Analysis of water management in Sirsa District in Haryana; model testing and application

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ABSTRACT

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Through model simulations different managerial solutions were evaluated for increasing water-logging and secondary salinization in irrigated areas without sufficient natural drainage and suitable drainage outlets. Aquifer recharge in the already highly efficient irrigation system could be reduced by shifting to a delivery-based water-pricing system. The problems were significantly delayed and crop production slightly increased. Distribution of canal water proportional to the demands produced similar results while declining water-tables were also arrested. The tested solutions delay the occurrence of water-logging and secondary salinization, hence giving more time for the implementation of definite solutions: adequate drainage systems, drainage outlets and adapted water management.

Keywords: drainage, groundwater, India, irrigation, salinization, water-logging

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Preface

The Indo-Dutch Operational Research Project for Hydrological Studies is a cooperative venture of three technical agencies: the CCS Haryana Agricultural University in Hisar, India, The International Institute for Land Reclamation and Improvement (ILRI) and the DLO Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), both in Wageningen, The Netherlands. The project has been in operation since 1985 and aims at safeguarding the soil productivity in the 'cornbelt' of India.

Lack of suitable drainage outlets in canal irrigated regions and over-exploitation in groundwater irrigated regions are key issues addressed by this project. Within the framework of this project, several studies have been undertaken to find and test solutions for water-logging and secondary salinisation. A number of solutions can be implemented at farm level, while especially managerial solutions would be implemented at a regional level. This report deals with the evaluation of the effectiveness of managerial solutions at a regional scale through simulations.

The SIWARE model package, developed in the framework of the Reuse of Drainage Water Project by SC-DLO and the Drainage Research Institute in Cairo, Egypt, and the regional groundwater model SGMP, developed by ILRI, have been integrated for the simulations in this study.

All views, conclusions and recommendations expressed in this report are those of the cooperating University and Institutes, and do not represent any official views of the Indian Council for Agricultural Research, or the Ministry of Foreign Affairs of The Netherlands.

Summary

Irrigation in India has undergone continuous development, from about one million ha in 1850, 11.7 million ha in 1900 until the actual situation of about 42 million ha. The Indian Government is planning to attain gradually its ultimate irrigation potential of about 110 million ha.

The significant increase in irrigated area has India successfully transformed from a food deficient state to one which is self-sufficient in the production of grains.

With the introduction of canal irrigation the recharge of the aquifers was increased, causing in relatively low elevated areas water-logging and secondary salinization, amounting about 7 million ha at this moment. Without adequate measure, this area will increase by several millions of ha in the coming few decades.

At the same moment groundwater-tables decline due to over-exploitation of the groundwater reservoirs.

To solve the problems or achieving a certain status quo, comprehensive changes are needed in the system and management of (irrigation) water and the exploitation of groundwater reservoirs. It is foreseen that solutions most likely will require the implementation of a coherent drainage system and facilities for safe disposal of excess of water and salts. As we believe that such definite solutions require a long period of preparation and execution, easy to implement and cost effective solutions should be found for the intermediate periods. For that reason, the Indo Dutch Operational Research Project for Hydrological Studies, was implemented.

A pilot area in Haryana, Sirsa District, has been selected to test managerial solutions for the reduction of aquifer recharge to be implemented by regional water managers. A package of simulation models has been used to simulate the effects of the solutions. The package (SIWARE) includes a surface water model, a on-farm water management model, a regional drainage model (REUSE) and a regional groundwater model (SGMP). In this report SGMP and REUSE have been integrated and given the working title FRAME.

Sirsa District is located in the extreme west corner of the state Haryana and downstream end of the Ghaggar river basin and comprising of nearly 4200 km^2. It is surrounded by the states of Punjab in the north and Rajastan in the west and south. Rainfall in Sirsa is erratic and shows a large spatial variability. The annual rainfall varies from less than 300 mm to 550 mm with less than 25 rainy days and an annual potential evapotranspiration of 1500 to 1650 mm. The soil texture of the area varies from loamy sand to sandy loam and all soils have low organic carbon content. The groundwater quality on both sides of the Ghaggar river was generally good. However, groundwater quality in the western side was quite poor. The movement of groundwater on one side of the Ghaggar river was towards the north-west. The water-table depths during 1992 ranged from 1.5 m to 25 m. On both sides of the Ghaggar

river, the water-table has been declining, whereas serious water-logging and salinization problems had developed in certain other regions.

Canal water supply to Sirsa District was through three canals: Bhakra Main Line in the north serving about 344,000 ha, Sukchain Distributary in the central part serving about 29,500 ha and Fatebad in the south serving 182,000 ha. The average annual canal water supply amounts about 2,000 million m^3. The supply is rather uniform during the year and covers more than fully the requirements in the first and last four months of the year.

In Sirsa District the major crops are wheat, cotton and gram. About 16% of the potential cultivated land is kept fallow, while of the remaining area on a yearly basis about 60% of the area is irrigated.

The FRAME model has been calibrated to increase its accuracy and through a validation the reliability of the model to predict effects has been determined. Model calibration was very successful in 82% of the study area with a correlation coefficient between observed and computed groundwater levels of more than 75%. Insufficient calibration was achieved in 7% of the study area with values for the correlation of less than 50%. Validation results were satisfactory for the complete study area with predictive values of 75% and higher. In 52% of the study area the predictive value was even above 90%

Model calculations reveal that on the average, the supply with canal water and rainfall exceeded the crop demands with about 15% during the first four months of the year and with about 90% in December. In the months May and June the supply covered the demands for about 70%, while the demands were almost fully met during July till mid August. Thereafter until December, the supply was 50-60% of the total requirements. During the period 1977-1991 the average shortage amounted 210 mm in periods with insufficient supply, with a minimum of 75 and a maximum of 330 mm. In periods with sufficient supply, the average excess was 50 mm with a minimum of 25 and a maximum of 125 mm.

Canal seepage shows a moderate fluctuation during the period 1977-1991, while the percolation losses from the cultivated land fluctuate from 70 mm to as much as 160 mm annually. Defining the overall project efficiency as the ratio of crop evapotranspiration over the total water supply (including rainfall and groundwater use), the system can be classified as highly efficient with values varying between 68 and 79% for the different years. The on-farm water losses accounted for about 60% of the total aquifer recharge and 25% of the water supply. Seepage losses from canal seepage account for about 10% of the total supply while the Ghaggar river seepage losses account for only a few percent of the total supply. The spatial distribution, however, shows a large variability.

Four components of the aquifer recharge were identified, of which two (canal seepage losses and the on-farm water management losses) can be controlled by the regional water manager. The canal seepage losses were estimated at 10% of the canal water supply. Further reduction of these losses of this highly efficient system will be very difficult to achieve. At this moment, two major alternatives for the regional water management emerge:

- replacing the actual system of water pricing with a system based on received quantity;
- distribution of canal water according to spatial distributed demand.

Reducing the aquifer recharge by increasing the use of groundwater is a solution to be implemented at the farm level and should be pursued through extension to the farmers and application of water pricing mechanisms. This aspect is outside the scope of this report.

The water pricing option aims at abandon the actual water pricing system based on irrigated area. The proposed water pricing system is based on received quantities, which under the actual Warabandi system can be achieved by charging proportional to the potentially cultivable area. With this option the potential irrigated area increases from 50 % to 85%, while neither the total supplied canal water nor the distribution was changed. By adopting this strategy water-logging problems cannot be avoided, but the problem can be postponed by 5 to 10 years. At the same time total crop production in the area appeared to increase as well. With this strategy, declining water-tables in the central part of the area were not arrested.

With the water distribution option the same total annual canal water supply has been distributed proportional to the time and spatial distributed water requirements. In the reference situation with unchanged water management, in about 10% of the Sirsa District area water-logging problems will occur within 5 years. In an additional 35% of the area water-logging is expected within 5 to 15 years and in 5% of the area water-logging problems will occur within a time period of 15 to 45 years. With the water distribution option these percentages are considerably reduced. In about 5% of the area water-logging is expected within 5 years, in about 15% of the area within 5 to 15 years and in about 25% water-logging problems will occur within a time period of 15 to 45 years. An additional benefit from this alternative is that in the central part of Sirsa District with declining water-tables, a status quo or a reversed situation was created.

Compared to the present canal water management system in Sirsa District, both alternative strategies have the advantage that rising water-tables were delayed in the saline groundwater areas in the north and south of Sirsa district. Water distribution according to demand was slightly more effective in these areas. The strategy of changing water pricing has the obvious advantage that no investments are required and operation of the canal system can be maintained at the present mode. For the strategy with distribution according to demand a number of practical constraints have to be solved: water scheduling and control requires more labour and additional investments to adapt water control structures and most probably will require additional water storage facilities in the upstream canal and river reaches.

1 Introduction

1.1 Irrigated area

In India nearly 183 million ha are potentially cultivable. About 170 million ha are under cultivation, of which 43 million ha are irrigated. Irrigation in India has been practised for thousands of years. After the year 1836 a number of large scale irrigation projects were designed and constructed with a total area served of about 640,000 ha. Irrigation in India has undergone continuous development, from about one million ha in 1850, 11.7 million ha in 1900 until the actual situation of 42 million ha. The Indian Government is planning to attain gradually its ultimate irrigation potential of about 110 million ha.

The significant increase in irrigated area has India successfully transformed from a food deficient state to one which is self-sufficient in the production of grains. The total grain production, about 50 million tonnes in 1950, increased to 109 million tonnes in 1970 and to 172 tonnes in 1989.

1.2 Salinity and water-logging

With the introduction of canal irrigation the recharge of the aquifers was increased, causing in relatively low elevated areas water-logging and secondary salinization. Although India has a record of salinity research which goes back more than 100 years, major detailed scientific investigations were initiated only a few decades ago.

According to the Central Soil Salinity Research Institute in Karnal an area of about 7 million ha of (irrigated) land in India suffer from water-logging and secondary salinization. These areas are found in Uttar Pradesh (1,300,000 ha); Gujarat (1,210,000 ha); West Bengal (850,000 ha); Rajastan (730,000 ha); Punjab (700,000 ha); Haryana (530,000 ha); Maharastra (530,000 ha); Orissa (400,00 ha); Karnataka (400,00 ha); Madhya Pradesh (220,000 ha); Andra Pradesh (40,000 ha) and other states (40,000 ha). Groundwater observations in different states show a rate of groundwater rise varying from 0.3 till more than 1 m (certain areas in Punjab and Haryana) per year. With groundwater-tables varying from only a few meter below soil surface till about 20-30 m (Ghassemi et al., 1995).

The major water management problems of Haryana State are (Agrawal and Khanna, 1983):
- scarcity of good irrigation water;
- poor quality of groundwater in two thirds of the State;
- erratic, ill distributed and undependable rainfall;
- semi-arid to arid climate in most of the state;
- inadequate natural drainage and absence of drainage outlets;
- rise of water-tables in the canal irrigated areas.

It is expected that when no appropriate remedial measures are taken, the existing salt affected area in Haryana will expand to an additional 2 million ha during the next 30 years. At this moment a program for lining of irrigation canals is under execution. But despite of these efforts, still too high recharge rates of the groundwater system and associated groundwater table rise is observed. It is believed that the irregular canal water supply causes part of this problem (Singh, 1995)

In Punjab it is expected that the salt and water-logging affected area will increase from an area of about 180,000 ha in 1988 to about 600,000 ha in the year 2000.

In Rajastan the groundwater tables rise in canal irrigated areas with a rate of 0.3 m (Gang Canal) and 1.5 m (Bhakra canal). The associated human induced salinization became manifest at an area of about 613,5000 ha. An another 320.000 ha of irrigated land, is irrigated from shallow wells yielding water with a moderate to low quality. In spite of cultivating these lands every alternate year, this practice has rendered such lands saline and unproductive.

In regions where groundwater irrigation dominates, falling water-tables are observed due to an over-exploitation of these reservoirs. Induced problems by falling water-tables are increasing costs and consequently increasing use of energy resources. Besides that the access of the population to these reservoirs for the abstraction of drinking water reduces, threatening locally the drinking water supply.

1.3 Future water management

The actual canal water management in India is state based with inter state agreements concerning the delivery of water. The exploitation of groundwater reservoirs is only state oriented.

The above referenced problems are all well documented and among scientists and water managers awareness concerning the impact of the problems exists. Given the legal basis for water management, the tendency exists to solve problems on a state level. However, for solving the problems or achieving a certain status quo, comprehensive changes are needed in the system and management of (irrigation) water and the exploitation of groundwater reservoirs. Many of those, will require the tuning of solutions in different states.

This implies that also the objectives of water management and the associated priority rating of different users categories (agriculture, population, industry) most probably needs a revision in the near future. The majority of the solutions will have a technical and managerial basis, but will in certain circumstances require revision of legislation and legal institutions.

1.4 Constraints

Prior to the implementation of solutions for the referenced problems, in depth strategic studies of different alternative solutions will be needed to achieve optimum solutions. At this moment the planning sectors of the ministries of Irrigation in different states are not equipped, nor have the expertise for performing such studies. This situation is not likely to change in the near future. The universities, however, potentially have the required knowledge for these types of studies, but are missing the experience and required interdisciplinary organisation.

1.5 Aim of this study

The solution of future salinization and water-logging hazards is not simple. Different solutions for the problem are available but each solution has its own time horizon. A definite solution of the problems is to achieve a closed water and salt balance through the installation of drainage systems and associated safe disposal of excess of salts and water. However, disposal of drainage water is a problem because of the absence of suitable drainage outlets. Disposal to rivers will deteriorate the water quality for downstream users. Reuse of drainage water without drainage will promote soil salinization, while the construction of evaporation ponds can affect the groundwater quality or create unforeseen environmental problems. Disposal to the sea is the most convenient solution, but is constrained in Haryana and its surrounding states by the long distances and the large difference in surface elevations. Hence huge investments will be necessary in the future.

An intermediate solution which can delay the implementation of final solutions, is the reduction of aquifer recharge. Such reductions can be realised at a farm level as well as at a regional level. This report deals with regional solutions and because of its intermediate character, especially managerial solutions have been sought which can be implemented without extreme additional investments or operational costs.

For testing the feasibility of solutions, the effects have been predicted through simulation models in a pilot area.

The Sirsa District in Haryana (430,000 ha) has been selected for this purpose. In certain parts of this area the groundwater tables decline due to over-exploitation, while in other parts the groundwater tables show a moderate to rapid rise. All problems the water managers face in Haryana and other neighbouring states, are found in this pilot area.

The SIWARE program package has been selected for the simulations. This package was developed for the simulation of water management in irrigated areas in arid regions with shallow water-tables (Anonymous, 1995). In India, however, relatively deep groundwater tables prevail. Therefor a regional groundwater model, SGMP, has been integrated in SIWARE.

Model adaptions, necessary for the integration of SIWARE and SGMP have been done by Ir. T.N.M. Visser, Ir. D. Boels and completed by Ir. A.A.M.F.R. Smit in the period 1993-1995. Data required for the models have been collected and elaborated by Dr. R. Kumar and Eng. J. Singh in 1993. Dr. R. Kumar, Dr. J. Boonstra and Eng. J. Singh analysed the input data for the groundwater model, SGMP, and were responsible for the calibration of that part of the integrated model of which the results have been reported in Boonstra et al. (1996). Model calibration and validation was done in Wageneningen by Eng. R.K. Jhorar and Ir. A.A.M.F.R. Smit in 1995-1996 in cooperation with Dr. J. Boonstra. The different alternatives for watermanagement have been drafted in cooperation with the Chief Technical Advisor of the project, Ir. C.W.J. Roest. These alternatives have been discussed with water managers in Haryana during a workshop in March, 1995. Ir. D.Boels was responsible for the analysis of the water management and evaluation of water management alternatives.

The program package is outlined in Chapter 2. Chapter 3 deals with the soils, actual groundwater situation and the water management system. The required schematization of the study area, the irrigation canal system and model inputs has been presented in Chapter 4. The model calibration and validation results and an analysis of the actual water management in Sirsa District is discussed in Chapter 5. Calibration includes the adjustment of a limited number of (spatial distributed) model parameters in order to match the model results with observations. Validation includes the determination of the reliability and accuracy of the model for the prediction of effects of water management alternatives. Finally the effectiveness of two alternative water management scenarios is shown in Chapter 6. One alternative deals with changing of the actual system of water pricing, based on the irrigated area to a system based on potential cultivable area. The second one deals with water distribution proportional to the spatial distributed water requirement in stead of irrigated area.

2 Description of the simulation model package FRAME

FRAME is the working title of an integrated model for the simulation of time dependent, spatial distributed water and salt balances in irrigated regions with humid or semi-humid climatical conditions. FRAME includes the REUSE submodel from the SIWARE model package (De Visser and Visser, 1993; Sijtsma et al., 1995) and the dynamic groundwater model SGMP (Boonstra en De Ridder, 1990). To apply FRAME, a number of closely related programs are required for preprocessing of data, calculation of water distribution, canal leakage and seepage and spatial distributed crop water requirements. Figure 1 shows the different programs and the in- and output.

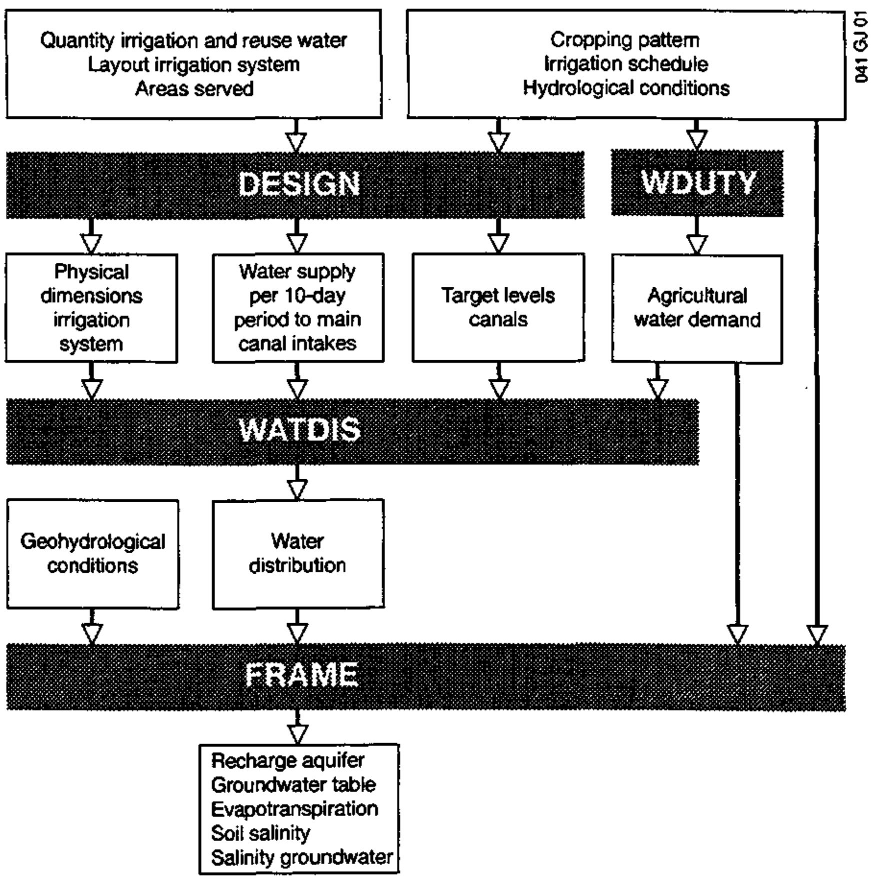

Fig. 1 Schematization of the FRAME simulation model, its sub-models, and the required in- and output.

Sub model DESIGN (Rijtema et al., 1994; Smit et al., 1989) deals with the allocation (distribution) of available water among the intakes of main canals which is based on the principle of proportionality between supply and irrigated area. Canal water is required to meet domestic, industrial and agricultural demands and to maintain water depths for navigation if the canal is navigable. The total demands of water per main canal intake per ten-day period, is reduced with the anticipated quantities of abstracted groundwater, the average rainfall, and when such is relevant, the anticipated quantities of drainage water returned to the canal through reuse pumps. Because farmers supply certain quantities of water to the crops they think necessary, while the water manager supplies quantities according to certain distribution rules, locally a difference between demand and supply will occur. Under such conditions, farmers will try to meet their requirements, leading to higher or lower abstractions from irrigation canals. This phenomenon will affect the actual distribution and is built in the program package. The agricultural demand for water is determined from the area of different crops and average crop water requirements per ten-day period. Only major crops are included. The area of the minor crops is added to the most resembling major crop. Once the supply rates to the main canal intakes are determined, the flow rates in the (hierarchical) canal system are calculated, assuming a water distribution proportional to the demands (irrigated areas). Also the water depths upstream and downstream of control structures and the required settings of the control structures (gates or weirs) are calculated as an option.

The water requirement of each crop in each calculation unit for each irrigation interval is calculated with the program WDUTY. The potential crop evapotranspiration is calculated from local meteorological stations and tabulated for different crop heights and soil cover. The actual evapotranspiration is bound to the potential evapotranspiration and is reduced when moisture stress, depending on crop physiology, is experienced between two successive irrigations. In the WDUTY model effects of soil salinity on crop evapotranspiration is ignored in order to calculate the maximum possible evapotranspiration. For the calculation of the actual evapotranspiration the model assumes abundant water supply. The total quantity, however, depends on the moisture deficit, on-farm conveyance losses and drainage or percolation losses during and after irrigation. Furthermore, percolation and upward seepage is accounted for. The total quantity of water passing the soil surface is limited by the maximum infiltration opportunity time of the different crops, expressing their susceptibility for prolonged oxygen deficiency. The average actual evapotranspiration equals or is less than the potential evapotranspiration. The actual evapotranspiration calculated through the WDUTY model is referred to as the maximum or the optimum evapotranspiration.

The actual water distribution among the sub areas is calculated with the WATDIS program (Smit et al., 1989; Rijtema et al., 1994). This distribution will deviate from the planned distribution through program DESIGN because farmers tend to over-irrigate their crops to a certain extent in order to cope with rough land levelling. Moreover the local crop water requirements deviate from the average demands in the study area because of different soil types, different climatic conditions (irregular and erratic rain fall) and different aquifer recharge conditions. The water distribution is calculated by means of a simplified approach of dynamic flow through canals, the simulation of the management of the control structures conform the planned water distribution, water abstraction for irrigation according to water requirements at this location, return flow of drainage water through reuse pumps, recharge of the irrigation system with groundwater and water withdrawal for municipal and industrial use.

For the simulation of aquifer recharge, actual evapotranspiration and when relevant also drainage from the calculation units by program REUSE (Boels et al., 1989), the calculated irrigation water abstraction by farmers in each calculation unit is proportionally distributed among the field crops. Use of groundwater for irrigation is a farmer's decision and built in the program as a decision procedure. The maximum rate of use, however, is bound to the installed pump capacity, the characteristics of the tubewell and the actual groundwater depth. Nevertheless when water shortage remains, water is distributed according to the drought sensitivity of crops ('farmers preference'). It is virtually impossible to include all field plots of all the crops in the model calculations. One representative plot for each different major crop in each calculation unit is considered in the model instead. A special algorithm is included in the model to determine the agricultural drain discharge and salinity, crop evapotranspiration, aquifer recharge or discharge, and soil salinity evolution for the whole calculation unit on the basis of corresponding calculated outputs of each representative plot. Furthermore the model calculates the salinity water in irrigation canals resulting from mixing with drainage water and groundwater at the delivery side of the pumps and upward seepage of saline groundwater in seepage effected areas.

The application efficiency is determined by the FAIDS model (Roest et al., 1993; Boels 1986 a and b; Abdel Gawad, 1987) through the simulation of the field irrigation. This model is built into both of the REUSE (Boels et al., 1989) and the WDUTY models. The calculations include the determination of on-farm conveyance losses, the movement of a water front across a representative field plot during irrigation, the simultaneous infiltration and loss of water at locations in the plot where the total infiltration exceeds the water holding capacity of the soil or losses due to surface run-off. The total infiltration is restricted by either the supplied quantity of irrigation water or by the maximum infiltration opportunity time, which is determined by the sensitivity of crops to prolonged oxygen deficiency in the root zone. The model determines the leaching of salts from the soil during the irrigation and subsequent drainage or percolation. On shrinking and swelling soils the losses of water during irrigation through the cracks to the drainage system is considered ('rapid drainage'). As the swelling proceeds the rate of the losses diminish and become insignificant when swelling is complete.

Water losses to the atmosphere through evaporation from the soil surface and transpiration of crops, to the drainage system, and recharge (leakage) or discharge (seepage) of the groundwater system are calculated for each representative field plot during each period between two successive irrigations. The leaching rate of salts from the soil and the redistribution of salts in the soil profile, including the effect of upward capillary flow to the root zone, are also calculated during this period.

The quantity and salinity of drainage water from all representative field plots are combined and transformed through a special algorithm in the REUSE model, considering resident time, to the drainage of the whole calculation unit. This quantity and its salinity is combined with spill losses from distributaries, disposal of sewage water and losses over the tail ends of irrigation canals and added to the regional drains. The regional drains are considered as part of a hierarchical canal system where flow rates are not subject to dynamic changes. The flow rate changes when reuse pumps withdraw water from the drain, when drainage water from calculation units is disposed or when canal seepage occurs. Both the salinity and flow rate in the regional drains increases in seepage affected regions. At the locations of reuse pump stations the actual quantity of abstracted drainage water per ten-day period from drainage canals is calculated. The program gives a warning when the anticipated quantity or salinity cannot be realized and provides the calculated quantity and salinity.

When no open drainage system is present in a certain area, it is assumed that still surface drainage is diverted to the lower parts of the area where this quantity infiltrates into the soil and contributes to the recharge of the aquifer system.

The dynamic groundwater module SGMP (Boonstra en De Ridder, 1990) interacts with the surface system. Through the surface system (REUSE) the aquifer recharge from canals and cultivated land is determined. Based on these rates, the resulting groundwater depth distribution is determined by the groundwater model. The conditions at the border of the study area are prescribed time dependent piezometric heads. Implicitly it has been assumed that through the base of the aquifer system no recharge or discharge takes place.

3 Description of Sirsa District

The state of Haryana is situated in the North-West of India. It lies between the Tar desert in the south and Himalayas in the north at latitudes 27°039' to 30°5'5"N and longitudes 74°27'8" to 77°36'5"E. Its total geographical area is 44222 km^2. The state of Haryana has a sub-tropical, seme-arid, continental monsoon climate. Maximum temperatures in May and June can be up to 48 °C and minimum temperature in January down to 3 °C. The average annual rainfall is approximately less than 300 mm in the south-west and more than 1000 mm in the north-east. The rainfall, however, is highly irregular and over 70% of annual rainfall is received in months of July to September (Agrawal et al., 1995)

Sirsa District is located in the extreme west corner of the state Haryana and downstream end of the Ghaggar river basin. The ephemeral river flowing from eastern to western direction drains through the central part and is the main source of surface water. The discharge in the river was regularly monitored at the Ottu weir during monsoon season. The project area comprising of nearly 4200 km^2 is surrounded by the states of Punjab in the north and Rajastan in the west and south.

Sirsa District belongs to the North-eastern agro-climatic zone presenting an arid climate (aridity index > 0.66) with annual rainfall from less than 300 mm to 550 mm, rainy days less than 25, coefficient of variance more than 45% and annual potential evapotranspiration of 1500 to 1650 mm (Oswal, 1995).

3.1 Soil and topography

The topographic map has been drawn from the available reduced levels of the observations wells, exploration bore holes and bench marks. The area represents gently sloping terrain with some isolated steep contours in the vicinity of the Ghaggar river (Boonstra et al., 1996). The different geomorphic units found in Sirsa District are the recent alluvial plains in a narrow belt along the Ghaggar river, old alluvial plains, aeolian plains with sand and sand dunes (Fig. 2). The soil texture of the area varies from loamy sand to sandy loam (Fig. 3). The alluvium is generally calcareous. Invariably, all the soils have low organic carbon content and light soil colour. The average water holding capacity of different soil types are presented in Table 1

Table 1 Water holding capacity ($cm.m^{-1}$) of different soil types in Haryana (after Agrawal et al., 1995)

Sand to sandy loam	4.8- 6.6
Loam to fine loam	10.2- 11.3
Loamy sand to loam	11.3- 12.3
Sandy loam to coarse loam	13.0- 14.1

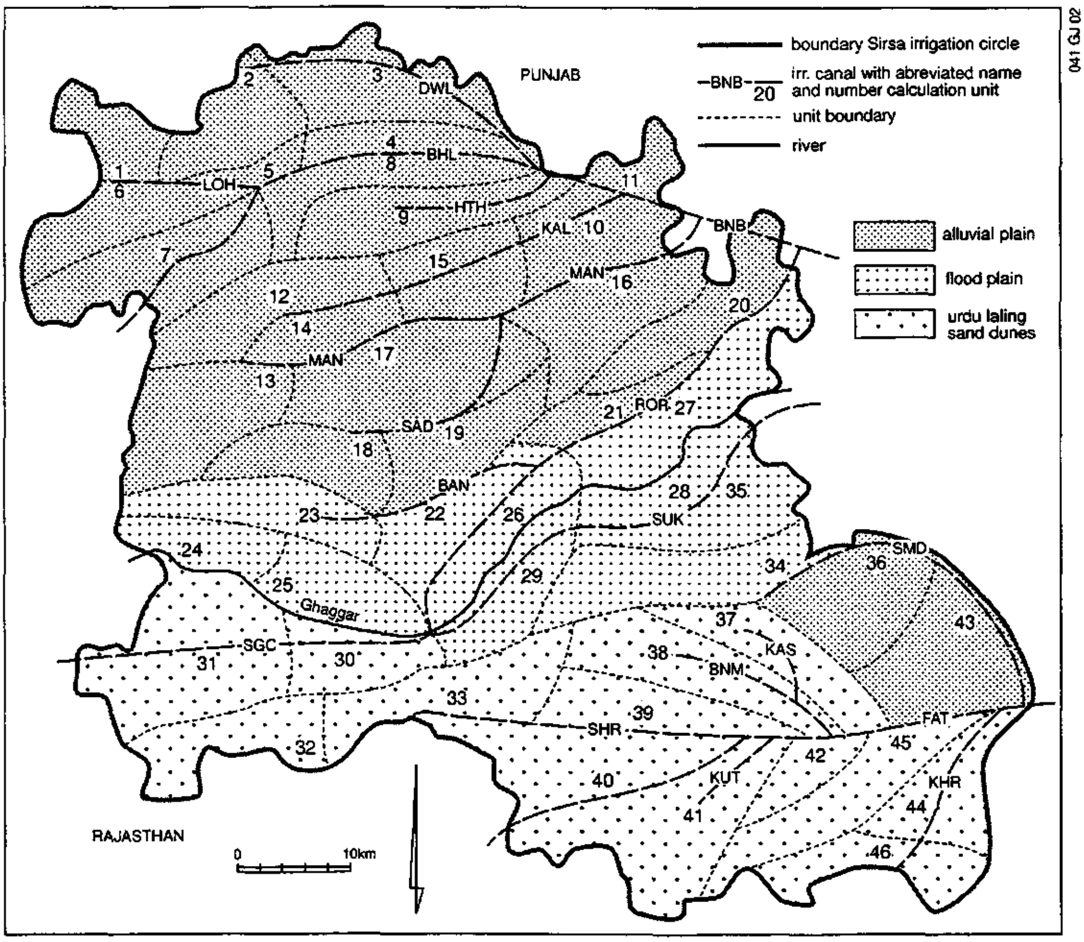

Fig. 2 Map of geomorphic units in Sirsa District

The soils of a light texture have usually high infiltration rates, but can also have a low infiltration rate. Infiltration rates for all the soils in Haryana vary form 0.8-7.2 $cm.h^{-1}$ between 30 and 90 minutes after infiltration started. The basic rates vary from 0.4-7.2 $cm.h^{-1}$. No detailed data for soils in Sirsa District are available. Through calibration of the model, the most probable physical characteristics have to be determined.

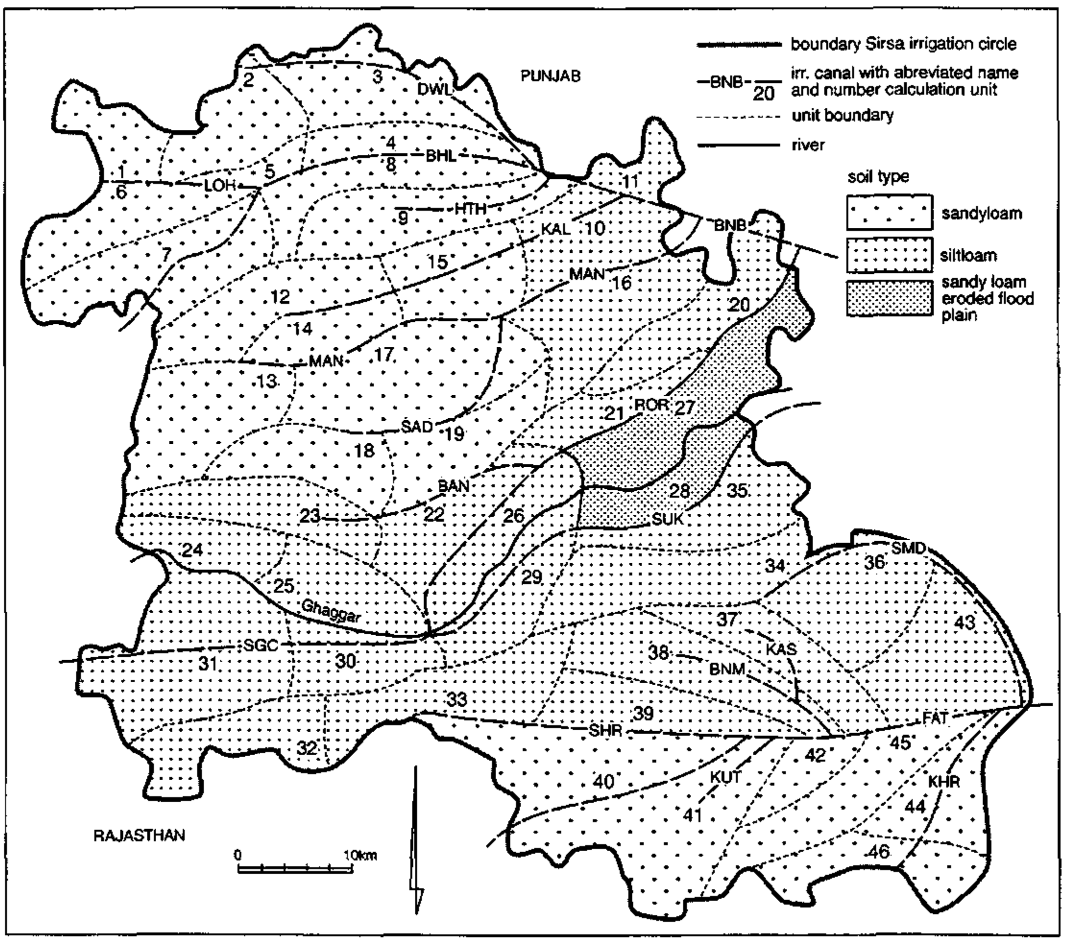

Fig. 3 Soil map of Sirsa District

3.2 Groundwater condition

The groundwater quality on both sides of the Ghaggar river was generally good resulting in the installation of numerous tubewells in the belt during the past several years. However, groundwater quality in the western side (Dabwali block) was quite poor (7-10 $dS.m^{-1}$) restricting the installation of tubewells. However, during the last five years, along the canals relatively good quality water has developed over the saline groundwater prompting the farmers to go in for shallow tubewells. The movement of groundwater on one side of the Ghaggar river was towards the north-west and a groundwater depression existed in the vicinity of Sikandarpur and flow is towards the south-east. The water-table depths during 1992 ranged from 1.5 m to 25 m. The area with the shallowest groundwater lies in Phaggu-Rori area and the deepest in Sikanderpur. On both sides of the Ghaggar river, the water-table has been falling from year to year due to the large number of tubewells. The serious water-logging and salinization problems had developed in Phaggu, Desu and Rohan villages of Rori area leading to the loss of large tracts of agricultural land (Fig. 16).

3.3 Irrigation system

The area was served by an extensive network of canal system originating from Bhakra Main Branch (BMB) which in turn originated from Gobind Storage Reservoir located at about 400 km in the state of Himachal Pradesh. The area was fed by three main canals namely Bhakra Main Line (BML) serving an area of 3440 km^2, Sukhchain Distributary, serving 295 km^2 and Fatebad Branch (FB), serving an area of 1820 km^2 which entered at reduced distance (RD) 100 BMB, head of the Sukhchain distributary and Bighar fall-RD 219954 FB and left at the tails of Jandwalaa distributary, Southern Ghaggar Canal (SGC), and Baruwali distributary respectively to irrigate the areas in Rajastan (about 700 km^2).

During monsoon both NGC and SGC were supplied water from Ottu weir, however, during the rest of the year, both these channels were fed by Ottu Feeder which in turn originates from Rori Branch, a offshoot of BML. The details of the irrigation system including distributaries and minors are shown in Fig. 4.

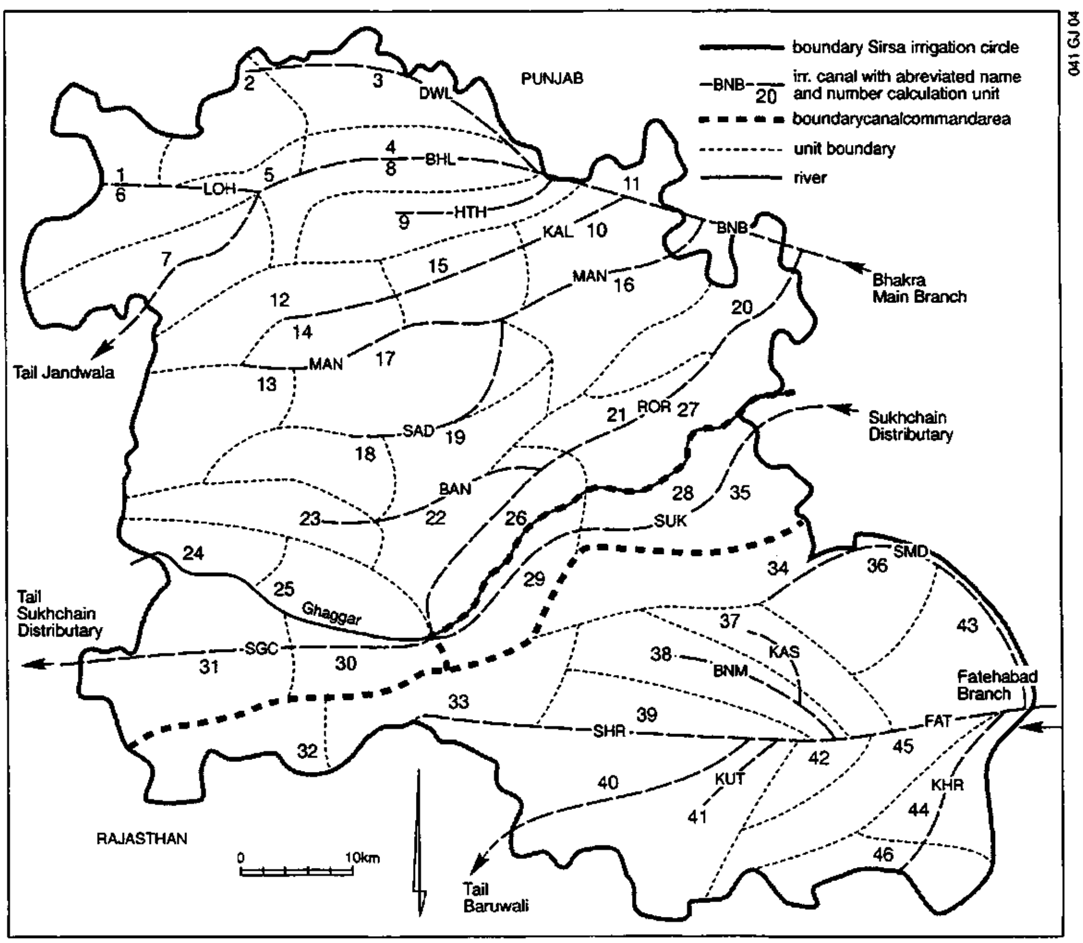

Fig. 4 Canal network of Sirsa District

The Irrigation Department at Sirsa was responsible for distributing the available water in proportional manner among the distributaries and also took care of adequate share of Rajastan State in the downstream end. To achieve this, entire Sirsa Circle was divided into almost three equal parts called A, B, and C. During first eight days of a rotation, water was supplied to area A and B. In case of shortage, supply to area B was reduced by the shortage. In case of excess supply, the excess was given to C. During next eight days of rotation the water was supplied to C and A. In case of shortage, A would get less in case of excess, B get the excess. During the last eight days of rotation, the water would be supplied to B and C and in case of excess A would get it, whereas in case of shortage, C get less. The outlets generally served CGA ranging between 200-400 ha. During 8 day, farmers rotate the discharge according to Warabandi system. In this system, the farmers receive the total water supply for the time in proportion to their area falling in the command outlet. The canal water allowance varied between 0.17-0.19 $m^3.s^{-1}$. At the place of branching of distributaries, the movable gates had been provided to regulate the discharges. In case of shortage of water in the main canal, gates (weir / karri type) were lifted completely and water distribution was proportional. The gates at the outlets supplying water to farmers, fields were generally of orifice type as they were less sensitive to water-level changes at the upstream. The discharges at all the six contact points as mentioned above (three incoming, three outgoing) were monitored twice a day (morning and evening) by measuring the stage through gauges by the Irrigation Department.

4 Model schematisation and input

Although all relevant processes were simulated in the model, implicit simplified assumptions limit the accuracy of model output. Also spatial variability and heterogeneity cannot be considered to the extent of their real occurrence, so averaging and regional schematisation are necessities when applying the integrated regional water and salt management model FRAME to all parts of Sirsa District. The required input data for running the model are described below. They comprise five main groups.

4.1 Spatial schematization of Sirsa District

The FRAME program package requires the subdivision (schematization) of the study area into a number of sub areas (calculation units) according to the model requirements and are to a certain extent uniform with respect to soil hydrological, climatic and water supply conditions. The occurrence of administrative units for the management and operation of the water distribution system and the further subdivision of these units into irrigation districts with a different number of distributary canals, has been reckoned by the model. Since the model calculation follows both the irrigation system hierarchy (and when present, the drainage system hierarchy), these districts have been split up into smaller units (Fig. 5). The size of sub areas typically ranges from 3,400 to 21,000 ha. The groundwater module requires a subdivision into sub areas around its nodal points. The boundaries of these sub areas doe not necessarily have to coincide with the sub divisions of FRAME when mathematical is not expected to affect the results. The boundaries of the nodal areas for the groundwater module are depicted in Figure 7.

4.2 Lay-out and design of irrigation system

This group of data includes the lay-out of the irrigation (and, if present, drainage) canal system, the position of control structures, reuse and drainage pump stations, major water intakes for drinking and industrial water (abstraction rates by minor intakes are combined per calculation unit) and the areas served downstream a number of strategic locations along the irrigation canals (Fig. 5).

The dimensions of canal sections and control structures is based on the area served downstream of the section. Semi-empirical relationships between area served and dimensions have been derived from Table 2.

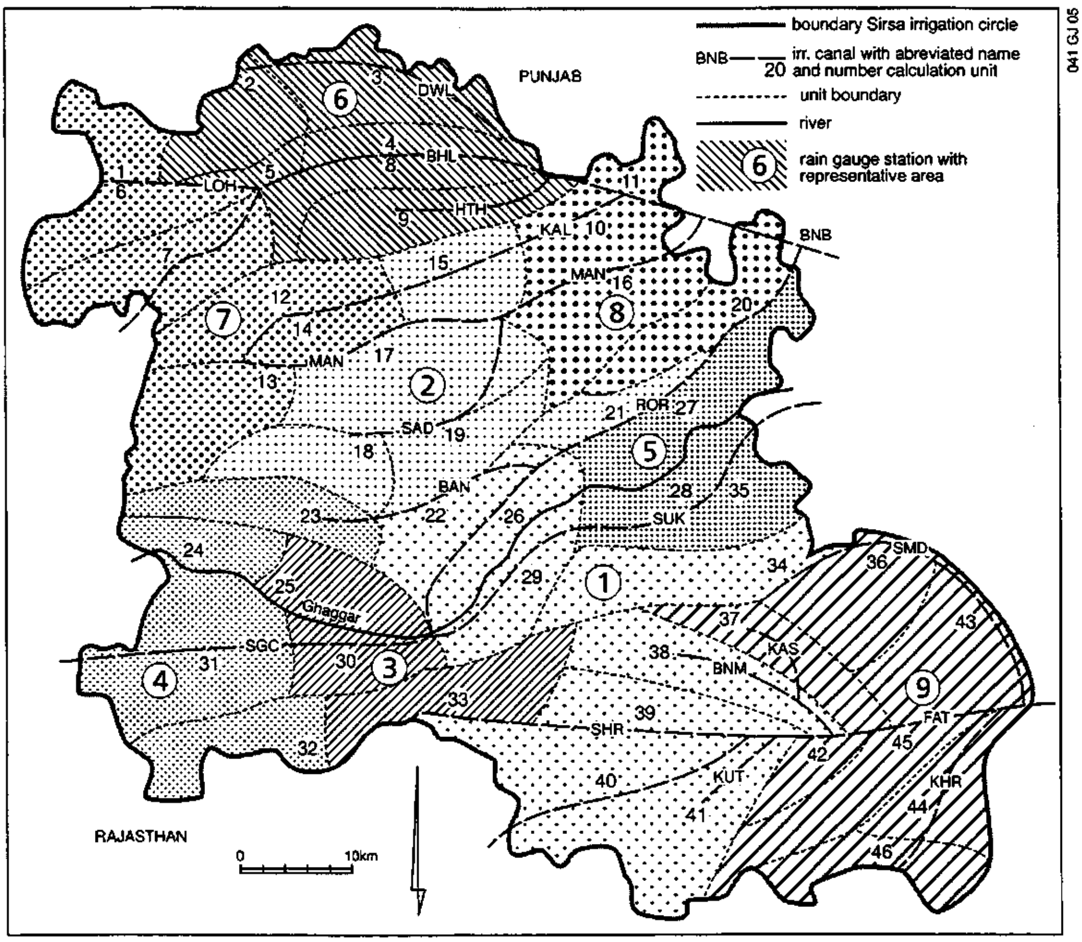

Fig. 5 Subdivision of the Sirsa District into calculation units for FRAME application

Table 2 Design characteristics of irrigation canals in Sirsa

Area (ha)	Maximum discharge ($m^3.s^{-1}$)	Water depth (m)	Bed width (m)	Bed slope ($m.m^{-1}$)
500	0.093	0.273	1.017	0.0025
1 000	0.186	0.351	1.301	0.0025
2 000	0.372	0.452	1.661	0.0023
3 000	0.558	.0524	1.918	0.0022
4 000	0.744	0.582	2.123	0.0022
5 000	0.930	0.631	2.298	0.0021
6 000	1.116	0.675	2.450	0.0021
7 000	1.302	0.714	2.587	0.0020
8 000	1.488	0.750	2.712	0.0020
9 000	1.674	0.783	2.827	0.0020
10 000	1.860	0.813	2.935	0.0020
12 000	2.232	0.869	3.131	0.0019
15 000	2.790	0.943	3.387	0.0019
18 000	3.348	1.008	3.613	0.0019
20 000	3.720	1.047	3.750	0.0018
50 000	9.300	1.463	5.185	0.0017
100 000	18.600	1.885	6.623	0.0016
150 000	27.900	2.185	7.644	0.0015

The design formulae derived for the maximum and minimum discharge, maximum water depth, bed width of the canals and bed slope are:

$$Q_{max} = 0.000210 + 0.000186A_s \quad ; H_{max} = 0.0282A_S^{0.365}$$

$$Q_{min} = 0.000147 + 0.000131A_s \quad ; W_b = 0.1412A_s^{0.365} - H_{max}$$

$$S = 0.0047\ A_s^{-0.0942}$$

where:

Q_{max} = maximum discharge rate, $m^3.s^{-1}$
Q_{min} = minimum discharge rate, $m^3.s^{-1}$
A_s = area served, ha
H_{max} = maximum water depth at maximum discharge, m
W_b = bed width canal, m
S = bed slope $m.m^{-1}$

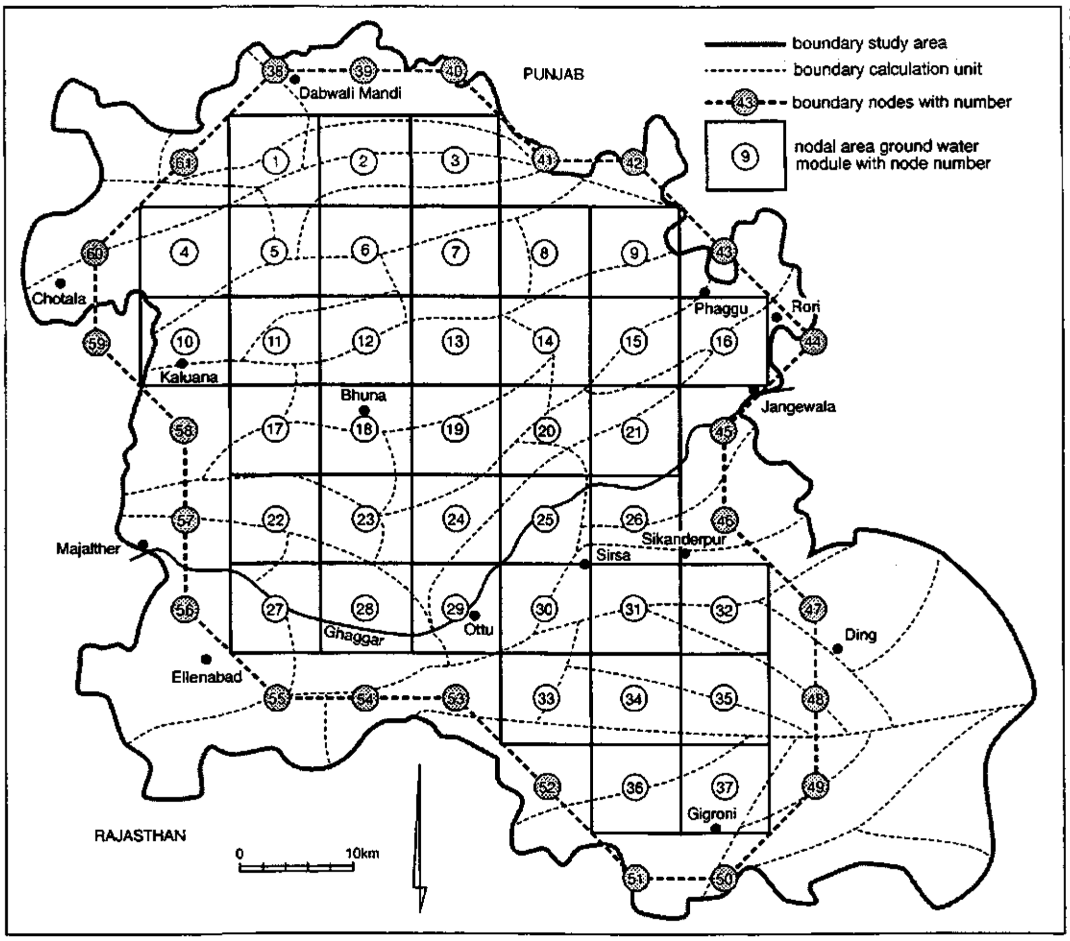

Fig. 6 Subdivision Sirsa District into nodal areas for the groundwater module SGMP

4.3 Soils and climate

This group of input data includes a soil map and a description of the physical characteristics of the different soil types, when relevant a map with thickness of the clay cap overlaying the aquifer system, together with a description of its physical characteristics. Information on soils in Sirsa District is limited as compared to the information requirement of the model at this scale. Especially the physical characteristics show a certain variability. During the calibration of the model, the soil characteristics have to be determined. The soil map is shown in Figure 3.

Information on rainfall and data for the determination of the potential crop evapotranspiration (net radiation, wind velocity, relative humidity, temperature, hours of sunshine) are required. From these data the potential evapotranspiration is calculated for different crop heights. Reduction factors for incomplete soil cover are provided (Table 3).

Table 3 Potential evapotranspiration ($mm.d^{-1}$) for different crop heights in Sirsa District

Month	Crop height (m)										E_w $mm.d^{-1}$	Rain $mm.d^{-1}$
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9		
JAN 1	2.51	3.38	3.91	4.17	4.38	4.57	4.72	4.88	4.99	5.06	2.21	0.50
JAN 2	2.51	3.38	3.91	4.17	4.38	4.57	4.72	4.88	4.99	5.06	2.35	0.50
JAN 3	2.51	3.38	3.91	4.17	4.38	4.57	4.72	4.88	4.99	5.06	2.69	0.50
FEB 1	3.37	4.37	4.99	5.30	5.55	5.77	5.96	6.14	6.27	6.36	2.97	0.28
FEB 2	3.37	4.37	4.99	5.30	5.55	5.77	5.96	6.14	6.27	6.36	3.14	0.28
FEB 3	3.37	4.37	4.99	5.30	5.55	5.77	5.96	6.14	6.27	6.36	3.61	0.28
MAR 1	4.56	6.08	6.97	7.42	7.78	8.09	8.36	8.63	8.81	8.94	3.98	0.18
MAR 2	4.56	6.08	6.97	7.42	7.78	8.09	8.36	8.63	8.81	8.94	4.25	0.18
MAR 3	4.56	6.08	6.97	7.42	7.78	8.09	8.36	8.63	8.81	8.94	4.82	0.18
APR 1	6.33	9.43	11.06	11.88	12.53	13.10	13.59	14.08	14.40	14.65	5.40	0.00
APR 2	6.33	9.43	11.06	11.88	12.53	13.10	13.59	14.08	14.40	14.65	6.13	0.00
APR 3	6.33	9.43	11.06	11.88	12.53	13.10	13.59	14.08	14.40	14.65	6.21	0.00
MAY 1	7.39	12.67	15.32	16.64	17.70	18.63	19.43	20.22	20.75	21.15	8.63	0.00
MAY 2	7.39	12.67	15.32	16.64	17.70	18.63	19.43	20.22	20.75	21.15	10.09	0.00
MAY 3	7.39	12.67	15.32	16.64	17.70	18.63	19.43	20.22	20.75	21.15	10.46	0.00
JUN 1	6.86	11.79	14.25	15.48	16.46	17.32	18.06	18.80	19.29	19.66	10.96	0.00
JUN 2	6.86	11.79	14.25	15.48	16.46	17.32	18.06	18.80	19.29	19.66	9.59	0.00
JUN 3	6.86	11.79	14.25	15.48	16.46	17.32	18.06	18.80	19.29	19.66	9.23	0.00
JUL 1	5.56	7.81	9.06	9.68	10.17	10.61	10.98	11.35	11.60	11.79	8.99	0.00
JUL 2	5.56	7.81	9.06	9.68	10.17	10.61	10.98	11.35	11.60	11.79	7.91	0.00
JUL 3	5.56	7.81	9.06	9.68	10.17	10.61	10.98	11.35	11.60	11.79	6.68	0.00
AUG 1	5.26	6.59	7.42	7.83	8.16	8.45	8.70	8.95	9.12	9.24	5.50	0.00
AUG 2	5.26	6.59	7.42	7.83	8.16	8.45	8.70	8.95	9.12	9.24	6.48	0.00
AUG 3	5.26	6.59	7.42	7.83	8.16	8.45	8.70	8.95	9.12	9.24	5.98	0.00
SEP 1	5.15	6.42	7.23	7.64	7.96	8.25	8.49	8.73	8.90	9.02	5.48	0.00
SEP 2	5.15	6.42	7.23	7.64	7.96	8.25	8.49	8.73	8.90	9.02	5.21	0.00
SEP 3	5.15	6.42	7.23	7.64	7.96	8.25	8.49	8.73	8.90	9.02	4.64	0.00
OCT 1	4.62	5.95	6.77	7.18	7.51	7.80	8.05	8.29	8.46	8.58	4.16	0.14
OCT 2	4.62	5.95	6.77	7.18	7.51	7.80	8.05	8.29	8.46	8.58	3.70	0.14
OCT 3	4.62	5.95	6.77	7.18	7.51	7.80	8.05	8.29	8.46	8.58	3.21	0.14
NOV 1	3.16	3.89	4.39	4.63	4.83	5.01	5.16	5.31	5.40	5.48	2.72	0.32
NOV 2	3.16	3.89	4.39	4.63	4.83	5.01	5.16	5.31	5.40	5.48	2.04	0.32
NOV 3	3.16	3.89	4.39	4.63	4.83	5.01	5.16	5.31	5.40	5.48	1.96	0.32
DEC 1	2.26	2.95	3.38	3.59	3.76	3.91	4.04	4.17	4.26	4.32	1.52	0.56
DEC 2	2.26	2.95	3.38	3.59	3.76	3.91	4.04	4.17	4.26	4.32	1.37	0.56
DEC 3	2.26	2.95	3.38	3.59	3.76	3.91	4.04	4.17	4.26	4.32	1.31	0.56
	Reduction factors for soil cover											
	0	10	20	30	40	50	60	70	80	90	100%	
Winter	0.28	0.35	0.43	0.50	0.58	0.66	0.78	0.87	0.94	1.00	1.00	
Summer	0.38	0.47	0.54	0.62	0.69	0.78	0.86	0.91	0.96	1.00	1.00	

Rain fall is obtained from nine rain gauge stations at different locations in Sirsa District. The observed rainfall is representative in a certain but not well defined area. Because the rain fall is rather irregular (Fig. 7), the representative areas for rainfall gauge stations will be determined through calibration.

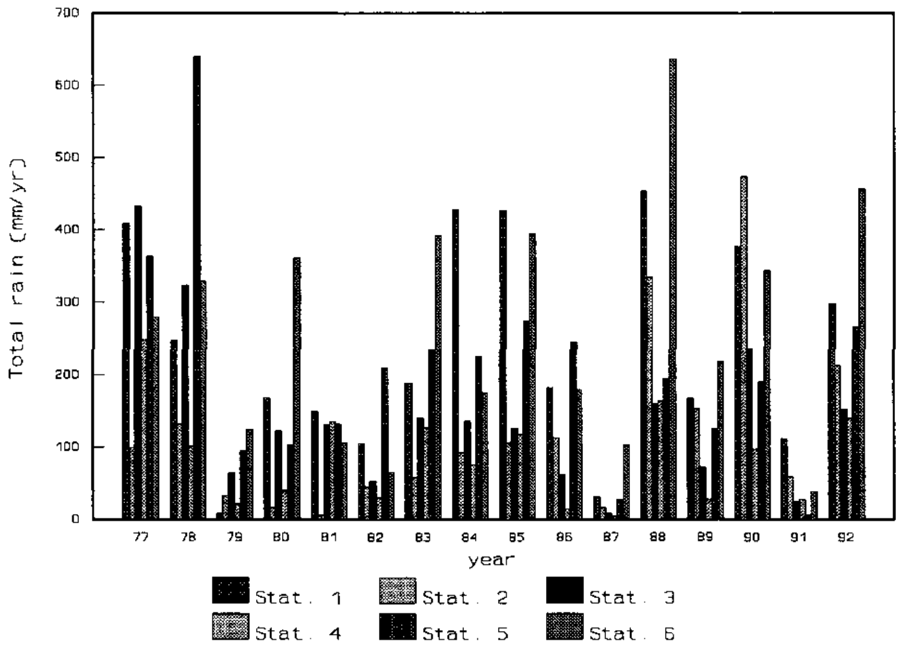

Fig. 7 A Observed annual monsoon rainfall at stations 1-6

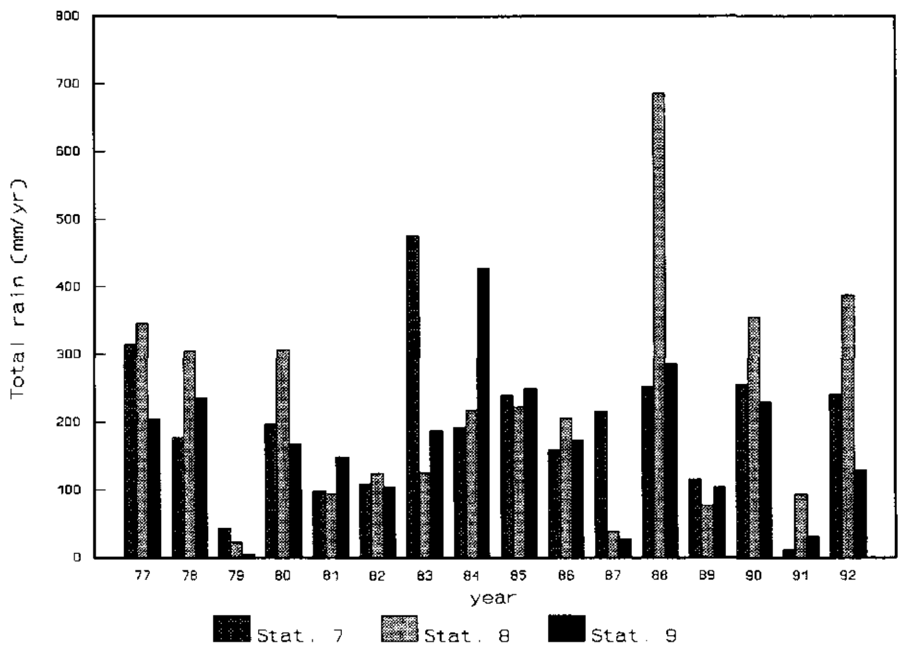

Fig. 7 B Observed annual monsoon rainfall at stations 7-9

4.4 Agriculture

Data of this group comprise crop physiology: crop growth development, sensitivity to oxygen deficiency, moisture deficit and salt stresses, and furthermore data related to farm management: irrigation schedules of different crops, crop rotation and irrigation capacity. The irrigation opportunity time of individual crops is related to the sensitivity to oxygen stress. Crop growth development is expressed in the evolution of crop height, soil cover and rooting depth. The irrigation schedule and the approximated relative are of different crops is shown in Figure 8.

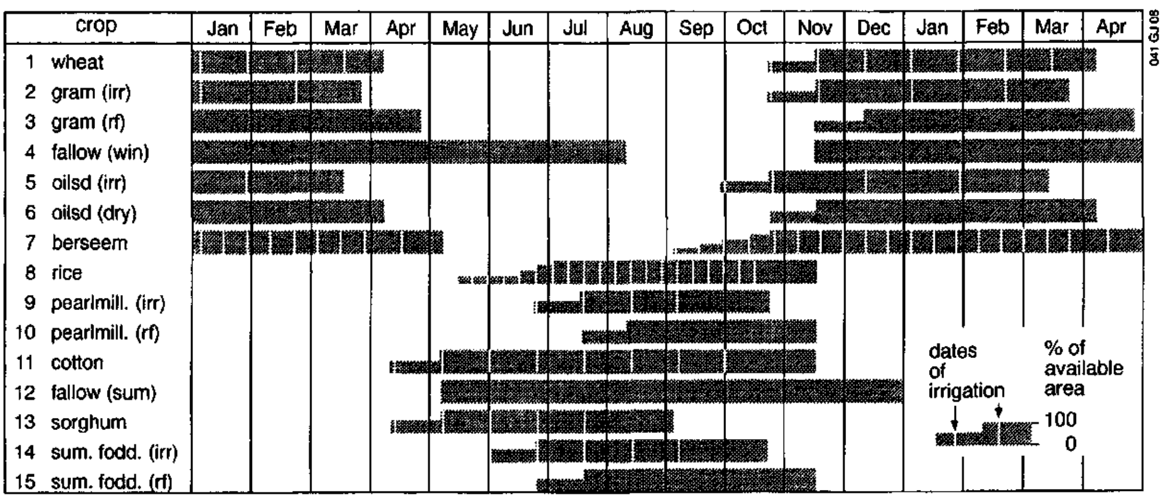

Fig. 8 Evolution of relative occupied area and irrigation schedule of major crops

Table 4 Relative area occupied by crops in Sirsa District

Crop		Area
Number	name	(%)
1	wheat	26.22
2	Gram(irr)	12.50
3	Gram(rf)	30.31
4	Fallow(win)	16.65
5	Oilseed(ir)	4.71
6	Oilseed(rf)	7.64
7	Berseem	1.96
8	Rice	5.67
9	Pearlmill.(irr)	2.80
10	Pearlmill.(rf)	8.11
11	Cotton	35.51
12	Fallow(sum)	16.62
13	Sorghum	0.14
14	Sum. fodd. (irr)	13.30
15	Sum. fodd. (rf)	17.81

irr. = irrigated
rf = rain fed

The area occupied by different crops in Sirsa District were obtained per village and aggregated at the level of calculation units (Kumar and Sing, 1994). For the whole study area the cropping pattern is presented in Table 4. From this table it can be seen that wheat, gram, oil seeds and cotton are the major crops.

4.5 Water management

This group of data relates to the total water demand: average crop water requirements, area grown with different crops in different regions, water requirement for municipal and industrial water use, navigation requirement and conveyance losses. Also included are data regarding the available water resources comprising quantity and salinity of irrigation water, groundwater abstraction for supplemental irrigation and its salinity, and drinking water supply and return flow of sewage water and salinity. When subsurface drainage is present, data on drain depth and spacing are required. Information concerning the water allocation procedures, which in general have a legal and operational background, and the priority ranking of different water users belongs to this group of data.

Data on the water supply to the three intake locations of Sirsa District have been derived from daily monitoring data obtained from the Irrigation department (Kumar and Singh, 1994). The total annual intake, including delivery to Rajastan, is presented in Figure 9. For the study area an annual amount of 1470-2260 million m^3 of water is available, but is in general more than 2000 million m^3. The total cultivable area of the entire District was around 4300 km^2. Groundwater abstraction has been obtained from data on the number and type of tube wells. For each type of well norms are used for annual abstraction: shallow tube wells 0.0145 million m^3, direct irrigation tube wells 0.1500 million m^3, augmentation tube wells 0.715 million m^3, dug wells 0.0045 million m^3 and pumping sets 0.0135 million m^3. The actual abstraction rates will deviate from the norms.

Data in the group of domestic and industrial water use deal with the locations, source (surface or groundwater) and required abstraction rates of water for municipal and industrial water use. Also included is information on the location, rates and salinity of released sewage water to either irrigation canals or the open drains. These data have not been considered in Sirsa District.

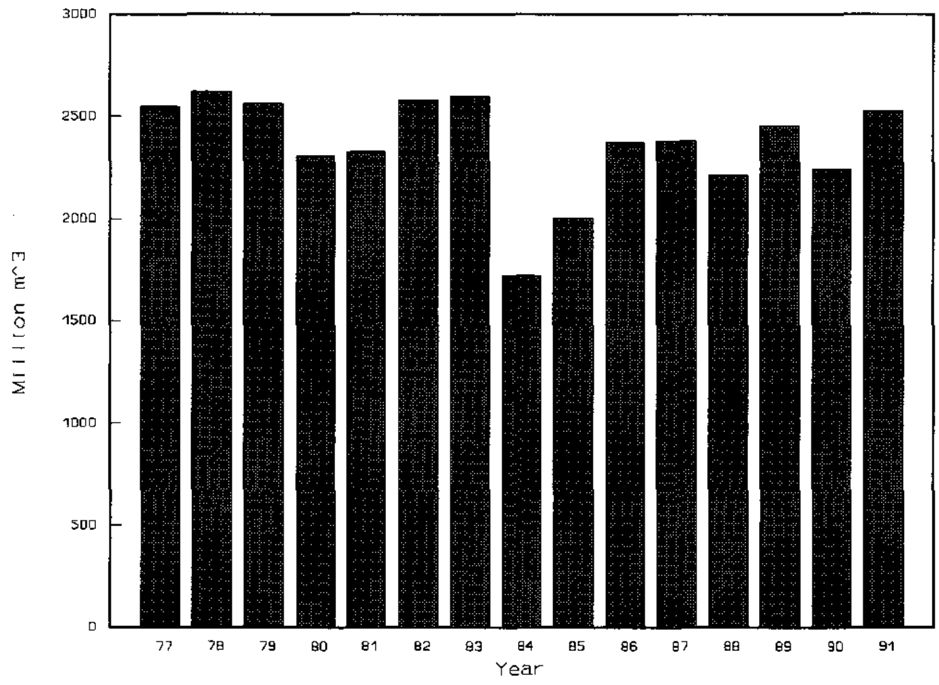

Fig. 9 Total annual intake of irrigation water in Sirsa District

The Ghaggar river in Sirsa District is a non-perennial river flowing from north-east to south-west. The discharges were monitored at the downstream end of the Ottu weir. During rainy season, the discharge from this river was fed to northern and southern Ghaggar canals and Sheranwali distributary through parallel channel while during the rest of the year, these channels were fed from Ottu Feeder. In case of low discharge in the river, it was augmented from the Ottu Feeder which received supply from Bhakra system. The daily river discharges were collected from the Drainage Division of the Irrigation Department. The weir was operated after fully meeting the requirements of the above mentioned channels. Therefor in order to estimate the upstream discharges, the maximum capacity of these channels was added to the measured river discharge at the downstream end. Data for 1982-1990 were missing and have been estimated on the basis of rainfall occurrence. Conveyance losses in the upstream reaches have been derived from emperical relationships.

Canal water supply to Sirsa District was through three canals: Bhakra Main Line in the north serving about 344,000 ha, Sukchain Distributary in the central part serving about 29,500 ha and Fatebad in the south serving 182,000 ha.

The on-farm application efficiency is determined by the irrigation capacity, the representative plot size and the on-farm conveyance losses. The average plot size is estimated at 60 * 25 m, with a range of on-farm conveyance losses of 40-1200 $m^3.d^{-1}$ (~ 1-35 mm per irrigation gift). The irrigation strength is estimated at 0.040 $m^3.s^{-1}$. The on-farm conveyance losses has to be determined in different calculation units through calibration.

5 Model calibration and validation

Calibration of a model includes the determination of the (spatial distributed) value of certain input parameters of which no exact information is available. Therefor the value of different input parameters are varied within a preset range. Model results obtained with the input parameters are compared with observed results and the parameters giving the best match of calculations with observations, are fixed for further model applications. Unfortunately no exact methods are available for calibration of spatial distributed parameters. The adjustments of the value of parameters is a matter of professional guessing based on the logic of the water and salt balance. Unlike the preset model performance criteria set for the model calibration in the Nile Delta of Egypt (Abdel Gawad et al., 1991), no such sets are available for Sirsa District.

In the previous chapter it has been explained that the definite value of certain spatial distributed parameters can be determined only through calibration. The calculated distribution of the groundwater depth evolution is the sole model output which can be compared with observations. The calibration procedure therefore aims at achieving a close match between the calculated and observed groundwater table depth.

Validation of the model includes the determination of the reliability of predictions made through the model for circumstances which differ from those for which the model was calibrated.

5.1 Calibration parameters

Model inputs showing a range of possible values, are subjected to changes for achieving a close match between calculated and observed results. The value of data must remain within the agreed or observed ranges. Table 5 shows these ranges of different parameters.

Table 5 Range of parameters used in model calibration

Parameter	Range	
	minimum	maximum
On-farm conveyance losses	40	1200 $m^3.d^{-1}$
Water holding capacity	0.15	0.35 $m^3.m^{-3}$
Representative area rain gauge station	-4	+4 calc. units
Groundwater use	0	3 times norm
Conveyance losses Irrigation canals	-	-
Effective porosity aquifer	0.08	0.16

Because the water distribution in Sirsa District is proportional to the irrigated area, changes in the parameters listed in Table 5, have no effect on the supplied quantities to the different calculation units. Changing the on-farm conveyance losses, however, changes the quantity supplied to the fields and may affect the percolation losses. When the on-farm losses increase percolation losses in general decrease. Although also the rooting depths of crops have a significant effect on the quantity of available water, they are not subjected to calibration procedures. By increasing the potential water holding capacity of soils, the quantity of water available for evapotranspiration increases which reduces the percolation losses to the aquifer and vice versa. Assigning calculation units to a certain representative area of rain gauge stations, offers the possibility to increase or decrease the total water supply to the unit concerned. This degree of freedom can be attributed to the irregular and erratic distribution of rainfall in the study area. Such assignments cannot be justified by scientific methods but are based on logic and knowledge of model behaviour instead. Groundwater abstraction can be seen as a means to reduce the effective recharge of the aquifer. Increasing the effective porosity of the aquifer increases the storage capacity and reduces the rate of groundwater depth changes.

5.2 Model performance criteria

The main objective of model application under conditions in Sirsa District is to predict or simulate the course of groundwater tables under changing circumstances. Therefor the calibration procedure aims at achieving the best match between calculated and observed groundwater table depth. The groundwater system is a slow reacting system, so a reasonable long period has to be considered to test the model performance. For Sirsa District the period 1977-1981 is used for the calibration of the model. The model performance is demonstrated through a relationship between the relative cumulative area of Sirsa Circle and the correlation coefficient between observed and calculated groundwater table depths. No criteria, however, are available for the minimum result to be achieved.

The model is validated for the period 1982-1991. The criterium for validation is the predictive value. This value is obtained by dividing the average deviation by the range of observation (difference between minimum and maximum value). This average deviation is obtained by dividing the square of the sum of quadrate of differences between calculation and observation by the number of data. According to Abdel Ghawad et al.(1991) the model is reasonable validated when the predictive value is 50% and sufficient when this value is 75%.

5.3 Calibration and validation results

Calibration starts with running of the model with an initial set of input data followed by an iterative procedure of adjusting different parameters and verification of model results. The adjustment of parameters follows a certain hierarchy of parameters: effective water holding capacity of soils, defining representative areas for rain gauge stations, on-farm conveyance losses and the effective storage capacity of the aquifer system. Each (spatial distributed) parameter is adjusted until no improvements of results could be achieved and then the next parameter in the hierarchy is calibrated.

The potential water holding capacity of soil different types was adjusted based on the deviation of calculated groundwater depths from the observed ones. This procedure has been repeated several times. The calibrated soil characteristics are for silt loam soils: porosity 0.509, moisture content at field capacity 0.461 and at wilting point 0.092 $m^3.m^{-3}$. For the sandy loam soils, these data are: 0.425, 0.260 and 0.110 $m^3.m^{-3}$ respectively.

The next step was to adapt the representative area of rain gauge stations. Respecting the rate of freedom, calculation units with relatively high rain fall and too fast rising groundwater tables were shifted to representative rain gauge areas with relatively low rain fall. The representative areas for different rain gauge stations as finally have been calibrated, are presented in Table 6.

Table 6 Calculation units falling under different rain gauge stations

Rain gauge station No.	Rain gauge station name	Calculation units
1	Sirsa	29, 34, 38, 39, 40, 41
2	Panjuana	21, 22, 17, 19, 26
3	Ottu	30, 33
4	Mojukhera	18, 23, 24, 25, 32
5	Jhande	20, 27, 28, 35
6	Khuyan	2, 3, 4, 5, 8, 9, 15
7	Abubshar	1, 6, 7, 12, 13, 14
8	Kalanwali	10, 11, 16
9	Daryapur	36, 37, 42, 43, 44, 45, 46

The following parameter to be calibrated is the 'on-farm' conveyance loss which relates to all the conveyance losses between the distributary canals and the irrigated field plots. Especially the seepage losses are closely related to the presence and quality of lining and will therefor show a wide range. The spatial distributed range was calibrated at 40 till 1200 $m^3.d^{-1}$, which means 1-35 mm per irrigation gift.

The last step in the calibration procedure is the adaption of the effective porosity of the aquifer, which initially was set to 0.1 $m^3.m^{-3}$. A spatial distributed range of 0.08-0.16 $m^3.m^{-3}$ could finally improve the results. This distribution is presented in Boonstra et al.(1996).

The coefficient of correlation between calculated and observed groundwater depth was finally calculated (Fig. 10).

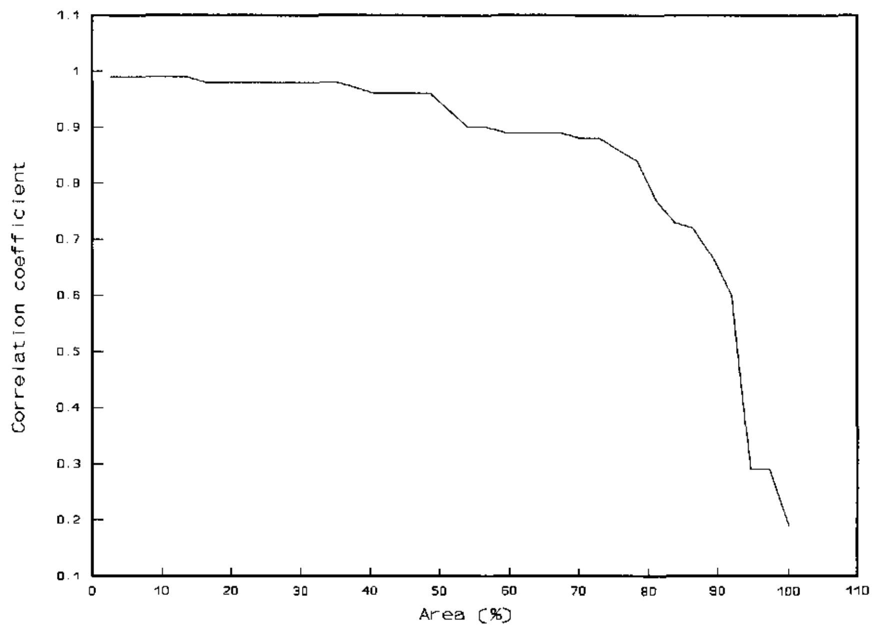

Fig. 10 Model performance at end of calibration

Calibration was very successful in about 82% of the study area with a correlation coefficient between observed and computed groundwater levels of more than 75%. In about 11% of the study area calibration was considered sufficient with correlation coefficients between 50 and 75%. Insufficient calibration was achieved in about 7% of the study area with values for the correlation of less than 50% (Fig. 10).

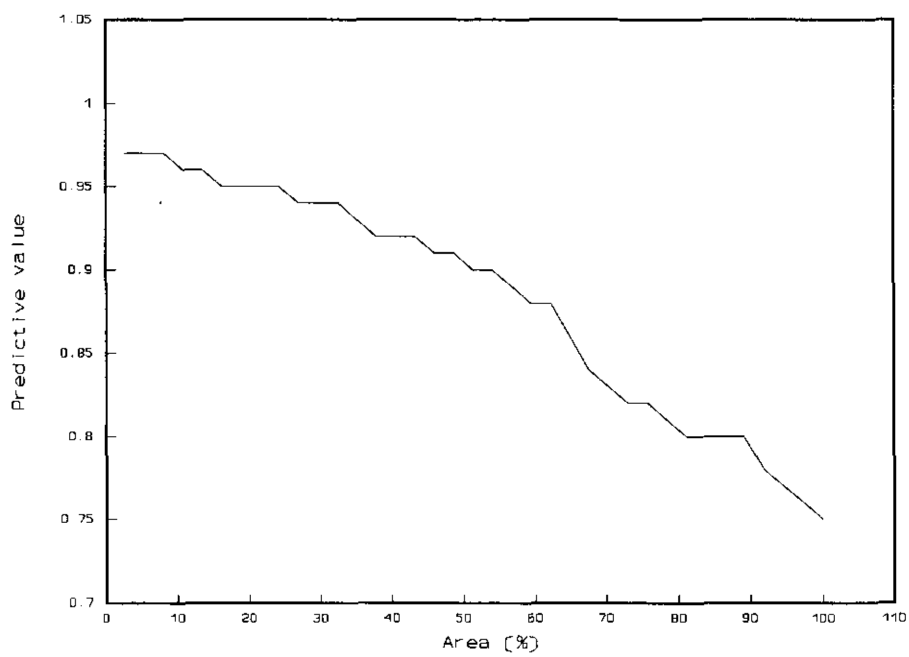

Fig. 11 Distribution of predictive value

After calibration of uncertain input parameters for the period from 1977 to 1981, the model was tested for the subsequent observation period from 1982 to 1991. The success of validation was expressed in the predictive value for the computed groundwater levels during the validation period. Validation results were satisfactory for the complete study area with predictive values of 75% and higher. In about 52% of the study area the predictive value was even above 90% (Fig. 11).

5.4 Analysis model results

Water supply and crop water requirement

In Sirsa District the major crops are wheat, cotton and gram. About 16% of the potential cultivated land is kept fallow, while of the remaining area on a yearly basis about 60% of the area is irrigated (Table 4). The water requirements of the irrigated crops is calculated with the model and include on-farm conveyance losses, percolation losses and evapotranspiration. These requirements should be met by canal water supply, rain fall and groundwater. In Figure 12 the crop water requirements of irrigated crops, relative to the total cultivated area, and the sum of canal irrigation and average rainfall are presented.

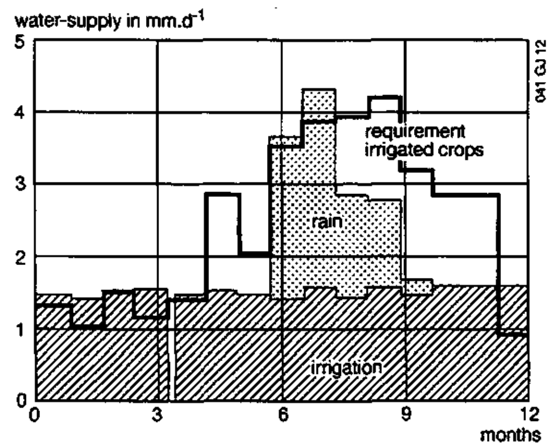

Fig. 12 Calculated water requirements of irrigated crops, average canal water supply and rainfall (1977-1991) relative to total cultivated area of Sirsa District.

On the average, the supply with canal water and rainfall exceeded the crop demands with about 15% during the first four months from January till April and with about 90% in December. In the months May and June the supply covered the demands for about 70%, while the demands were almost fully met during July till mid August. Thereafter until December, the supply was about 50-60 percent of the total requirements. During the period 1977-1991 the average shortage amounted 210 mm in periods with insufficient supply, with a minimum of 75 and a maximum of 330 mm. In periods with sufficient supply, the average excess was 50 mm with a minimum of 25 and a maximum of 125 mm. The irregular and erratic rainfall has caused significant deviations from these average figures as well in time as in place.

Recharge groundwater system

In the absence of drainage systems, water supplied through rainfall, groundwater use and canal irrigation in excess of the waterholding capacity of the soil, will percolate towards the groundwater system. Recharge causes groundwater tables to rise, but may also induce lateral flow towards neighbouring areas, called regional drainage. Groundwater tables remain stable in the long term when recharge and regional drainage are at equilibrium.

In Sirsa District a significant recharge was observed. Four component of this recharge were recognized:

- excess rainfall on non-agricultural areas,
- seepage losses from canals,
- on-farm water losses,
- aquifer recharge by the Ghaggar river during the monsoon period.

On-farm losses were caused by seepage losses from the field irrigation channels, percolation and leaching losses during field irrigation and leaching losses due to rainfall events, especially if they occurred just after field irrigation of crops. Percolation losses during field irrigation were generally not caused by excessive canal water supply, but due to the uneven field water distribution. The border and furrow irrigation methods applied by the farmers caused relatively more infiltration at the heads of the fields compared to the tail ends. Also imperfect land levelling and non ideal sloping fields promote inhomogeneous water distribution within agricultural fields. In the Warabandi distribution system, prevailing in Haryana State, the farmers get water on a fixed day of the week for a fixed time depending upon the area of his holding in the canal outlet command. As farmers are charged for the irrigated area, farmers tend to irrigate only this area, independent of the actual needs. During the monsoon rains this practise inevitably leads to locally significant percolation rates.

Also in the non-irrigated regions, the irregular and erratic rain fall can exceed the actual water holding capacity of soils and thus contribute to the recharge of the aquifers.

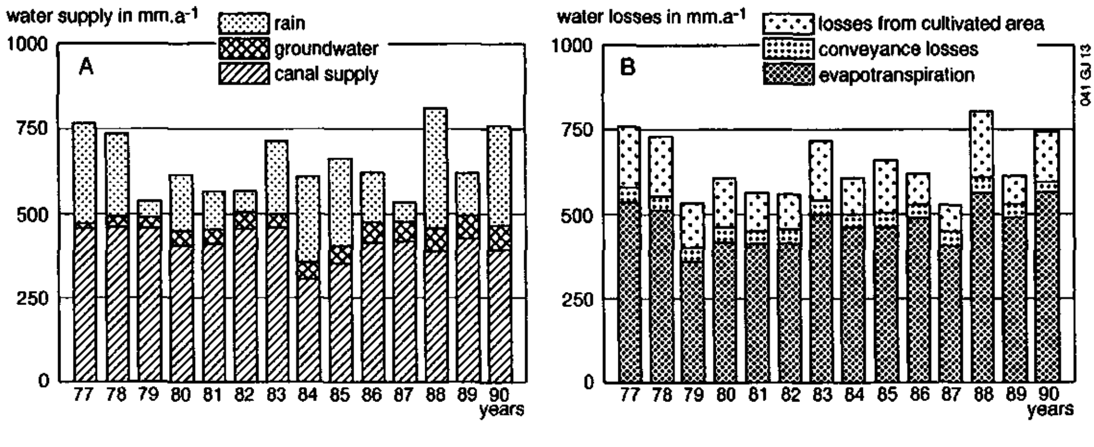

Fig. 13 Water balance of Sirsa District. A: Water resources, B: Evapotranspiration, conveyance losses and percolation losses from cultivated land.

The water balance of Sirsa District, obtained through model calculations, is shown in Figure 13. Neglecting the conveyance losses through evaporation, the sum of canal seepage, percolation losses in cultivated land and evapotranspiration equals roughly the total quantity of available water. Figure 13 shows a moderate fluctuating canal seepage during the period 1977-1991, while the percolation losses from the cultivated land fluctuate from 70 mm.y^{-1} to as much as 160 mm.y^{-1}. Defining the overall project efficiency according to Thompson, 1988, as the ratio of crop evapotranspiration over the total water supply (including rainfall and groundwater use), the system can be classified as highly efficient with values varying between 68 and 79% for the different years. The on-farm water losses accounted for about 60% of the total aquifer recharge and 25% of the water supply. Seepage losses from canal seepage account for about 10% of the total supply while the Ghagar river seepage losses account for only a few percent of the total supply. Large differences in aquifer recharge occurred in the area, however (Fig. 14).

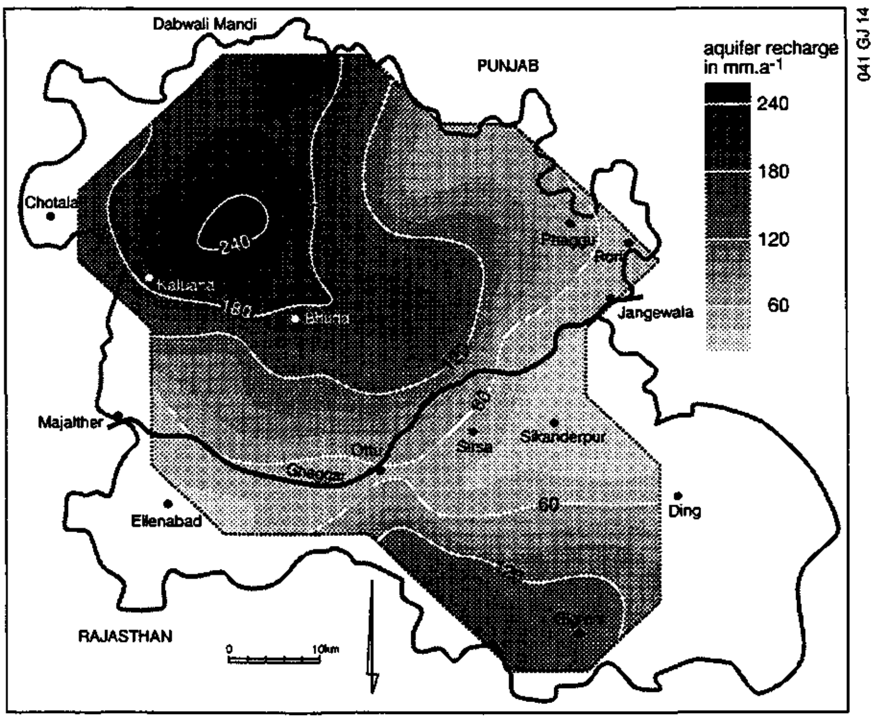

Fig. 14 Spatial distribution of average annual aquifer recharge from cultivated land (1977-1991).

Conclusion

The analysis of water management in Sirsa District revealed that irrigation performance was quite good resulting in a high overall project efficiency ranging from 68 to 79%. The average annual canal water supply was sufficient to meet the water requirements of irrigated crops during winter and early spring for the winter irrigation intensity of 45%. During summer and monsoon season the high water requirements for irrigated crops with irrigation intensity of 57% was met through canal irrigation and rainfall for 50 to 60%.

The combined effect of irregular rain fall, canal seepage and water holding capacity of soils and irrigation methods used by farmers resulted in percolation losses to the aquifer with a high spatial variability. On 20% of the area, percolation losses varied from 180 till 250 mm per year, on 60% of the area from 55 till 180 mm per year and in the remaining 20% from 30 till 55 mm per year. The annual canal seepage varied from 85-125 mm. The percolation losses together with canal seepage and conveyance losses from the Ghaggar river, caused in major parts of Sirsa District a groundwater table rise during the period 1977-1991 from 0 till 16 m. In the belt along the Ghaggar river, groundwater tables decline due to significant groundwater abstraction rates. Here the decline varied from 2 till 6 meter. The effective porosity in the aquifer system varies from 0.08 till 0.16 $m^3.m^{-3}$, so a change of on meter in water-table depth changes the groundwater reservoir with 80-160 mm.

An estimation of the rate of the regional drainage based on an average hydraulic gradient and the transmissivity of the aquifer, revealed a rate of about 20 mm annually in the northern part of Sirsa District in 1979. To arrest the rising water-tables, the nett recharge should not exceed this Figure. It is quite obvious, that with canal irrigation this situation cannot be achieved and a drainage system to remove excess of salts and water will be required in the future.

6 Alternative water management strategies

Future regional water management strategies for Sirsa District should solve the problem of rising water-tables in the north and southern part and the problem of declining water-tables in the central part of the study area. Although a complete solution cannot be achieved without drainage outlet to remove the salts imported with the irrigation water, the question remains whether an adapted regional water management could delay the rise of the water-tables in the endangered zones. This means that alternatives have to be found to arrest the rising groundwater tables by either reducing the aquifer recharge or increasing the groundwater use. Declining water-tables can be combated by increasing the recharge or reducing the groundwater use.

Increase of groundwater use in areas with rising water-tables and poor groundwater quality is an issue which should be solved at the farm level, although mixing of groundwater unsuitable for direct irrigation with canal water at a subregional level is an alternative. Implementation of such strategies has to be pursued through extension to farmers in order to show the profitability of extending their irrigated area by augmenting deficient canal water supply with saline groundwater. Using the waterpricing mechanisms can be combined with this approach.

Out of the four components of aquifer recharge, two are not controlled by the regional water manager. These are the recharge due to rainfall in the non-agricultural areas and the recharge from the Ghaggar river during monsoon. The latter takes place in the zone of declining water-tables and is rather beneficial. Two other recharge components are under control of the regional water manager: the canal seepage losses and the on-farm water management losses. The canal seepage losses were estimated at about 10% of the canal water supply. Further reduction of these losses of this highly efficient system will be very difficult to achieve.

An improvements of water use efficiency can be obtained by a reduction of the supply during the first four months of the year with about 15% and in the last month of the year with about 40%. This will save about 50 mm annually, but is insufficient to compensate the shortage of 210 mm during the summer season.

At this moment, water is distribution according to the irrigated area rather than to crop water requirements in irrigated regions. The actual irrigation supply is based on under-irrigation and proved to perform remarkably well. Additional improvements can be achieved when the distribution would be based on the spatial distributed crop water requirements. During the monsoon period, however, these requirements depend to a large extend on local rainfall, which would require a water distribution method accounting for irregular and spatially distributed requirements. Although solutions for the technical and managerial provisions needed for such a water distribution are beyond the scope of this study, we believe that the application of regional models as predictive tools, can play a prominent role in future operational water management.

The irregular and erratic rain fall during the monsoon together with the Warabandi

distribution system and water pricing based on the irrigated area, causes locally over-irrigation and excessive percolation losses. When water pricing would be based on supplied quantity rather than on area, farmers most probably will optimize the on-farm water management by considering irrigation of rain fed crops. This practise will most probably improve the utilization rate and reduce percolation losses.
Two water management strategies addressing the reduction of on-farm water losses to the aquifer were tested and will be treated in the next paragraphs. Both strategies were tested for the period between 1971 and 1990, to enable comparison with the historical water-table development.

6.1 Alternative water pricing

The actual system of water pricing is based on the irrigated area. Farmers are charged with a fixed price per unit irrigated area, independently of the number of irrigations. When the water pricing is changed to a system based on delivered quantity, the farmers have the opportunity to seek the most profitable water application. The determination of the delivered quantity is not simple. A solution could be a certain farmers involvement in the local water management. Under such systems, the regional water manager is entrusted with delivery of certain quantities to the farmers associations, while these associations are responsible for the local water distribution and system of water pricing. On the other hand, the present Warabandi water supply system which is based on equity, such a change in water pricing methodology does not involve expensive and laborious monitoring of volumes delivered, but simply changing the basis of pricing from irrigated area to cultivable area.

The effects of the change of the water pricing system is simulated with the model. The water distribution among the calculation units has not been changed. Irrigation of other crops has been facilitated through assigning a certain demand for canal water to the previously rainfed crops. In the model this is obtained by defining a certain irrigation opportunity time for these crops. With program WDUTY an effective demand is calculated, which is used in the REUSE module to distribute the supplied quantity of water among the field crops. In this approach a low irrigation preference score was assigned to the previously rainfed crops. These crops will only be irrigated when sufficient canal water is available. However, a minimum irrigation has been forced because in the model formulation implicitely a minimum supply to each (canal) water demanding crop has been assumed. An increase of irrigated area from 50% to about 85% was obtained in the simulations by converting the rainfed crops to irrigated crops.

As a result of this strategy, the crop evapotranspiration increased at the expense of water losses to the aquifer. The annual rise in water-table in the utmost north-western and south-eastern part of Sirsa District reduced with about 15%. By adopting this strategy water-logging problems cannot be avoided, but the problem can be postponed by 5 to 10 years (Fig. 15). At the same time total crop production in the area appeared to increase as well. With this strategy, declining water-tables in the central part of the area were not arrested.

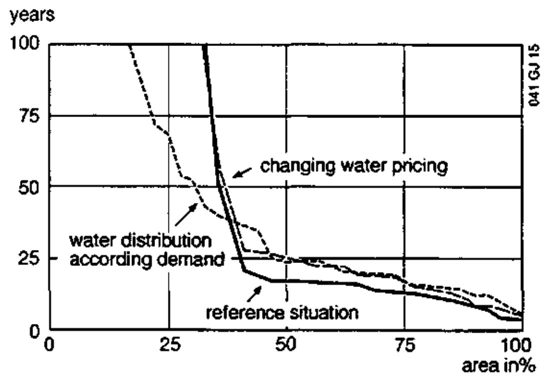

Fig. 15 Distribution of elapsed time after which water-logging is expected for different alternatives.

6.2 Water supply according to demand

Presently, canal water distribution is based on cultivable area rather than on water requirements of the irrigated cropping pattern. This could be improved by discarding the Warabandi system and by distributing canal water based on the spatially distributed crop water requirements. During the monsoon period, irrigation water requirements depend to a large extend on rainfall. Solutions for the technical and managerial provisions to adjust canal water supply to the erratic and spatially distributed rainfall conditions were considered beyond the scope of our study. A full control of water supply to the main canal intakes is assumed. Although application of regional models as predictive tools, can play a prominent role in future water management accounting for rainfall, at this stage, long-term average rainfall has been assumed as input for matching the water distribution with the spatial and temporal distributed water requirements.

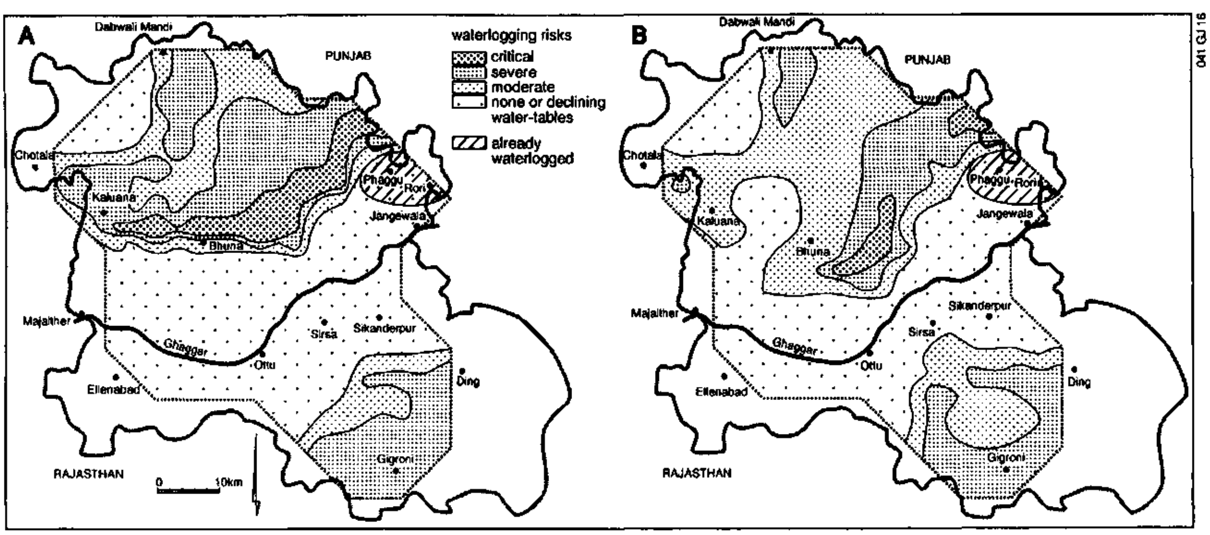

Fig. 16 Endangered zones by water-logging. A: actual situation, B: water distribution according to demand

In the model the total annual canal water supply has been kept at the same level as during the reference situation but the distribution was taken proportional to the time and spatial distributed water requirements. The effects of this regional water management strategies were expressed in the number of years elapsed until water-logging occurred.

In the reference situation (Fig. 15, 16A) with unchanged water management, in about 10% of the Sirsa District area water-logging problems will occur within 5 years. In an additional 35% of the area water-logging is expected within 5 to 15 years and in 5% of the area water-logging problems will occur within a time period of 15 to 45 years. With water distribution matching the temporally and spatially distributed water requirements, these percentages are considerably reduced (Fig. 15, 16B). In about 5% of the area water-logging is expected within 5 years, in about 15% of the area within 5 to 15 years and in about 25% water-logging problems will occur within a time period of 15 to 45 years. An additional benefit from this alternative is that in the central part of Sirsa District with declining water-tables, a status quo or a reversed situation was created. The area in the vicinity of Rori, Phaggu and Jangewala now already experiences water-logging and secondary salinization and has therefor not been included in the endangered zone.

6.3 Evaluation of alternatives

Compared to the present canal water management system in Sirsa District, both alternative strategies have the advantage that rising water-tables were delayed in the saline groundwater areas in the north and south of Sirsa district. Water distribution according to demand was slightly more effective in these areas. In the central part of Sirsa District water distribution according to demand led to slightly rising water-tables. This could easily be corrected by reducing canal water supply to these areas or by compensating the increased recharge with more groundwater use.

The strategy of changing water pricing has the obvious advantage that no investments are required and operation of the canal system can be maintained at the present mode. The strategy with distribution according to demand requires a differentiated allocation and distribution of canal water and the present system of distribution based on equity has to be abandoned.

For the strategy with distribution according to demand a number of practical constraints have to be solved: water scheduling and control requires more labour and additional investments to adapt water control structures and most probably will require additional water storage facilities. Such a system will be more susceptible to sabotage and bribery by influential farmers trying to receive more canal water. Following the distribution according to the model, farmers in the advantageous situation (the Ghaggar river belt) with access to good quality groundwater will receive more canal water than their colleagues in the poor quality groundwater zones.

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