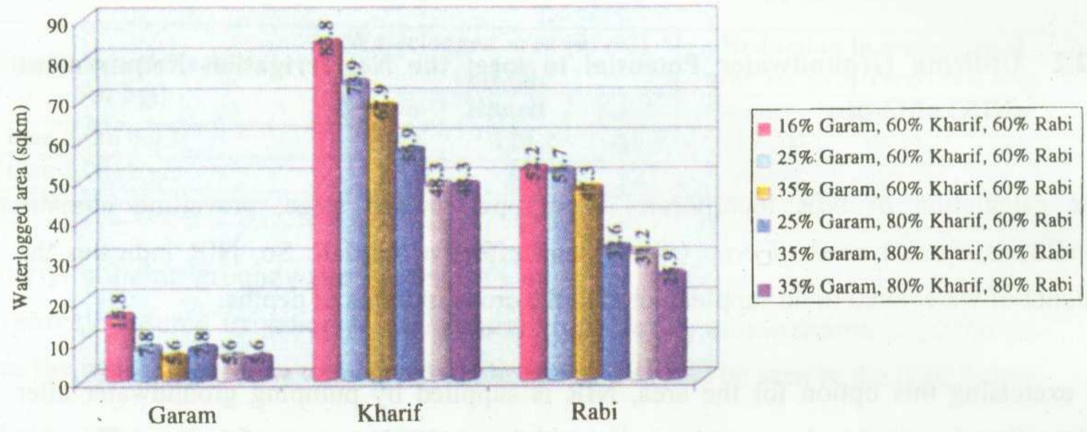


Figure 17: Effect of crop coverage on waterlogged areas (< 0.0m bgl).

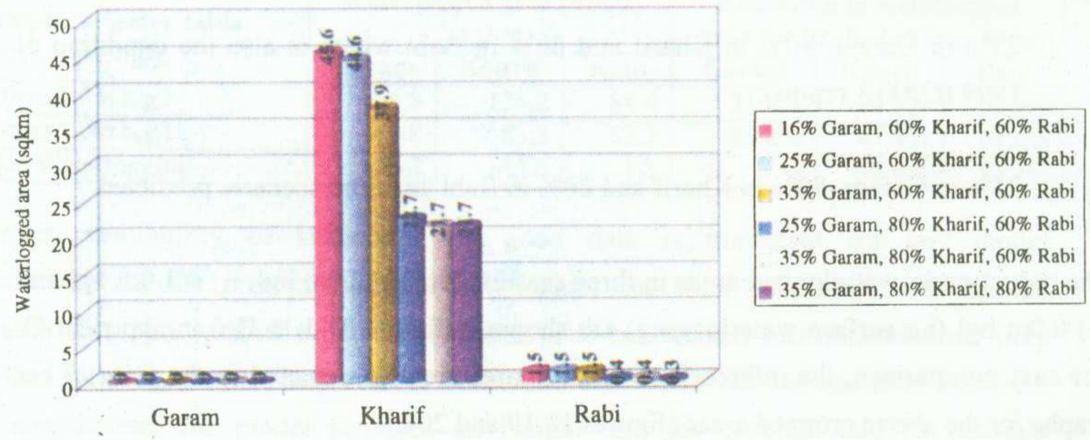


Figure 18: Effect of groundwater utilization on waterlogged areas (< 2.0m bgl).

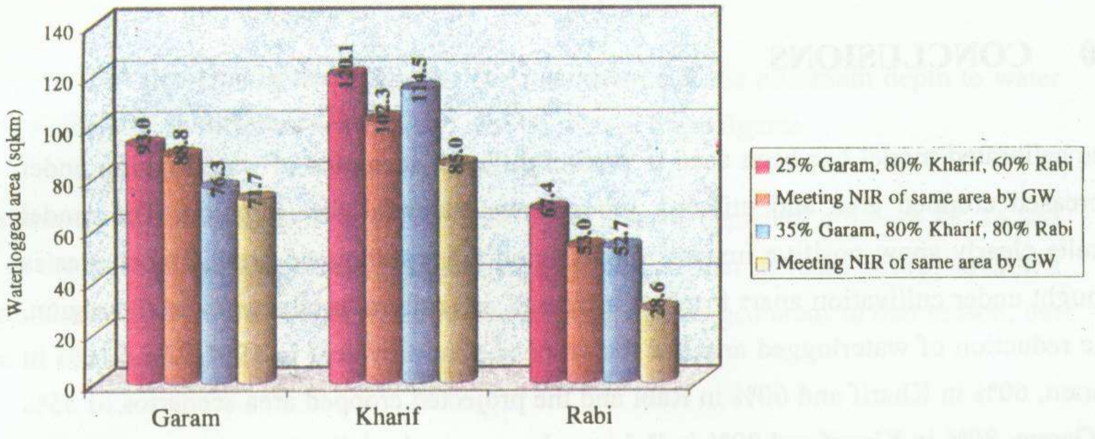


Figure 19: Effect of groundwater utilization on waterlogged areas (< 1.0m bgl).

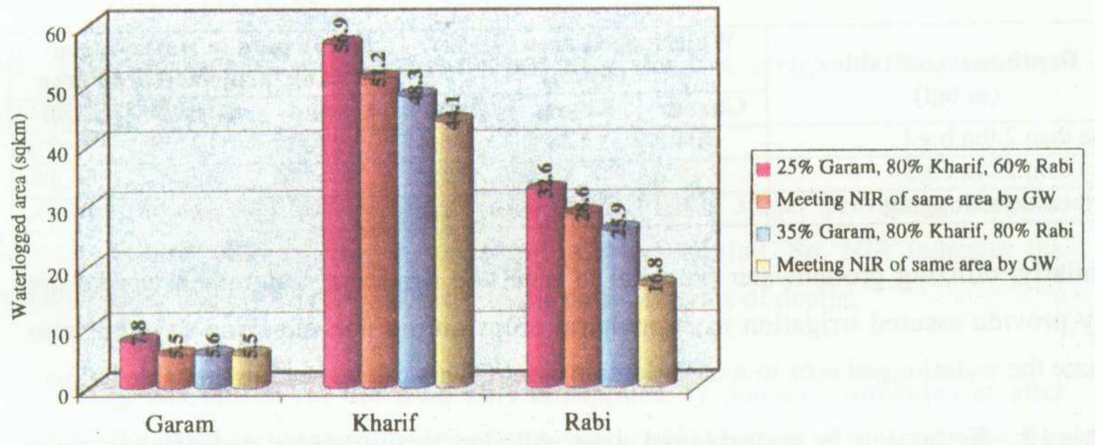
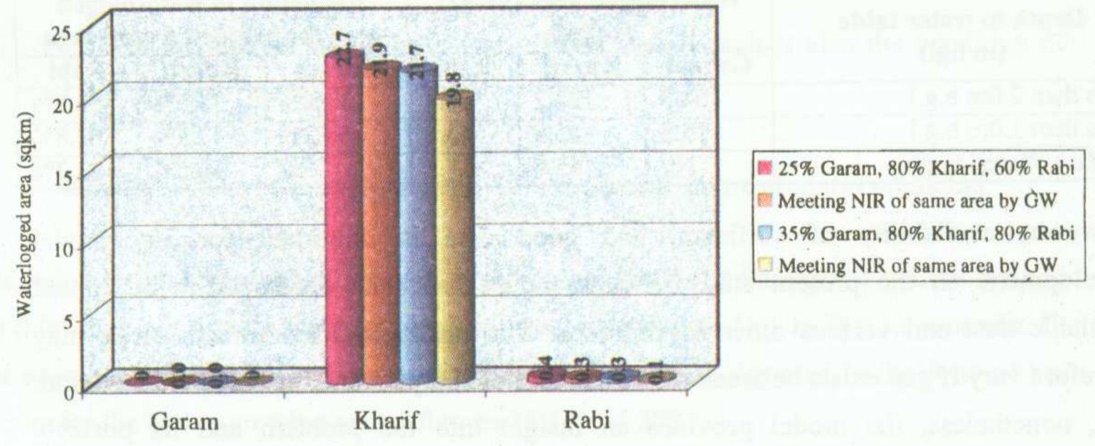


Figure 20: Effect of groundwater utilization on waterlogged areas (< 0.0m bgl).



7.0 CONCLUSIONS

The calibrated model has been used to predict different scenarios of waterlogging under increased cropped area and utilizing groundwater potential for irrigation. The model results clearly show positive impacts on reducing the waterlogged area if more area is brought under cultivation apart from an increased agricultural productivity in the region. The reduction of waterlogged area for the cropped area prevalent in 1991-92 i.e 16% in Garam, 60% in Kharif and 60% in Rabi and the projected cropped area scenarios of 35% in Garam, 80% in Kharif and 80% in Rabi can be seen in the following table:

Table 18: Reduction in waterlogged area for the projected cropped area.

Depth to water table (m bgl)	Walerlogged area (91-92) (sqkm)			Reduction in waterlogged area for projected crop area		
	Garam	**Kharif**	**Rabi**	**Garam**	**Kharif**	**Rabi**
Less than 2.0m b.g.l	104.8	128.2	86.4	27.2%	10.7%	39.0%
Less than 1.0m b.g.l	15.8	83.8	52.2	64.6%	42.4%	50.4%
Surface Waterlogging	Nil	45.6	1.5	--	52.4%	80.0%

Similarly, utilizing groundwater potential to meet the irrigation requirement would not only provide assured irrigation to agricultural crops during non-monsoon days but also reduce the waterlogged area to a considerable extent. This can be seen in the table below:

Table 19: Reduction in waterlogged area utilizing groundwater potential to meet the NIR of crops for the projected area.

Depth to water table (m bgl)	Walerlogged area (91-92) (sqkm)			Reduction in waterlogged area for projected crop area		
	Garam	**Kharif**	**Rabi**	**Garam**	**Kharif**	**Rabi**
Less than 2.0m b.g.l	104.8	128.2	86.4	31.6%	33.7%	66.9%
Less than 1.0m b.g.l	15.8	83.8	52.2	65.2%	47.4%	67.8%
Surface Waterlogging	Nil	45.6	1.5	--	56.6%	93.3%

However, availability of sufficient and good data is important for any model development. In the present study, a flow model has been developed with limited available data and various other assumptions. The results and recommendations may therefore vary if gap exists between the assumed model inputs and the real field situation. But, nonetheless, the model provides an insight into the problem and its possible solutions.

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Table A-1 : Geological formations of different locations in the study area.

Sl.	Classification	Depth Range(m) From	To	Thickness(m)
1.	**CHAKRANDAS (Tubewell No. 2)**			
	Surface soil	0.00	2.44	2.44
	Sand	2.44	9.75	7.32
	Soil	9.75	18.90	9.14
	Kankar	18.90	24.38	5.49
	Clay	24.38	33.53	9.14
	Clay and Sand	33.53	35.36	1.83
	Sand	35.36	49.38	14.02
	Sand with Kankar	49.38	51.21	1.83
	Sand	51.21	53.04	1.83
	Sand with Kankar	53.04	55.47	2.44
	Clay	55.47	Contd.	
2.	**PARAMANDPUR**			
	Surface soil	0.00	2.44	2.44
	Sand with Kankar	2.44	4.27	1.83
	Sand	4.27	7.92	3.66
	Clay	7.92	11.58	3.66
	Sand	11.58	15.24	3.66
	Clay with Kankar	15.24	18.90	3.66
	Clay	18.90	31.70	12.80
	Clay with Kankar	31.70	35.36	3.66
	Sand	35.36	54.86	19.51
	Clay	54.86	55.47	0.61
3.	**CHAKRAMDAS (Tubewell No.7)**			
	Surface soil	0.00	2.44	2.44
	Sand	2.44	9.75	7.32
	Black Clay	9.75	11.58	1.83
	Sand with Clay	11.58	13.41	1.83
	Clay	13.41	20.73	7.32
	Sand	20.73	26.21	5.49
	Clay	26.21	29.26	3.05
	Sand	29.26	49.07	19.81
	Sandstone	49.07	49.99	0.91
4.	**LALPURA**			
	Surface soil	0.00	2.44	2.44
	Sand	2.44	7.92	5.49
	Clay	7.92	13.41	5.49
	Kankar with Clay	13.41	18.90	5.49
	Clay	18.90	33.53	14.63
	Sand Stone	33.53	35.36	1.83
	Sand	35.36	51.82	16.46
	Sand Stone	51.82	55.47	3.66

5. UFRAUL

Surface soil	0.00	2.44	2.44
Clay	2.44	4.27	1.83
Sand	4.27	15.24	10.97
Kankar with Sand	15.24	20.73	5.49
Sand	20.73	26.21	5.49
Clay	26.21	28.04	1.83
Clay with Kankar	28.04	29.87	1.83
Clay	29.87	31.70	1.83
Kankar with Clay	31.70	33.53	1.83
Clay	33.53	35.36	1.83
Sand	35.36	55.47	20.12
Hard Clay	55.47	56.69	1.22

6. VAISHALI

Surface soil	0.00	2.44	2.44
Sandy soil	2.44	4.27	1.83
Sand	4.27	7.92	3.66
Clay	7.92	11.58	3.66
Sand	11.58	15.24	3.66
Clay	15.24	18.90	3.66
Hard Clay	18.90	20.73	1.83
Clay	20.73	35.97	15.24
Sand	35.97	53.04	17.07
Clay with Kankar	53.04	55.47	2.44

7. SAIMVARUNNA

Surface yellow clay	0.00	3.05	3.05
Fine sand with Kanka	3.05	6.09	3.04
Yellow medium Sand	6.09	9.14	3.05
Medium Sand	9.14	15.24	6.10
Clay with fine Sand	15.24	18.29	3.05
Hard Soil	18.29	27.43	9.14
Hard soil with Gravel	27.43	33.53	6.10
Clay with Kankar	33.53	36.58	3.05
Fine with Clay	36.58	39.62	3.04
Fine Sand with Kank	39.62	42.67	3.05
Fine Sand with Clay	42.67	48.77	6.10
Medium Sand	48.77	60.96	12.19
Fine Sand with Clay	60.96	70.10	9.14
Medium Sand	70.10	90.22	20.12

Table A-2 : Reclassified formations of lithologs in the study area

Sl.	Classification	Depth Range From	To	Thickness
1.	**CHAKRANDAS (Tubewell No. 2)**			
	Fine Sand with Silt	0.00	24.38	24.38
	Clay mixed with fine	24.38	35.36	10.98
	Sand with Kankar	35.36	55.47	20.11
	Clay	55.47	Contd.	
2.	**PARAMANDPUR**			
	Fine Sand with Silt	0.00	7.92	7.92
	Clay with Kankar	7.92	35.36	27.44
	Coarse Sand	35.36	54.86	19.51
	Clay	54.86	55.47	0.61
3.	**CHAKRAMDAS (Tubewell No. 7)**			
	Fine Sand with Silt	0.00	9.75	9.75
	Clay	9.75	29.26	19.51
	Sand	29.26	49.07	19.81
	Sandstone	49.07	49.99	0.91
4.	**LALPURA**			
	Fine Sand with Silt	0.00	7.92	7.92
	Clay with Kankar	7.92	35.36	27.44
	Sand	35.36	51.82	16.46
	Sand Stone	51.82	55.47	3.66
5.	**UFRAUL**			
	Fine Sand with Silt	0.00	15.24	15.24
	Kankar with Sand	15.24	26.21	10.97
	Clay with Kankar	26.21	35.36	9.15
	Sand	35.36	55.47	20.12
	Hard Clay	55.47	56.69	1.22
6.	**VAISHALI**			
	Fine Sand with Silt	0.00	7.92	7.92
	Clay	7.92	11.58	3.66
	Sand	11.58	15.24	3.66
	Clay	15.24	35.97	20.73
	Sand	35.97	53.04	17.07
	Clay with Kankar	53.04	55.47	2.44
7.	**SAIMVARUNNA**			
	Fine Sand with Silt	0.00	15.24	15.24
	Clay with fine Sand	15.24	39.62	24.38
	Fine Sand with Kank	39.62	90.22	50.60

Table B-1: Calculation of NIR for different crops in Rabi season

	Months	Days	ETo	Kc	Cu	Pre sowing	WR	P	Pe	NIR
Wheat	Nov 1-15 (LP)	15	4.05	0.35	21.26	50.00	71.26	4.50	0.00	71.26
	Nov 16-30 (Sow)	15	4.05	0.35	21.26	0.00	21.26	4.50	0.00	21.26
	Dec 1-31	31	3.15	0.75	73.24	0.00	73.24	3.40	0.00	73.24
	Jan 1-31	31	3.16	1.14	111.67	0.00	111.67	22.40	19.00	92.67
	Feb 1-28	28	4.10	1.10	126.28	0.00	126.28	14.80	10.00	116.28
	Mar 1-31	31	5.63	0.70	122.17	0.00	122.17	8.70	0.00	122.17
	Apr 1-15	15	6.93	0.25	25.99	0.00	25.99	7.80	0.00	25.99
	Total	166			501.88		551.88			522.88
Maize	Nov 1-15 (LP)	15	4.05	0.35	21.26	50.00	71.26	4.50	0.00	71.26
	Nov 16-30 (Sow)	15	4.05	0.35	21.26	0.00	21.26	4.50	0.00	21.26
	Dec 1-31	31	3.15	0.60	58.59	0.00	58.59	3.40	0.00	58.59
	Jan 1-31	31	3.16	1.14	111.67	0.00	111.67	22.40	19.00	92.67
	Feb 1-28	28	4.10	0.70	80.36	0.00	80.36	14.80	10.00	70.36
	Total	120			293.15		343.15			314.15
Potato	Oct 1-15 (LP)	15	5.40	0.40	32.40	50.00	82.40	26.00	17.00	65.40
	Oct 16-31 (Sow)	16	5.40	0.40	34.56	0.00	34.56	26.00	17.00	17.56
	Nov 1-30	30	4.05	0.70	85.05	0.00	85.05	9.90	0.00	85.05
	Dec 1-30	31	3.15	1.14	111.32	0.00	111.32	3.40	0.00	111.32
	Jan 1-31	31	3.16	0.85	83.27	0.00	83.27	22.40	19.00	64.27
	Feb 1-28	28	4.10	0.70	80.36	0.00	80.36	14.80	10.00	70.36
	Total	151			426.96		476.96			413.96
Mustard	Oct 1-15 (LP)	15	5.40	0.40	32.40	50.00	82.40	26.00	17.00	65.40
	Oct 16-31 (Sow)	16	5.40	0.40	34.56	0.00	34.56	26.00	17.00	17.56
	Nov 1-30	30	4.05	0.70	85.05	0.00	85.05	9.90	0.00	85.05
	Dec 1-30	31	3.15	1.10	107.42	0.00	107.42	3.40	0.00	107.42
	Jan 1-31	31	3.16	1.12	109.72	0.00	109.72	22.40	19.00	90.72
	Feb 1-28	28	4.10	0.70	80.36	0.00	80.36	14.80	10.00	70.36
	Mar 1-15	15	5.63	0.60	50.67	0.00	50.67	8.70	0.00	50.67
	Total	166			500.17		550.17			487.17
Tobacco	Oct 1-15 (LP)	15	5.40	0.40	32.40	50.00	82.40	26.00	17.00	65.40
	Oct 16-31 (Sow)	16	5.40	0.40	34.56	0.00	34.56	26.00	17.00	17.56
	Nov 1-30	30	4.05	0.70	85.05	0.00	85.05	9.90	0.00	85.05
	Dec 1-30	31	3.15	1.10	107.42	0.00	107.42	3.40	0.00	107.42
	Jan 1-31	31	3.16	0.90	88.16	0.00	88.16	22.40	19.00	69.16
	Feb 1-28	28	4.10	0.70	80.36	0.00	80.36	14.80	10.00	70.36
	Total	151			427.95		477.95			414.95
Gram	Oct 1-15 (LP)	15	5.40	0.35	28.35	50.00	78.35	26.00	17.00	61.35
	Oct 16-31 (Sow)	16	5.40	0.35	30.24	0.00	30.24	26.00	17.00	13.24
	Nov 1-30	30	4.05	0.70	85.05	0.00	85.05	9.90	0.00	85.05
	Dec 1-30	31	3.15	1.05	102.53	0.00	102.53	3.40	0.00	102.53
	Jan 1-31	31	3.16	0.95	93.06	0.00	93.06	22.40	19.00	74.06
	Feb 1-28	28	4.10	0.70	80.36	0.00	80.36	14.80	10.00	70.36
	Mar 1-15	15	5.63	0.30	25.34	0.00	25.34	8.70	0.00	25.34
	Total	166			444.93		494.93			431.93

Table B-2: Calculation of NIR for different crops in Garam (Summer) season

	Months	Days	ETo	Kc	Cu	Pre sowing	WR	P	Pe	NIR
Vegetables	Mar 1-15 (LP)	15	5.63	0.35	29.56	50.00	79.56	4.40	0.00	79.56
	Mar 16-31(Sow)	16	5.63	0.35	31.53	0.00	31.53	4.30	0.00	31.53
	Apr 1-30	30	6.93	0.70	145.53	0.00	145.53	7.80	0.00	145.53
	May 1-31	31	7.70	1.05	250.64	0.00	250.64	27.90	25.00	225.64
	Jun 1-30	30	6.67	0.95	190.10	0.00	190.10	151.20	117.00	73.10
	Total	122			647.35		697.35			555.35
Maize	Mar 1-15 (LP)	15	5.63	0.35	29.56	50.00	79.56	4.40	0.00	79.56
	Mar 16-31(Sow)	16	5.63	0.35	31.53	0.00	31.53	4.30	0.00	31.53
	Apr 1-30	30	6.93	0.70	145.53	0.00	145.53	7.80	0.00	145.53
	May 1-31	31	7.70	1.14	272.12	0.00	272.12	27.90	25.00	247.12
	Jun 1-30	30	6.67	0.80	160.08	0.00	160.08	151.20	117.00	43.08
	Total	122			638.81		688.81			546.81

Table B-3: Calculation of NIR for different crops in Kharif season.

	Months	Days	ETo	Kc	Cu	S&P	WR	P	Pe	NIR
Paddy	Jun 16-30(Nurser	15	6.67	0.90	4.50	2.50	7.00	75.00	47.00	0.00
	Jul 1-15(LP)	15	4.90	0.35	25.73	45.00	70.73	131.00	92.00	0.00
	Jul 16-31(TP)	16	4.90	0.40	31.36	48.00	79.36	131.00	92.00	0.00
	Aug 1-31	31	4.65	0.70	100.91	93.00	193.91	284.00	202.00	0.00
	Sep 1-30	30	5.20	1.14	177.84	90.00	267.84	201.00	135.00	132.84
	Oct 1-31	31	5.40	1.00	167.40	93.00	260.40	52.00	21.00	239.40
	Nov 1-15	15	4.05	0.85	51.64	0.00	51.64	4.50	0.00	51.64
	Total	153			559.37		930.87		589.00	423.88
Maize	Jun 1-30	30	6.67	0.36	71.04	50.00	121.04	151.00	117.00	4.04
	Jul 1-31	31	4.90	0.60	91.14	0.00	91.14	262.00	69.00	22.14
	Aug 1-31	31	4.65	1.12	161.45	0.00	161.45	284.00	133.00	28.45
	Sep 1-30	30	5.20	1.02	159.12	0.00	159.12	201.00	133.00	26.12
	Oct 1-15	15	5.40	0.70	56.70	0.00	56.70	52.00	40.00	16.70
	Total	137			539.44		589.44			97.44

LP = Land preparation; TP = Transplanting; Sow = Sowing.
ETo = Potential evapotranspiration (mm/day); K_c = Crop coefficient; Cu = Consumptive use (mm).
WR = Water requirement (mm); P = Rainfall (mm); P_e = Effective rainfall (mm).
NIR = Net irrigation requirements (mm).

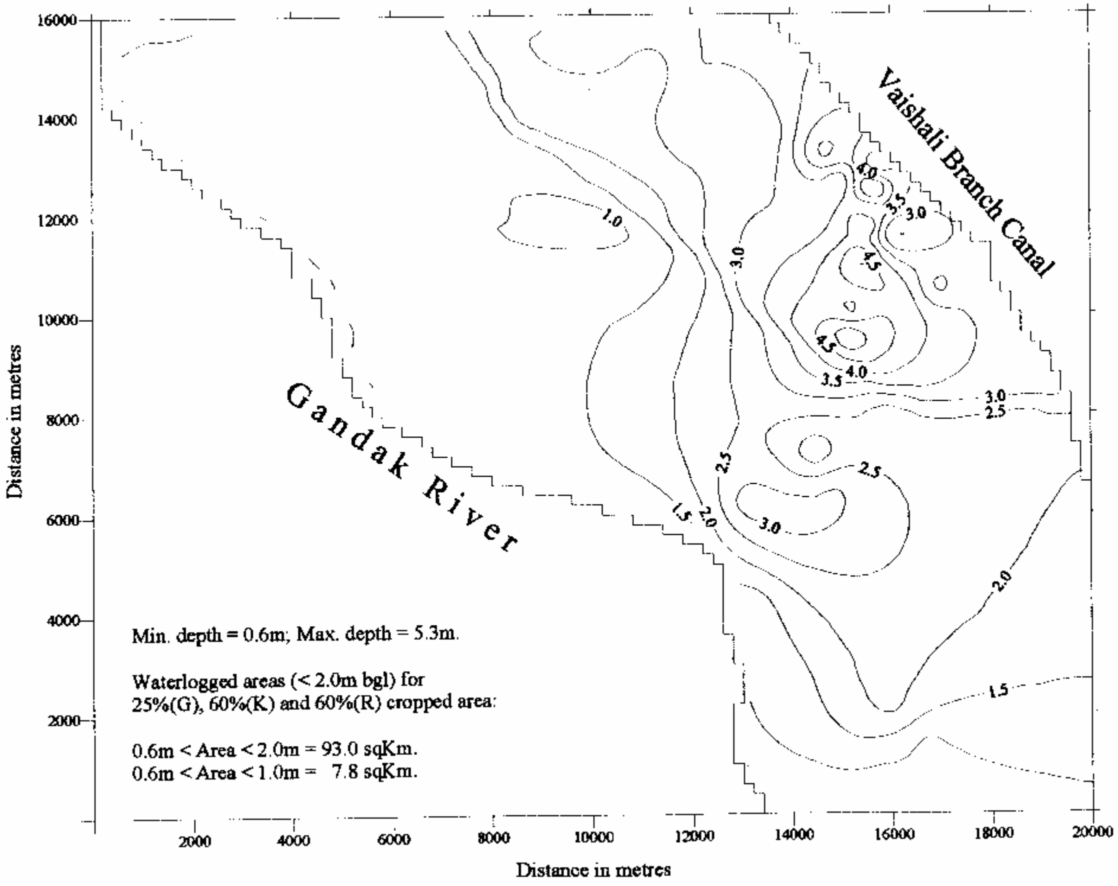
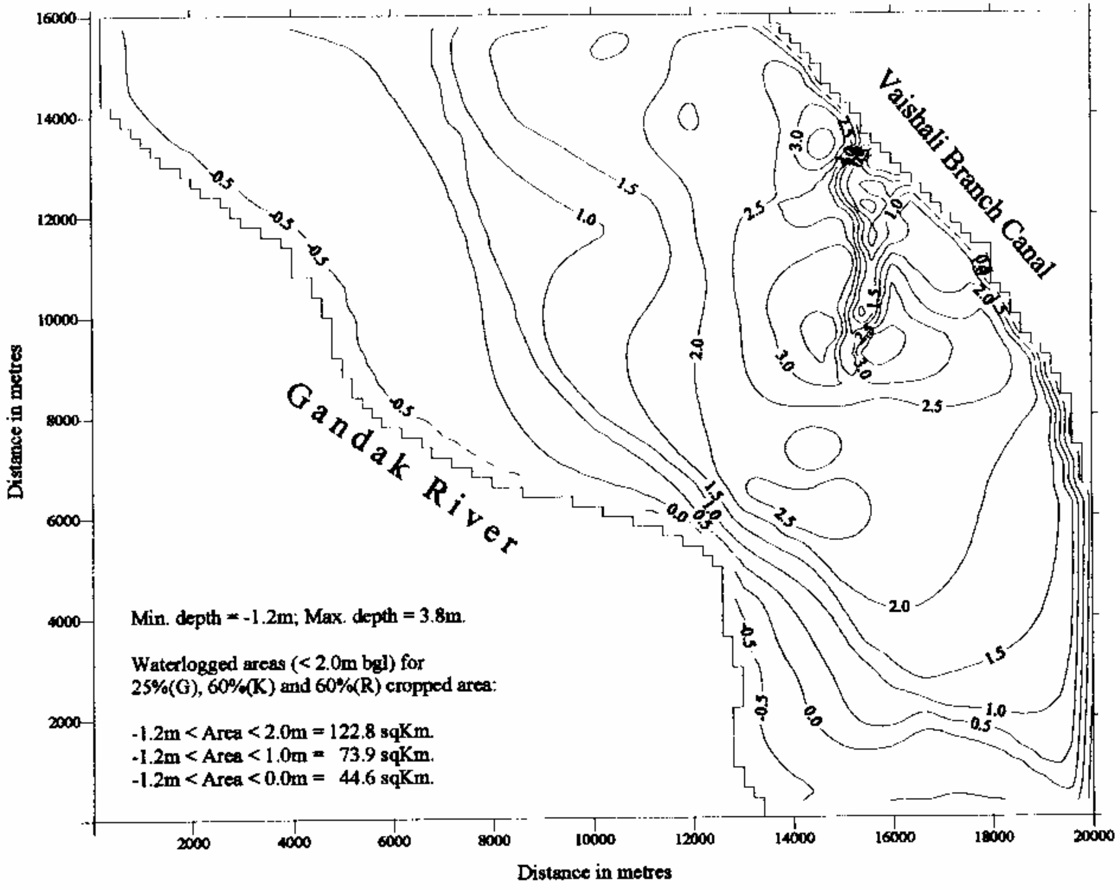


Figure C-1 : Depth to water table contours (m) at the end of 1st stress period (Garam season).



Min. depth = -1.2m; Max. depth = 3.8m.

Waterlogged areas (< 2.0m bgl) for
25%(G), 60%(K) and 60%(R) cropped area:

-1.2m < Area < 2.0m = 122.8 sqKm.
-1.2m < Area < 1.0m = 73.9 sqKm.
-1.2m < Area < 0.0m = 44.6 sqKm.

Figure C-2 : Depth to water table contours (m) at the end of 2nd stress period (Kharif season).

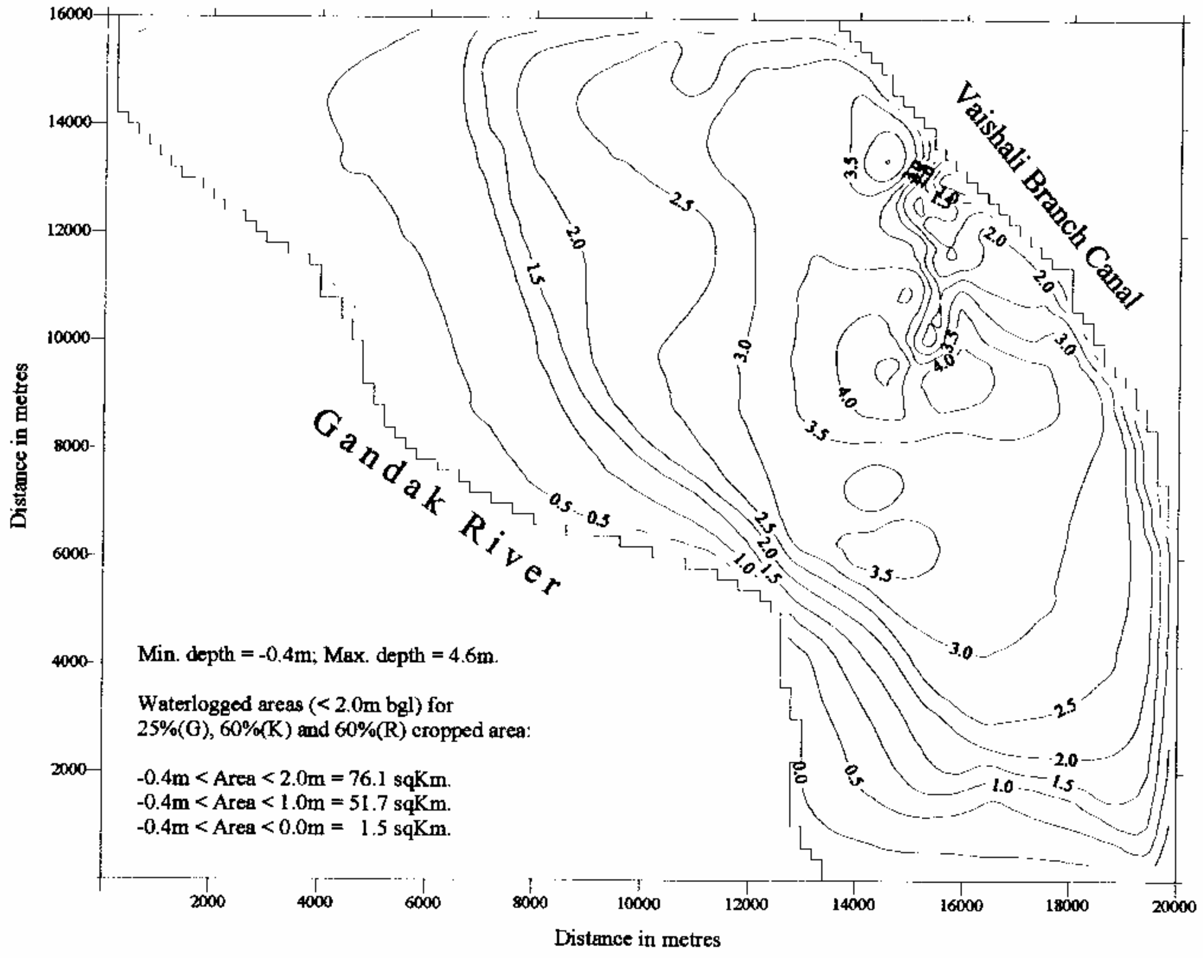


Figure C-3 : Depth to water table contours (m) at the end of 3rd stress period (Rabi season).

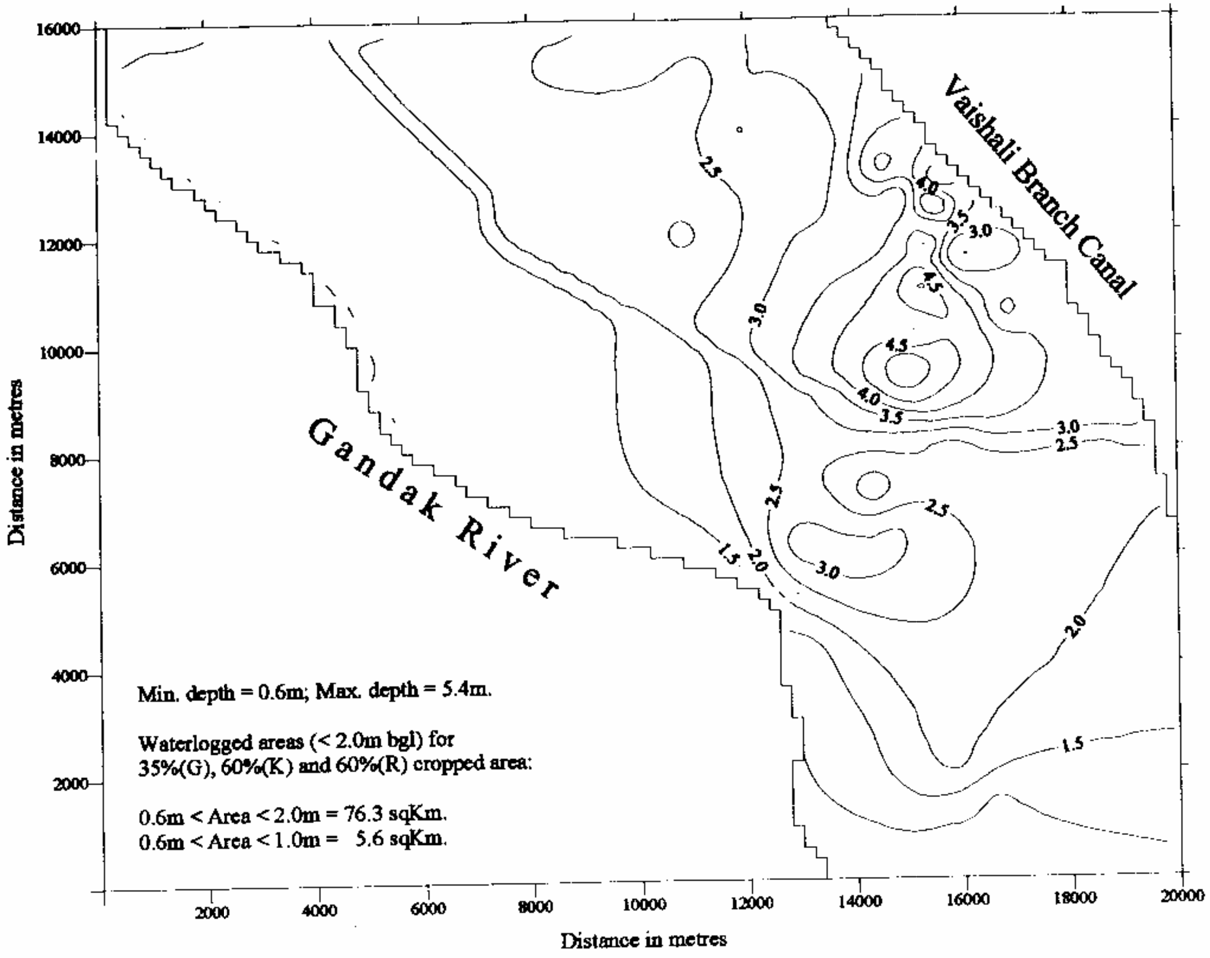


Figure C-4 : Depth to water table contours (m) at the end of 1st stress period (Garam season).

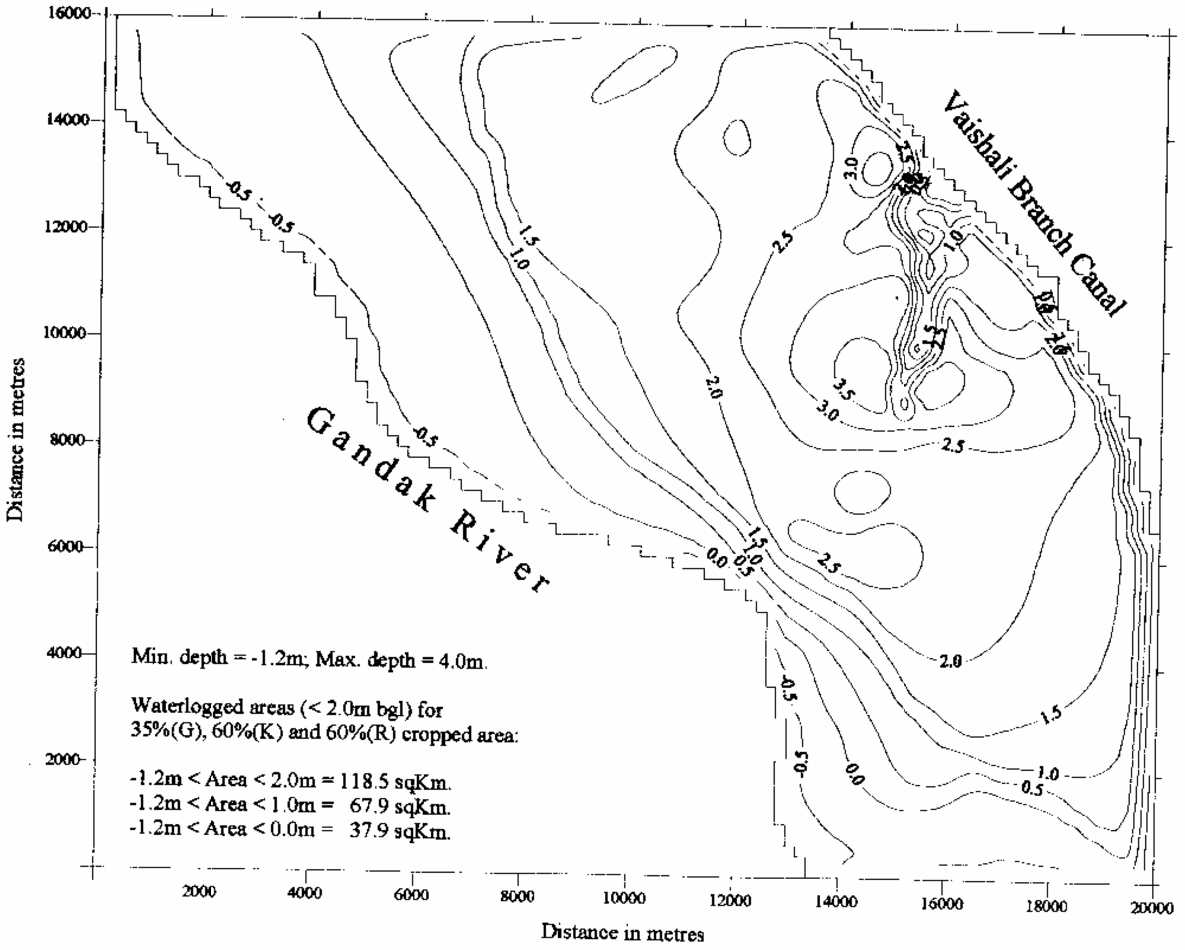
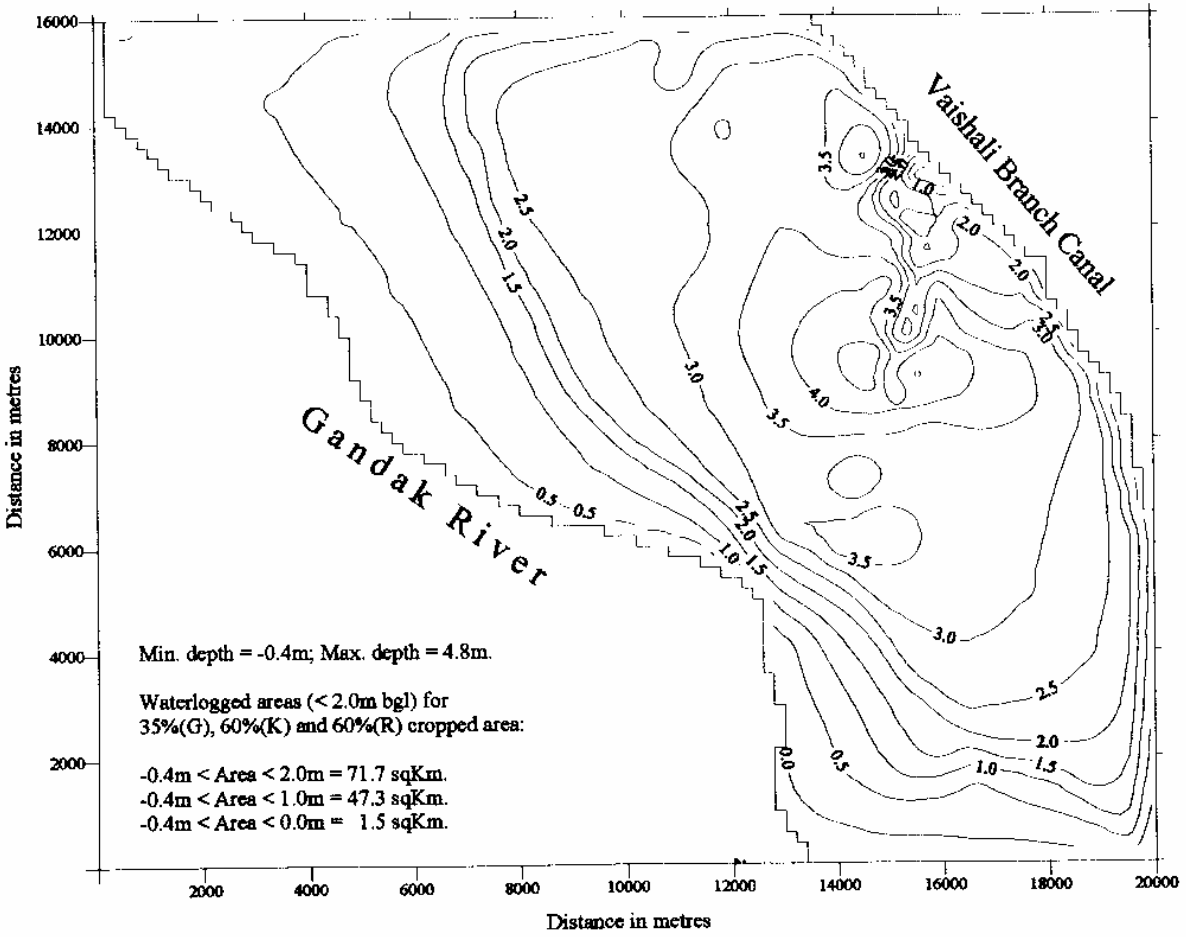


Figure C-5 : Depth to water table contours (m) at the end of 2nd stress period (Kharif season).

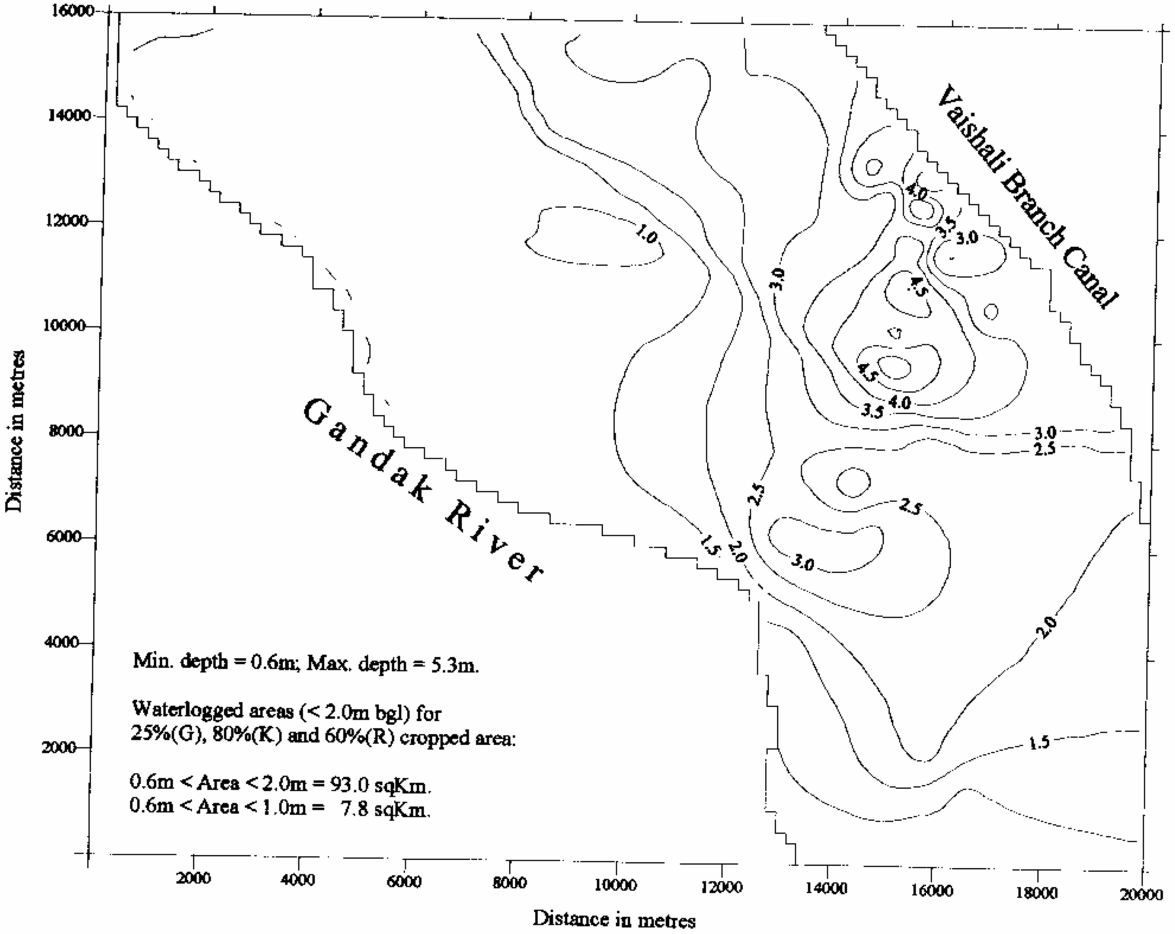


Min. depth = -0.4m; Max. depth = 4.8m.

Waterlogged areas (< 2.0m bgl) for
35%(G), 60%(K) and 60%(R) cropped area:

-0.4m < Area < 2.0m = 71.7 sqKm.
-0.4m < Area < 1.0m = 47.3 sqKm.
-0.4m < Area < 0.0m = 1.5 sqKm.

Figure C-6 : Depth to water table contours (m) at the end of 3rd stress period (Rabi season).



Min. depth = 0.6m; Max. depth = 5.3m.

Waterlogged areas (< 2.0m bgl) for
25%(G), 80%(K) and 60%(R) cropped area:

0.6m < Area < 2.0m = 93.0 sqKm.
0.6m < Area < 1.0m = 7.8 sqKm.

Figure C-7 : Depth to water table contours (m) at the end of 1st stress period (Garam season).

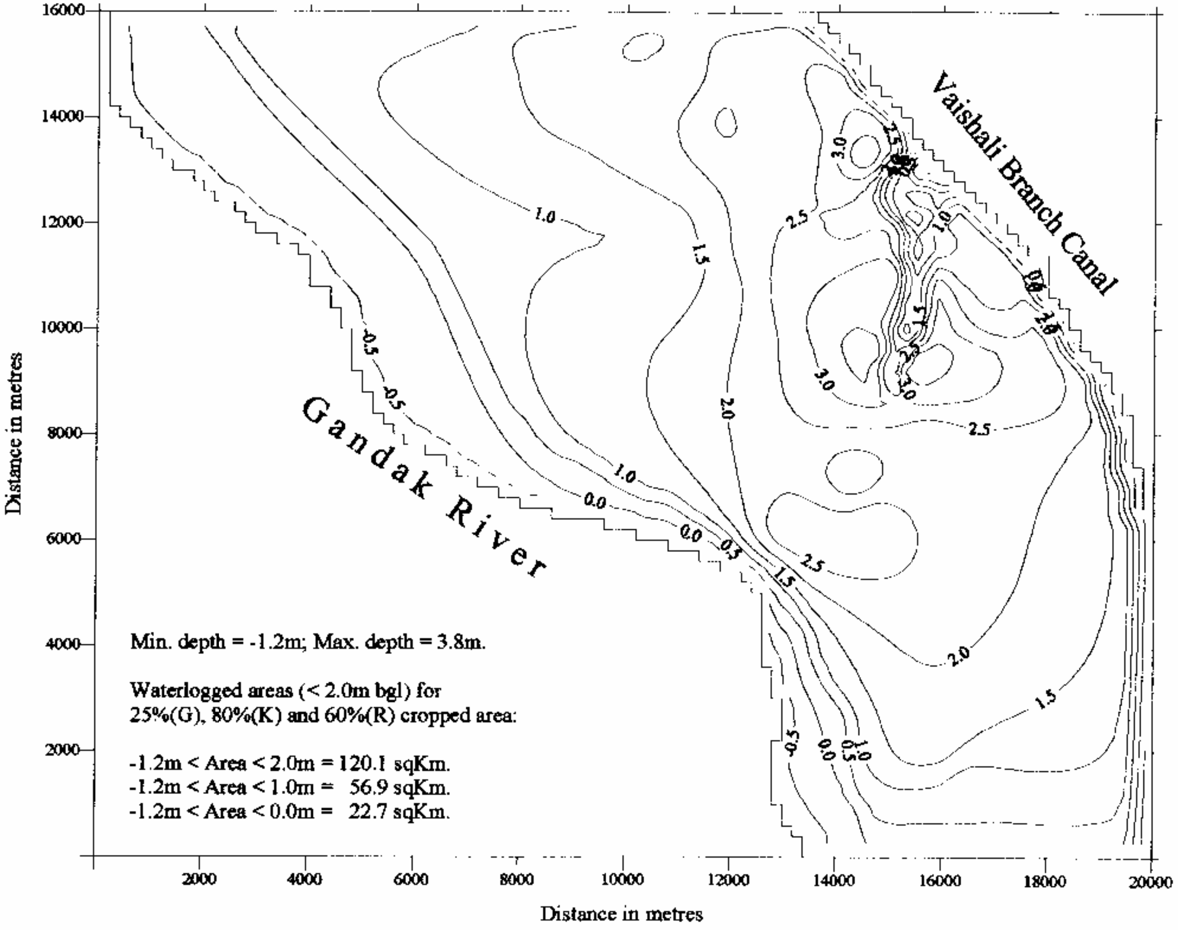
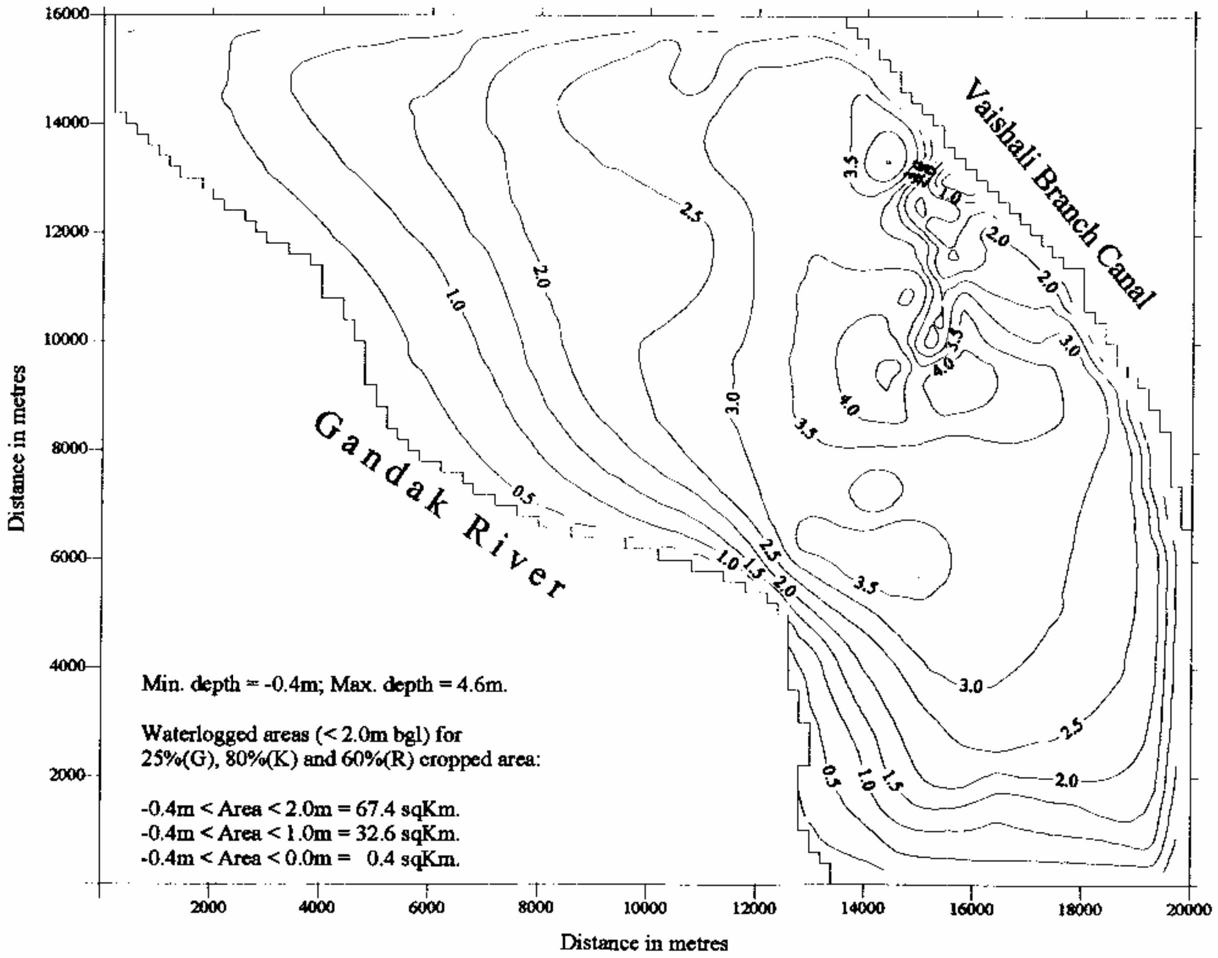


Figure C-8 : Depth to water table contours (m) at the end of 2nd stress period (Kharif season).

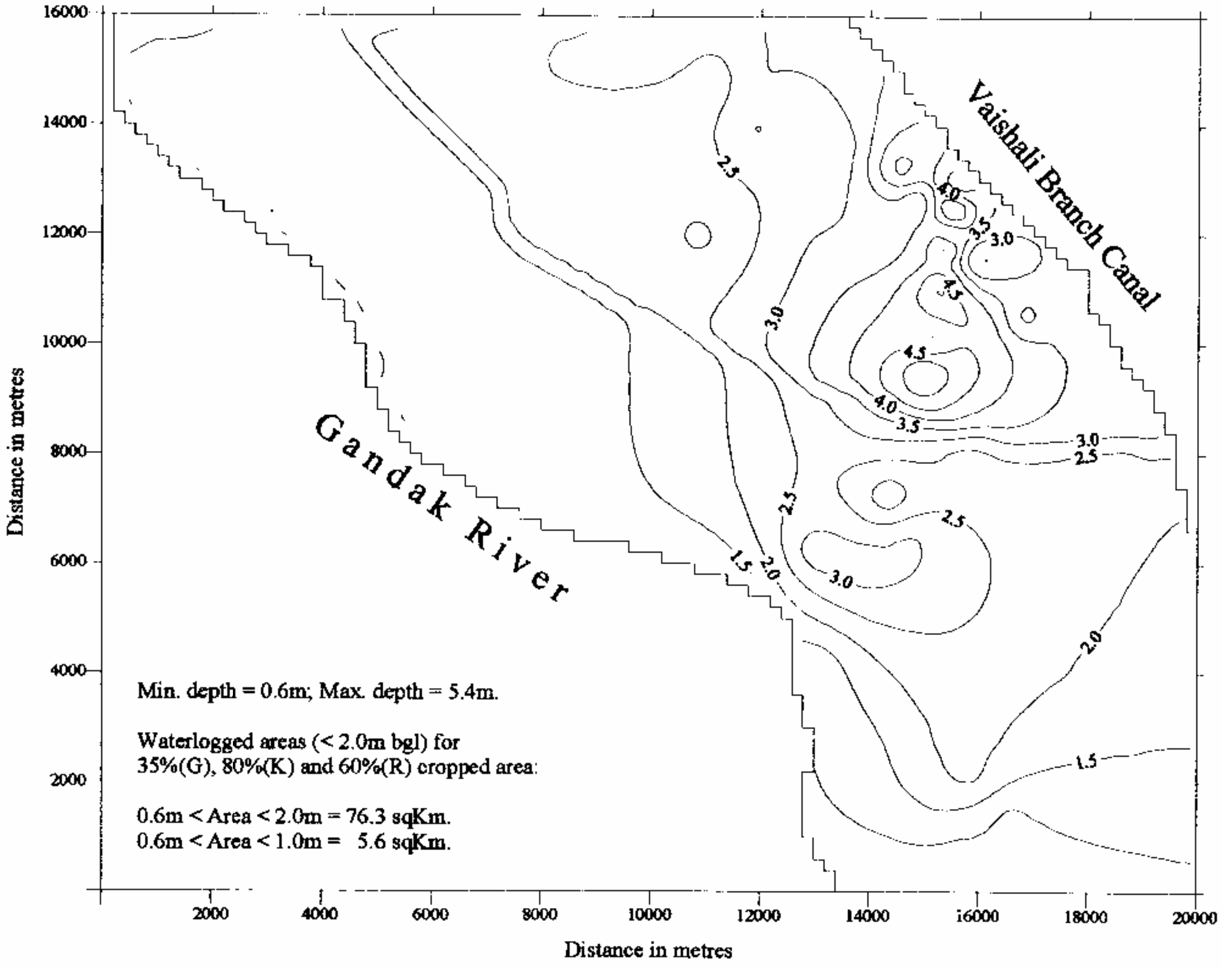


Min. depth = -0.4m; Max. depth = 4.6m.

Waterlogged areas (< 2.0m bgl) for
25%(G), 80%(K) and 60%(R) cropped area:

-0.4m < Area < 2.0m = 67.4 sqKm.
-0.4m < Area < 1.0m = 32.6 sqKm.
-0.4m < Area < 0.0m = 0.4 sqKm.

Figure C-9 : Depth to water table contours (m) at the end of 3rd stress period (Rabi season).

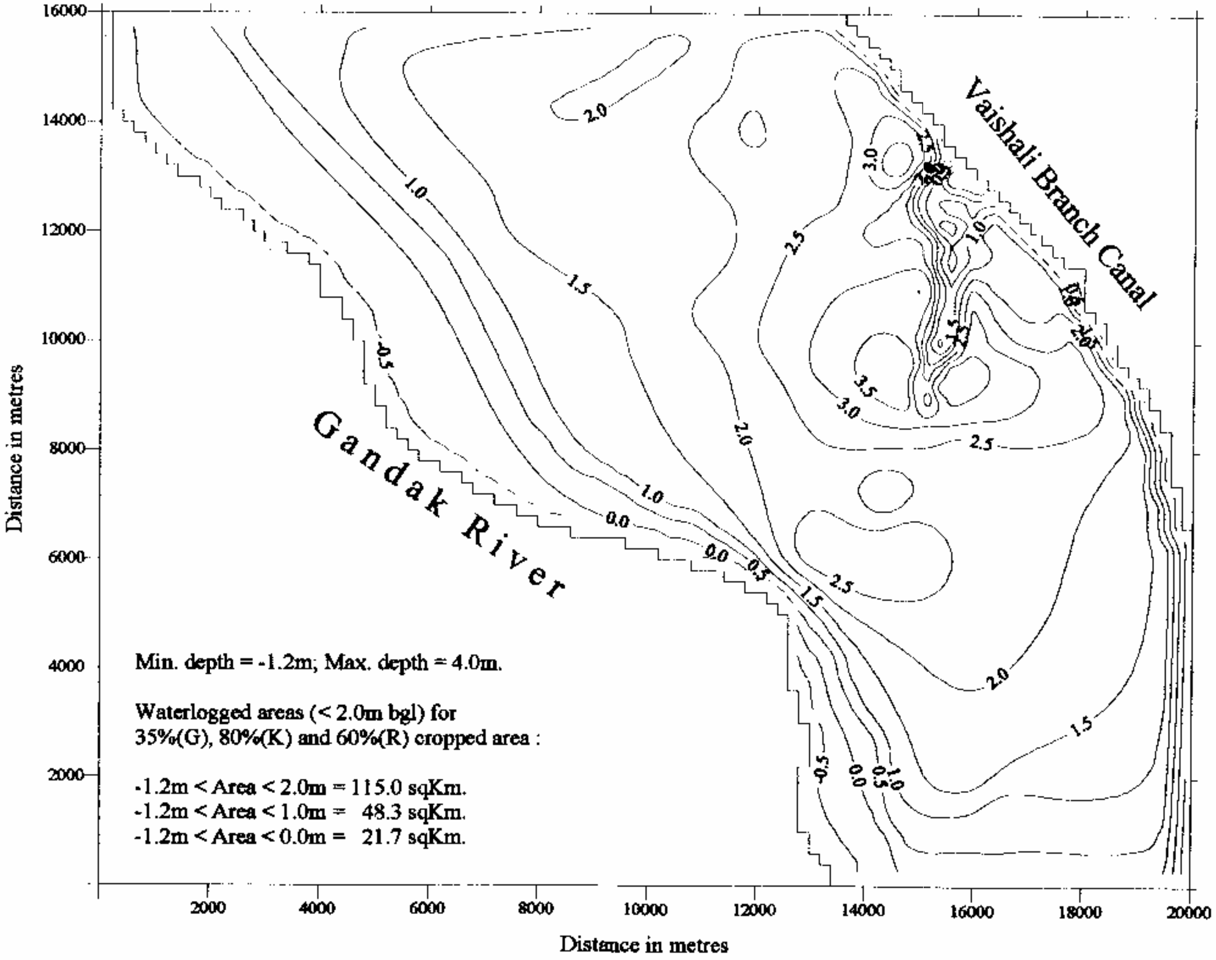


Min. depth = 0.6m; Max. depth = 5.4m.

Waterlogged areas (< 2.0m bgl) for
35%(G), 80%(K) and 60%(R) cropped area:

0.6m < Area < 2.0m = 76.3 sqKm.
0.6m < Area < 1.0m = 5.6 sqKm.

Figure C-10 : Depth to water table contours (m) at the end of 1st stress period (Garam season).

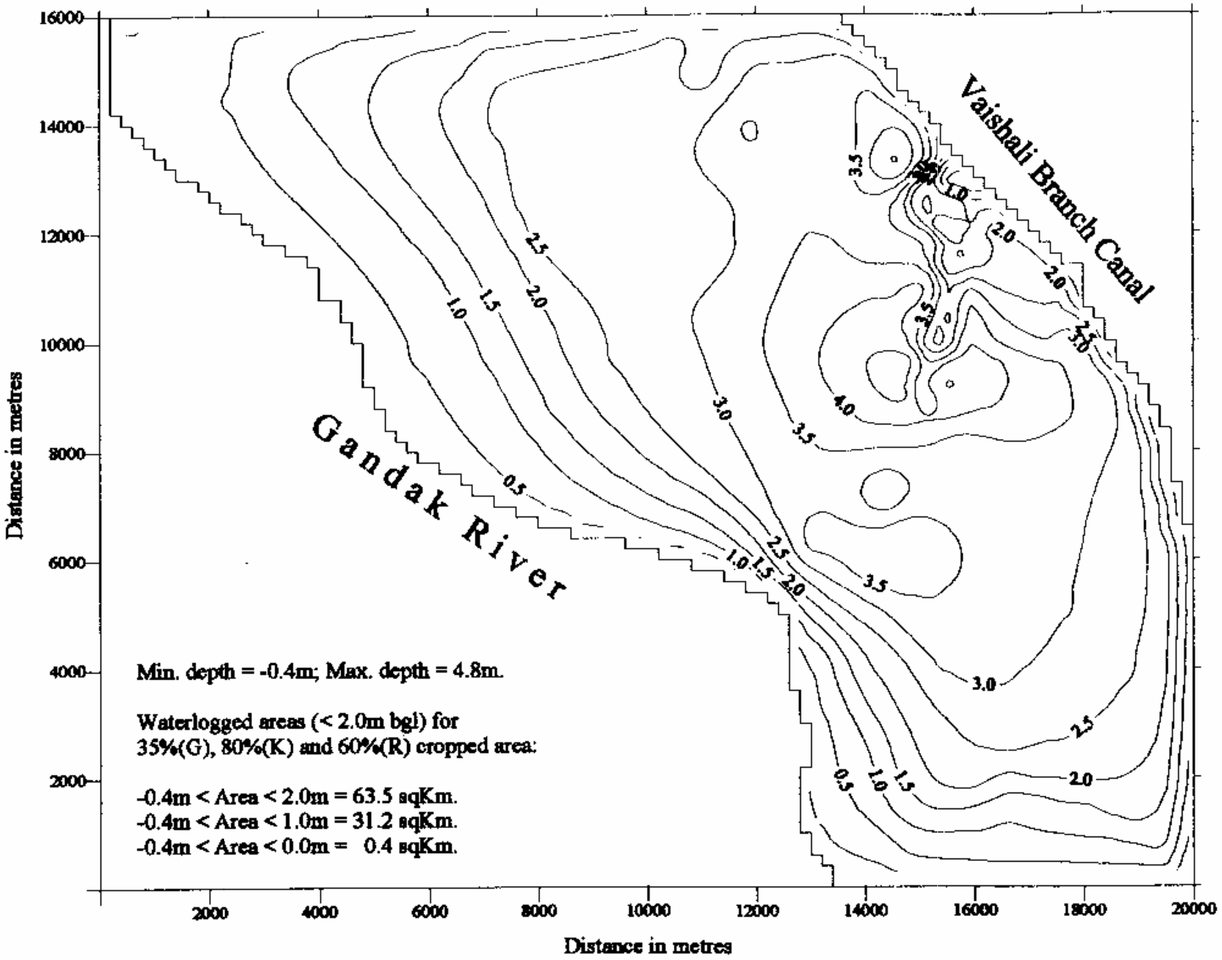


Min. depth = -1.2m; Max. depth = 4.0m.

Waterlogged areas (< 2.0m bgl) for
35%(G), 80%(K) and 60%(R) cropped area :

-1.2m < Area < 2.0m = 115.0 sqKm.
-1.2m < Area < 1.0m = 48.3 sqKm.
-1.2m < Area < 0.0m = 21.7 sqKm.

Figure C-11 : Depth to water table contours (m) at the end of 2nd stress period (Kharif season).



Min. depth = -0.4m; Max. depth = 4.8m.

Waterlogged areas (< 2.0m bgl) for
35%(G), 80%(K) and 60%(R) cropped area:

-0.4m < Area < 2.0m = 63.5 sqKm.
-0.4m < Area < 1.0m = 31.2 sqKm.
-0.4m < Area < 0.0m = 0.4 sqKm.

Figure C-12 : Depth to water table contours (m) at the end of 3rd stress period (Rabi season).

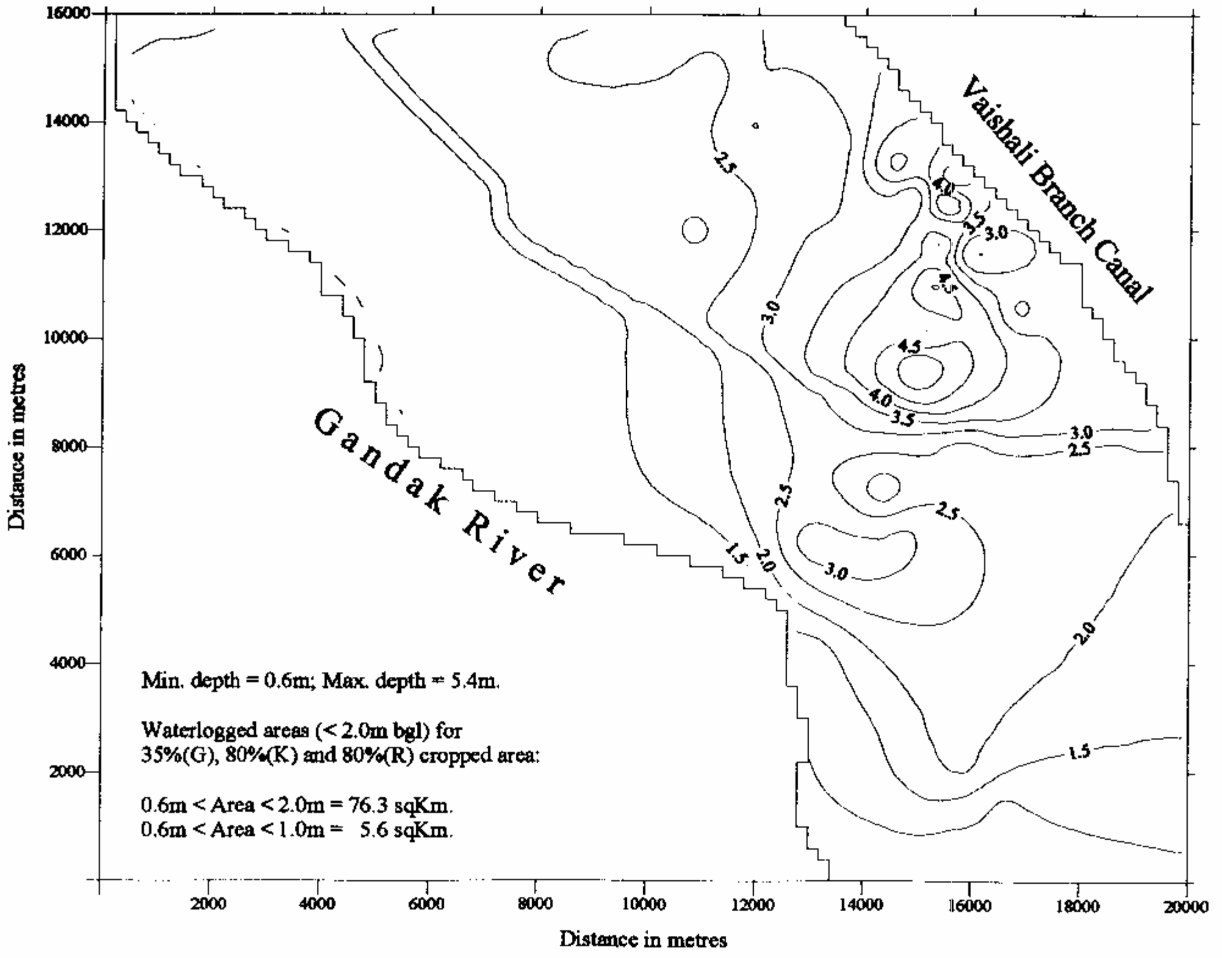
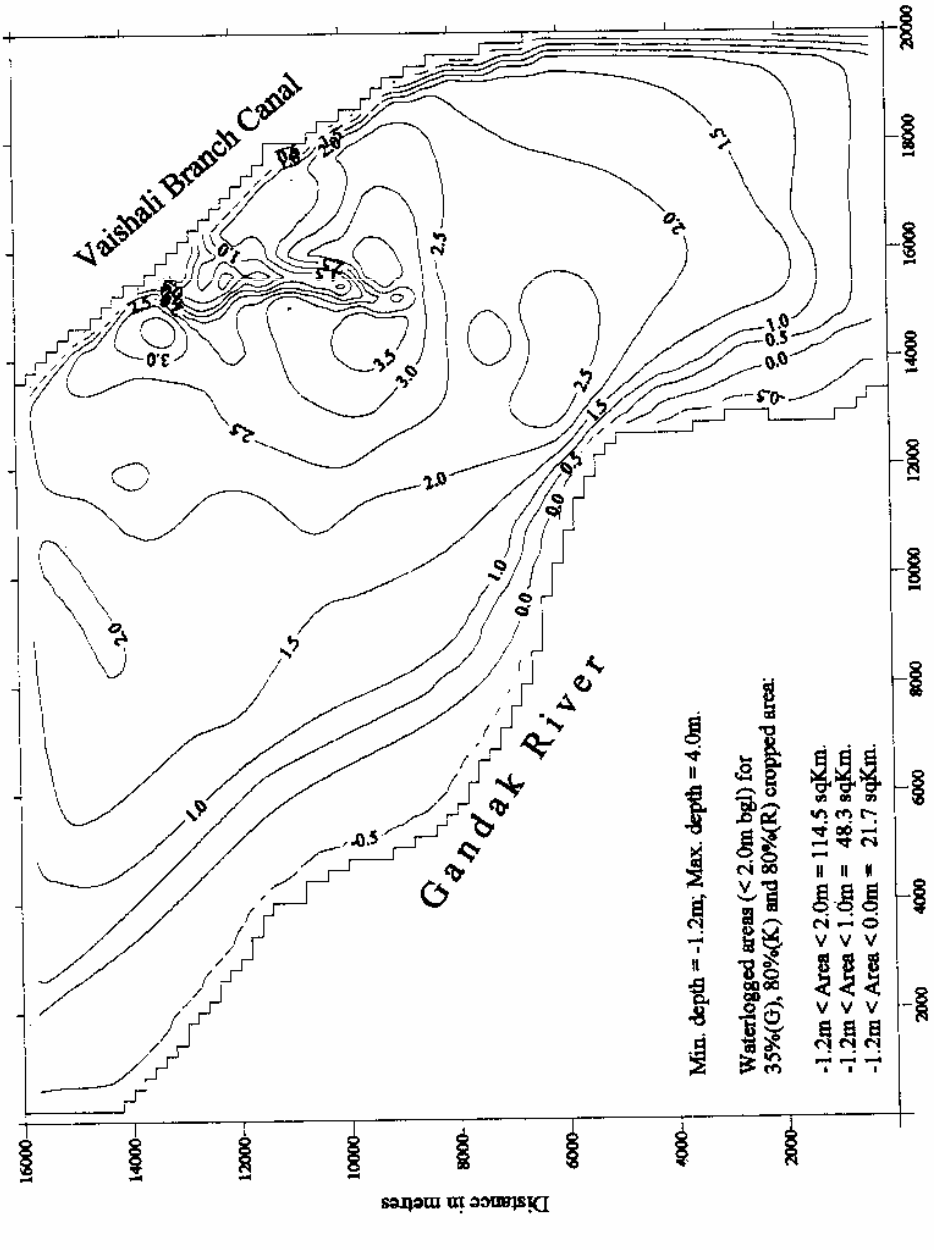


Figure C-13 : Depth to water table contours (m) at the end of 1st stress period (Garam season).



Min. depth = -1.2m; Max. depth = 4.0m.

Waterlogged areas (< 2.0m bgl) for 35%(G), 80%(K) and 80%(R) cropped area:

-1.2m < Area < 2.0m = 114.5 sqKm.
-1.2m < Area < 1.0m = 48.3 sqKm.
-1.2m < Area < 0.0m = 21.7 sqKm.

Figure C-14 : Depth to water table contours (m) at the end of 2nd stress period (Kharif season).

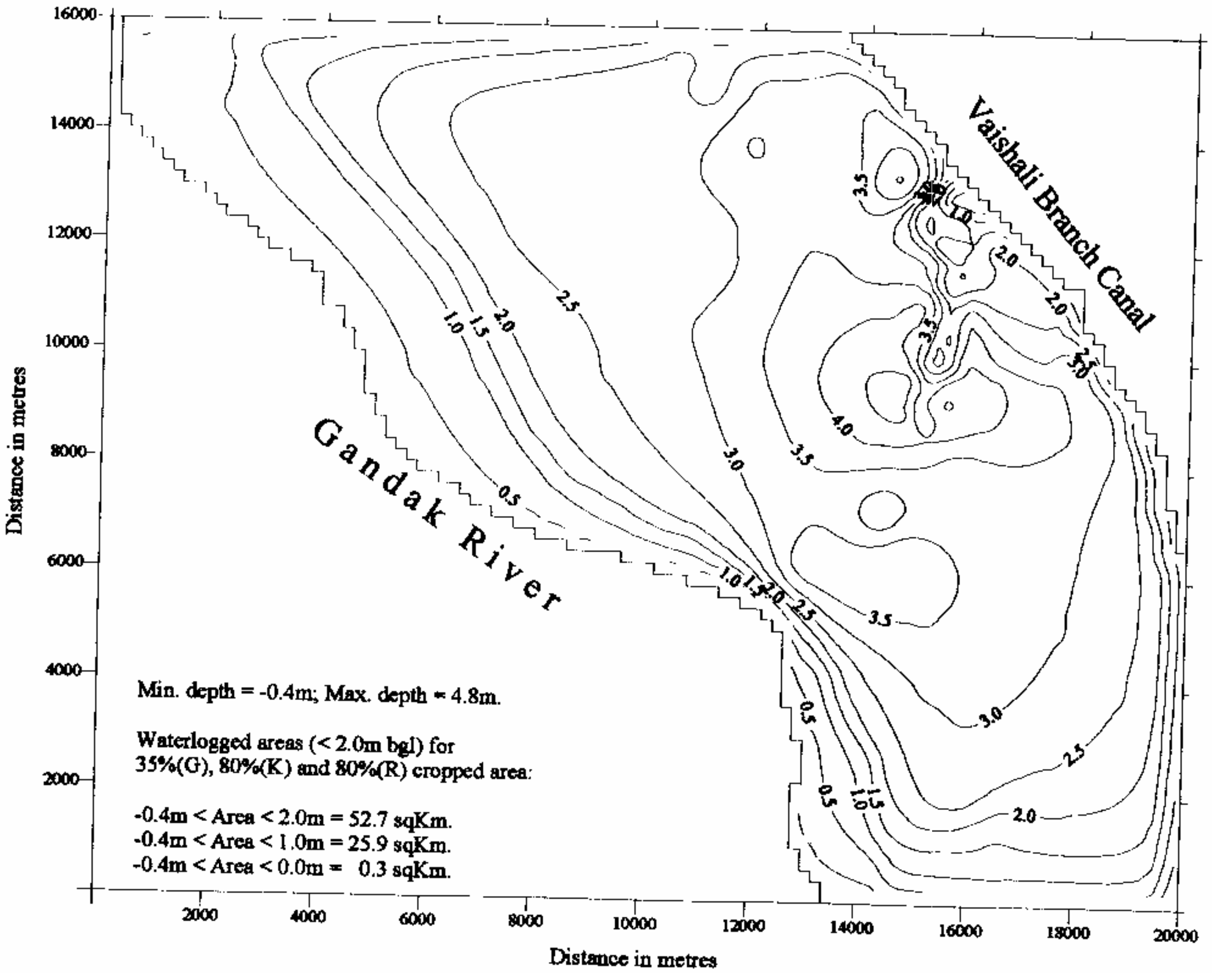
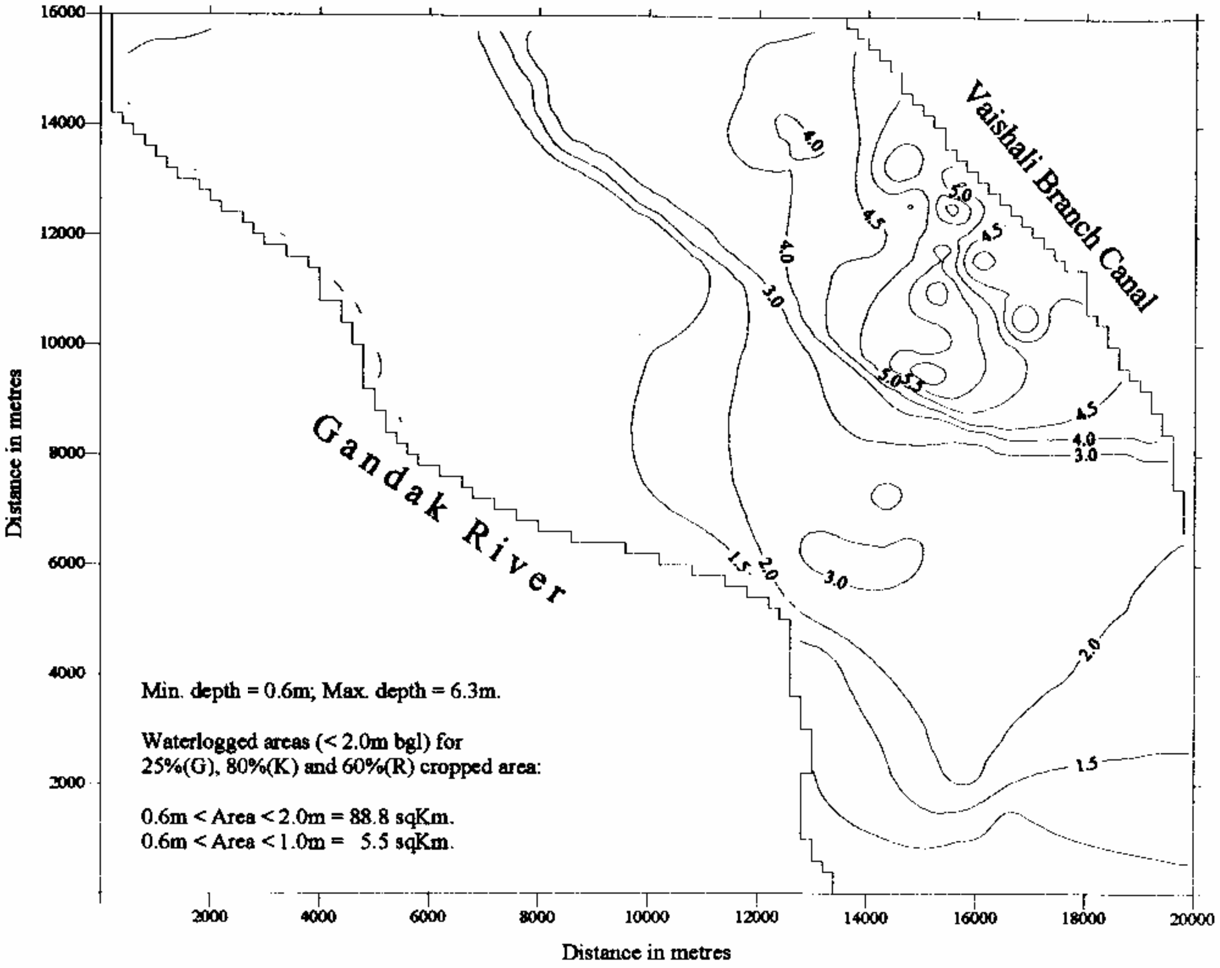


Figure C-15 : Depth to water table contours (m) at the end of 3rd stress period (Rabi season).



Min. depth = 0.6m; Max. depth = 6.3m.

Waterlogged areas (< 2.0m bgl) for
25%(G), 80%(K) and 60%(R) cropped area:

0.6m < Area < 2.0m = 88.8 sqKm.
0.6m < Area < 1.0m = 5.5 sqKm.

Figure D-1 : Depth to water table contours(m) at the end of 1st stress period (Garam season) with pumpage.

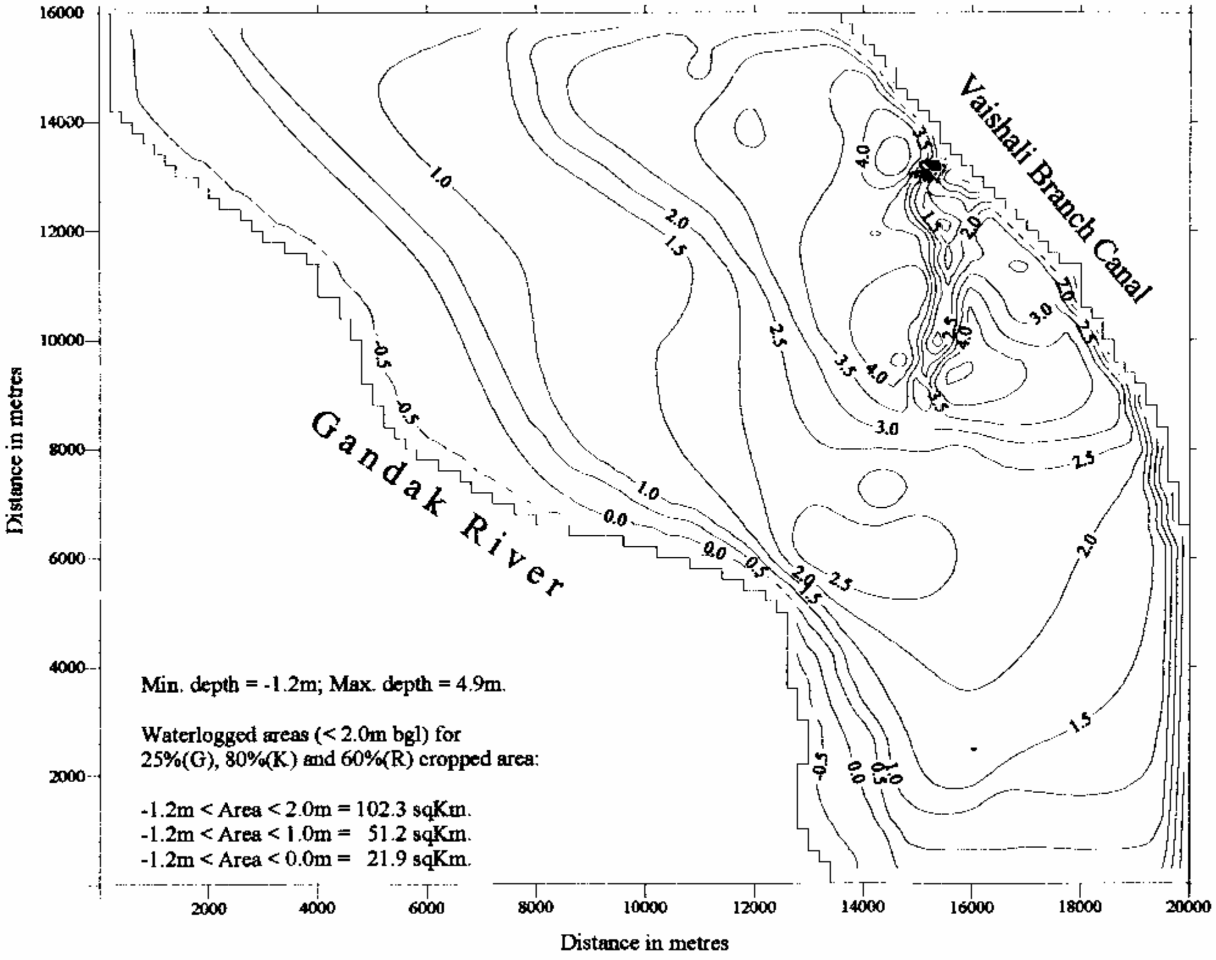
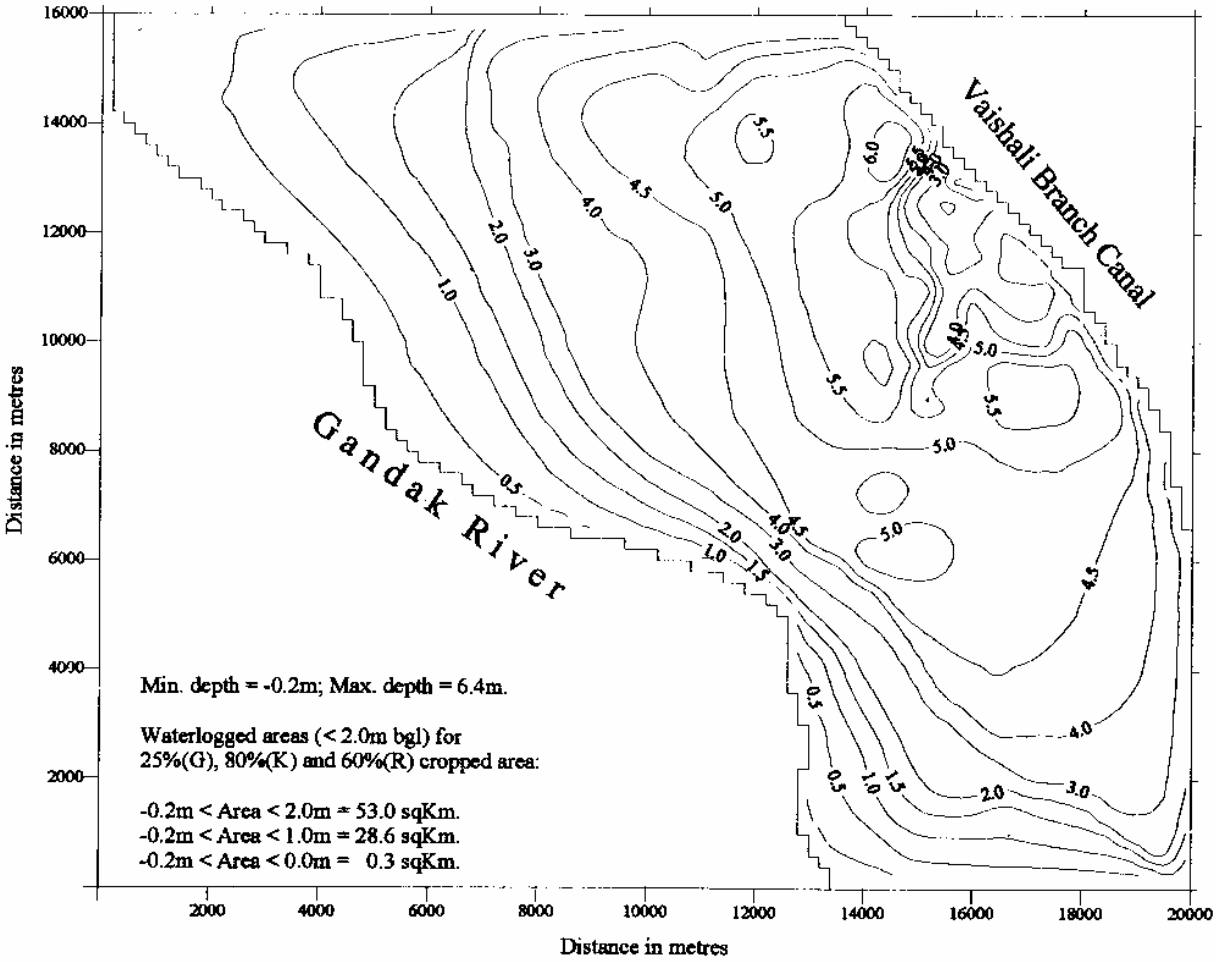


Figure D-2 : Depth to water table contours (m) at the end of 2nd stress period (Kharif season) with pumpage.

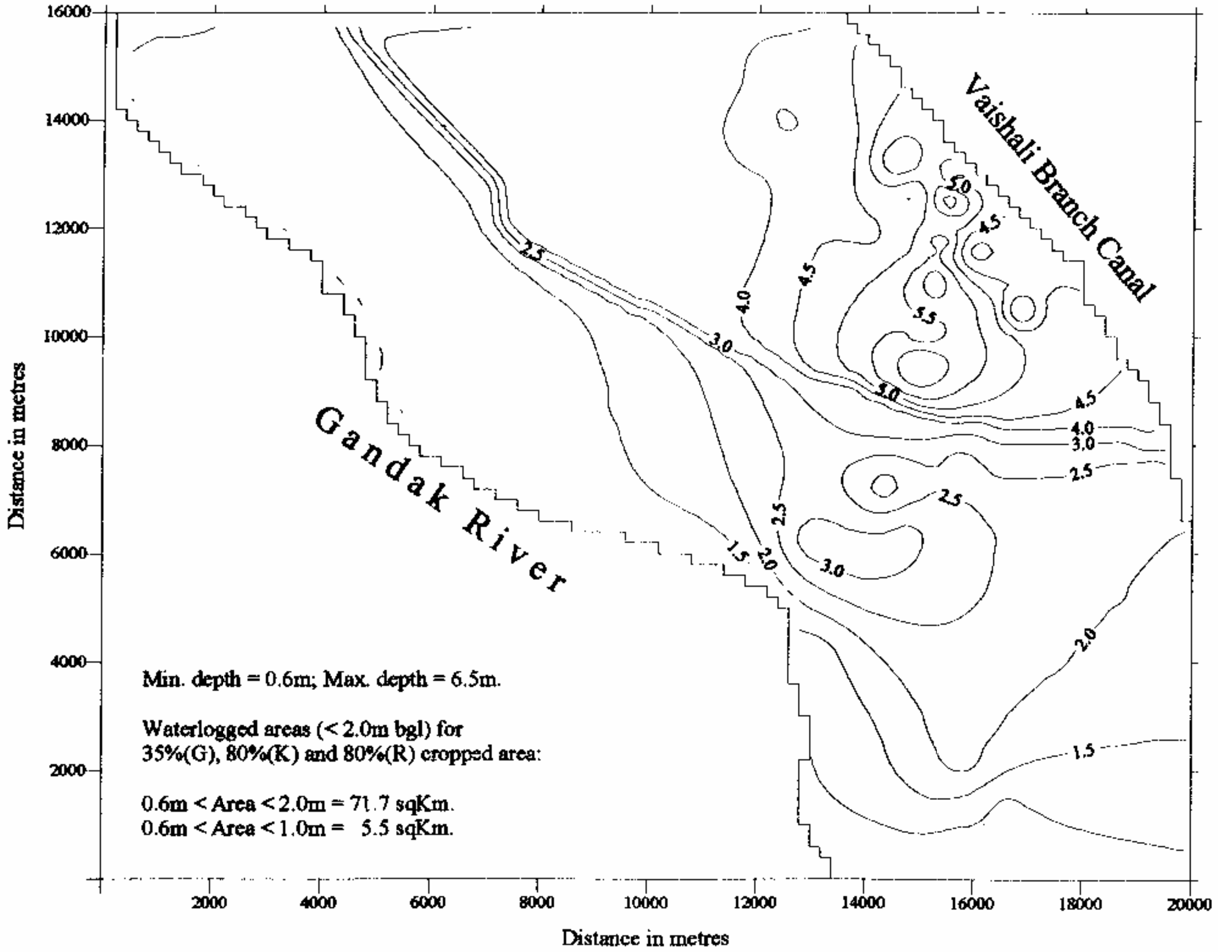


Min. depth = -0.2m; Max. depth = 6.4m.

Waterlogged areas (< 2.0m bgl) for
25%(G), 80%(K) and 60%(R) cropped area:

-0.2m < Area < 2.0m = 53.0 sqKm.
-0.2m < Area < 1.0m = 28.6 sqKm.
-0.2m < Area < 0.0m = 0.3 sqKm.

Figure D-3 : Depth to water table contours (m) at the end of 3rd stress period (Rabi season) with pumpage.

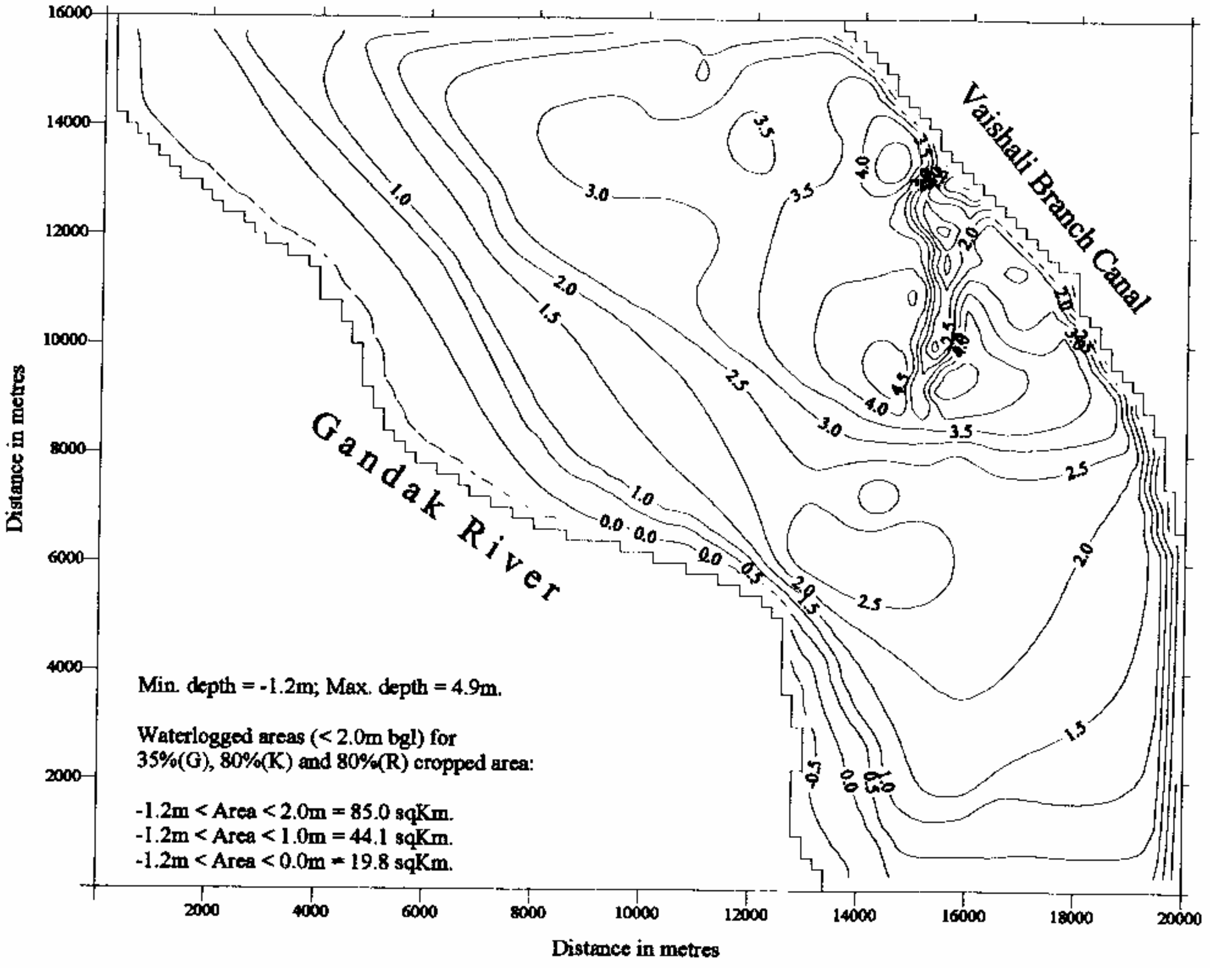


Min. depth = 0.6m; Max. depth = 6.5m.

Waterlogged areas (< 2.0m bgl) for
35%(G), 80%(K) and 80%(R) cropped area:

0.6m < Area < 2.0m = 71.7 sqKm.
0.6m < Area < 1.0m = 5.5 sqKm.

Figure D-4: Depth to water table contours (m) at the end of 1st stress period (Garam season) with pumpage.



Min. depth = -1.2m; Max. depth = 4.9m.

Waterlogged areas (< 2.0m bgl) for
35%(G), 80%(K) and 80%(R) cropped area:

-1.2m < Area < 2.0m = 85.0 sqKm.
-1.2m < Area < 1.0m = 44.1 sqKm.
-1.2m < Area < 0.0m = 19.8 sqKm.

Figure D-5 : Depth to water table contours (m) at the end of 2nd stress period (Kharif season) with pumpage.

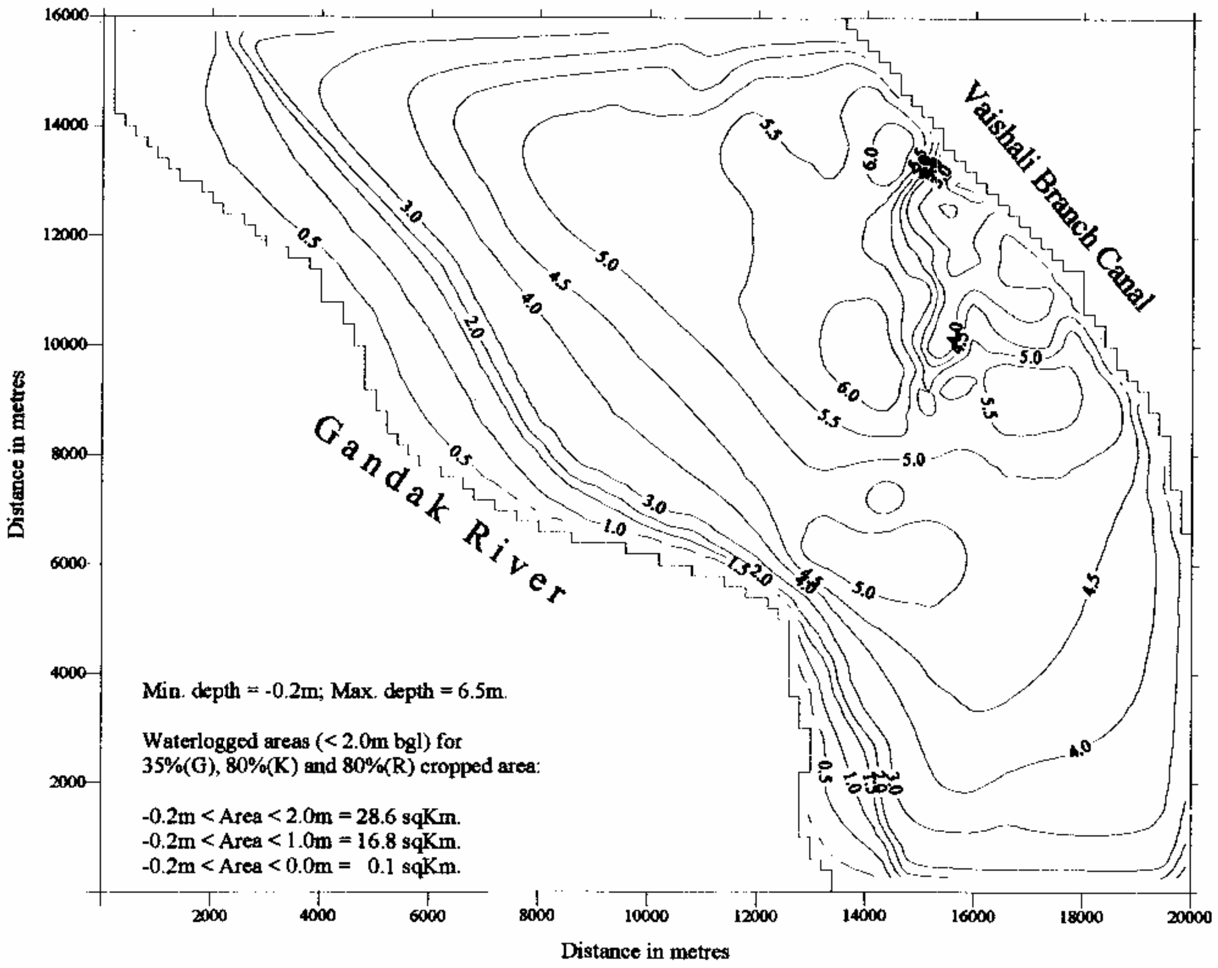


Figure D-6 : Depth to water table contours (m) at the end of 3rd stress period (Rabi season) with pumpage.

Appendix - E

ABBREVIATIONS USED

VBC : Vaishali Branch Canal.
HSD : Habibpur sub-distributary.
RD : Reduced Distance = 1000 feet.
GADA : Gandak Area Development Authority.
VASFA : Vaishali Small Farmer's Association.
CWC : Central Water Commission.
CGWB : Central Ground Water Board.
CWRS : Centre for Water Resources Studies, Patna.
Garam season : Hot weather season (March to June).
bgl : Below ground level.
ET : Evapotranspiration.
CWR : Crop Water Requirement.
NIR : Net Irrigation Requirement.
GHB : General Head Boundary.
GW : Groundwater.

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