TR-37

SYSTEMS APPROACH TO OPTIMIZE CONJUNCTIVE USE OF SURFACE AND GROUND WATER

SATISH CHANDRA
DIRECTOR

STUDY GROUP

A G CHACHADI
ASHA SINHA

NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAWAN
ROORKEE-247 667 (UP)
INDIA

1987-88

TABLE OF CONTENTS

LIST OF SYMBOLS

A_i = total area under i^{th} crop

A_t = total area available for cultivation at t^{th} season

A_T = total gross area of cultivation

a_{it} = Variable (0-1), equal to 1 if the i^{th} crop is grown in t^{th} season, zero otherwise

a_j = coefficients

b_{it} = water requirement of i^{th} crop in t^{th} season at saturation level

b = resource availability

C_i = cost of total input

C_w = unit cost of irrigation water

m = total number of crop activities

P_i = selling price of i^{th} produce

WR_t = available water for irrigation in the t^{th} season

x_j = decision variable

Y_i = yield of i^{th} crop

$Q_{1,\ldots n}$ = input resources

K = consumptive use coefficient

= E_t/E_p

E_p = pan evaporation

R_e = effective rainfall

E_t = consumptive use = C_u

NIR = Net irrigation requirement = $C_u - R_e$

FIR = Field irrigation requirement = NIR/0.85

GIR = Gross irrigation requirement = FIR/0.75

LS = Lump sum

r_j = average rainfall in the j^{th} month

p_j = pan evaporation in the j^{th} month

K_{ij} = the crop coefficient of i^{th} crop in the j^{th} month

EP_{ij} = consumptive use = $p_j \times K_{ij}$

R_{ij} = net water requirement in the j^{th} month for the i^{th} crop

e_{ij} = effective rainfall for i^{th} crop in j^{th} month

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

In the present study a conjunctive use model for optimum agricultural production in the sub-basin of the Ghataprabha command area in Karnataka State has been formulated. The aim is to develop an optimal crop plan, which is economically feasible and socially acceptable exploiting the irrigation potential both from surface and groundwater.

Ten crops have been identified for production on the basis of soil and climate and the cropping pattern observed in the area. The consumptive use and the net irrigation requirement of each crop have been computed. The groundwater resources and surface water availability over a time period have been estimated. A linear programming model has been used to allocate the optimal areas to different crops subject to the constraint of surface and groundwater availability.

1.0 INTRODUCTION

The quantity and quality of available water resources have long been recognized as limiting factors in the development of most arid and semi-arid regions. The optimal utilization of existing water resources is therefore of ever increasing importance.

While water supply is replenished in a general recurring seasonal and annual pattern, it is not yet within man's power to significantly increase the over-all supply. The best that can be done is to conserve the recurring supply and bring it under control, to preserve the quality, and to better the more vital users. The planning and execution of the best possible programs for the conservation and control of water should be recognised as one of the nation's most important natural resource problems.

To attain this objective of conservation and control of the water resources, water must be stored at times when the supply exceeds the demands. The use of surface reservoirs to attain the objective of water supply and flood control and for better conservation and management of the water resources is a well established practice. Groundwater aquifers have also been long recognised as important sources of water. However, in the past, subsurface reservoirs have been used with almost complete disregard of surface storage and the interrelationships that exists between surface and groundwater supplies.

As more information is gathered concerning groundwater hydrology and as water demand increases, the requirement for an optimal development and use policy for groundwater and surface water resources is brought into sharper focus. It is both appropriate and necessary to develop a methodology for optimizing conjunctive use of these resources. The determination of optimal allocations of surface water and groundwater resources that will accomplish the objective of economic efficiency as measured by maximizing net benefits is the basic objective of the several models developed.

Water resources of the country are available from rainfall and melting of snow after meeting the evapotranspiration losses. A major portion of these waters flows down as surface water in rivers and streams while the remaining portion seeps into the ground. Khosla (1949) first made an estimate of the water resources of country. According to him, the total average annual runoff represents average annual runoff over a period of time. The actual runoff, however, varies considerably from year to year. Further, in any particular year, there is a wide seasonal variation in runoff as most of it is concentrated during the four months of the monsoon season when more than 85 percent of the total runoff of the year occurs. Based on the studies carried out by various organisations the average estimated water resources in India in a year consist of:

Surface water	1858000 mcm
Ground water(recharge)	422,000 mcm

The total annual utilisable water resources of the country have been worked out as follows:

Surface water	666,000 mcm
Ground water	322,000 mcm

Though the ground water potential is quite substantial, the irrigation projects in our country are so far planned and implemented separately for surface water and ground water. In general ground water has been developed by private sector and it has been found to be haphazard and unplanned. Over exploitation of ground water in areas like Mehasana in Gujarat, part of Meerut and Varanasi districts in U.P., Coimbatore in Tamilnadu, and Karnal district in Haryana has resulted in mining of ground water. On the other hand in some major irrigation project commands such as that of Sharada Sahayak in U.P., Chambal in Rajasthan, Nagarjuna Sagar in Andhra Pradesh, Ghatprabha and Malprabha in Karnataka, problems of water logging have been experienced. Water logging problems could be checked if during the project planning conjunctive use is envisaged in the canal command area. Areas which have already been affected by water logging and secondary soil salanization problems due to poor subsurface drainage should make use of ground water for irrigation purpose as abstraction of groundwater through dug wells and shallow tubewells will lower the water table and reclaim the affected soil.

The Irrigation Commission (1972) had in its report laid considerable emphasis on the conjunctive use of surface and groundwater. The commission was of the view that the planning of water resources had to be related to a defined area or region, with due regard to inter-regional needs. An overall plan for the development of water resources requires not only a full knowledge of the quantity, quality and distribution of water resources, but also an evaluation of land uses and their effects on stream flow and the production and movement of sediments. The first step in making plans for the utilisation of the available surface and groundwater resources of a basin is an accurate assessment of the available surface and groundwater resources. Planning for combined use of surface and groundwaters calls for greater ingenuity than is needed for their separate use. The commission also reported that the existing irrigation systems suffer from two kinds of inadequate supplies. The first being the lack of timely supplies and the second the inability to provide either the right quantity or the correct number of irrigations needed to raise a good crop. It is, therefore, in areas where surface water resources are not enough to meet the irrigation requirements, municipal needs etc the groundwater resources can be exploited to supplement the surface water resources.

Utilization of aquifer storage in conjunction with surface reservoir has been thought since 1940's. Aquifer may be considered as storage structure capable of performing two functions in many cases: control of floods and water supply for irrigation, domestic and industrial use. The former function is not always conspicuous and therefore often neglected. The complex groundwater management problems have been studied with inadequate importance to surface water. The specific problem of interrelationship between surface and groundwater for arid zones has been studied and reported by Khosla. The importance of conjunctive use of surface and groundwaters can be judged from the fact that in Central Valley of California at a depth of 200 ft. below ground surface, an aquifer reservoir of storage capacity six times larger than the feasible surface reservoir is available.

The various important advantages of conjunctive use highlighted by Clendenen (1954) are worth mentioning here. Operation of both surface and groundwater reservoirs provides for larger water storage and hence greater water conservation. Greater utilization of groundwater leads to smaller surface distribution system. Since pumping well would act as a vertical drainage and would aid in controlling the water table, a basin where conjunctive use is practised would require small drainage system. In conjunctive use planning, canal lining can be reduced as seepage from canal provides recharge to groundwater. Release of stored surface waters for artificial recharge provides greater flood control reservation. Conjunctive use leads to lesser evapotranspiration loss because of greater underground storage with lower groundwater table position.

1.1 Development of Conjunctive Use Planning in India

A number of developments took place in U.P., Punjab, Maharashtra, Tamilnadu and other States in the forties with respect to utilizations of groundwater. The Uttar Pradesh Govt. took up schemes of tapping deep aquifers (upto 100 m) in tail reaches of canal system to provide better irrigation facilities. However, combining of surface and groundwaters was mostly adopted to meet specific requirements without considering optimum utilization. It was from the sixties onwards, increased attention of Central and State Governments was focussed on increased use of surface and groundwater resources conjunctively.

The use of groundwater for irrigation purposes has been going on at a fast pace in different states. Besides providing more water for irrigation, these wells have also helped in vertical drainage thereby controlling waterlogging problems. For example, in Punjab the area that was under waterlogging was 971,000 ha. in 1964 which reduced to about 169,000 ha. by 1974 after sinking of a large number of tubewells. In Haryana, state tubewells are of two types, i) Augmentation Tubewells which are installed along existing canals which add water into canals for utilization in the canal command areas, ii) Direct Irrigation Tubewells which provide local irrigation facilities outside the canal commands. In Bihar, it is only in the command of the Sone Project that groundwater has been used with canal supplies. In Rajasthan, the eastern region is drained by Chambal and its tributaries and the southern part by the Mahi river. The part of Rajasthan west of the Aravallis comprising about 60% of the area is arid and is drained by Luni and its tributeries. Irrigation by open wells has always been the main source of irrigation in the state, and as there are very few surface water schemes in the state, there is not much scope for conjunctive use. However, conjunctive use of surface and ground waters has been introduced in certain areas in Chambal Command in Kota and Bundi districts. In Gujarat Government tubewells are being installed in the canal commands of the

Mahi, the Dantiwada etc. for integrated use of surface and groundwaters. Similar projects envisaging conjuncative use have also been taken up in the command areas of the Ghataprabha Left Bank Canal in Karnataka and the Godavari Canal Systems in Andhra Pradesh. In Madhya Pradesh the government has taken up a project with the help of World Bank for conjunctive use of surface and groundwaters in Chambal command. The Chambal project was envisaged to irrigate 3,30000 ha. at planning stage and after completion of project in 1960, an area of 1,51,000 ha. could be irrigated (1974 figures) due to the unlined canals and heavy seepage losses associated with them. After the modernisation project, the irrigated area increased to 2,41800 ha. which also included irrigation water supply from groundwater resources. Based on studies conducted by an expert committee, a statewise list of project commands wherein integrated and conjunctive use of surface and groundwaters is suggested to be taken up as pilot schemes has been prepared which is given in Table 1.1.

1.2 Study Area

The present study area of about 13,000Ha lying in Gokak Taluk forms part of the Ghataprabha command area in Karnataka State. Gokak town is the headquarter of the taluk is situated 51 km north east of Belgaum. The nearest railway station is Gokak road on Miraj-Bangalore metre-gauge line situated 8 km north west of Gokak town. The taluk lies between Lat: $15^{\circ}55'$ and $16^{\circ}24'$ north and Long: $74^{\circ}44'$ and $75^{\circ}15'$ east and falls in the surve of India toposheet Nos.47 L/12, L/15, L/16 and 47 P/3, P/4 (Fig.1).

Physiographically the area shows group of flat topped hills in the west getting discreted and a vast plain to the east. The region forms a transition between the hilly western ghats and the plains to the east. Gokak taluk has a dry climate. Hot season is from March through June. May is the

TABLE 1.1

STATEWISE LIST OF PROJECT COMMANDS WHEREIN INTEGRATED AND CONJUNCTIVE USE OF SURFACE AND GROUND WATERS IS SUGGESTED TO BE TAKEN UP AS PILOT SCHEMES

Sl.No.	State	Name of Project Command
1.	Andhra Pradesh	i) Krishna-Godavari Delta System ii) Nagarjunasagar
2.	Bihar	i) Sone ii) Gandak
3.	Gujarat	i) Mahi-Kadana ii) Ukai-Kakrapar
4.	Karnataka	i) Ghataprabha
5.	Maharashtra	i) Ghod ii) Nira
6.	Madhya Pradesh	i) Chambal ii) Tama
7.	Orissa	i) Mahanadi Delta ii) Hirakud
8.	Rajasthan	i) Chambal
9.	Tamilnadu	i) Cauvery Bhavani ii) Lower Bhavani
10.	Uttar Pradesh	i) Gandak ii) Sarda Sahayak
11.	West Bengal	i) Mayurakshi ii) Kangsabati

Note: Haryana and Punjab have not been included as integrated and Conjunctive Use of Surface and Ground Waters is already in vogue on a fairly large scale in these states. However, there is scope for making existing systems more efficient.

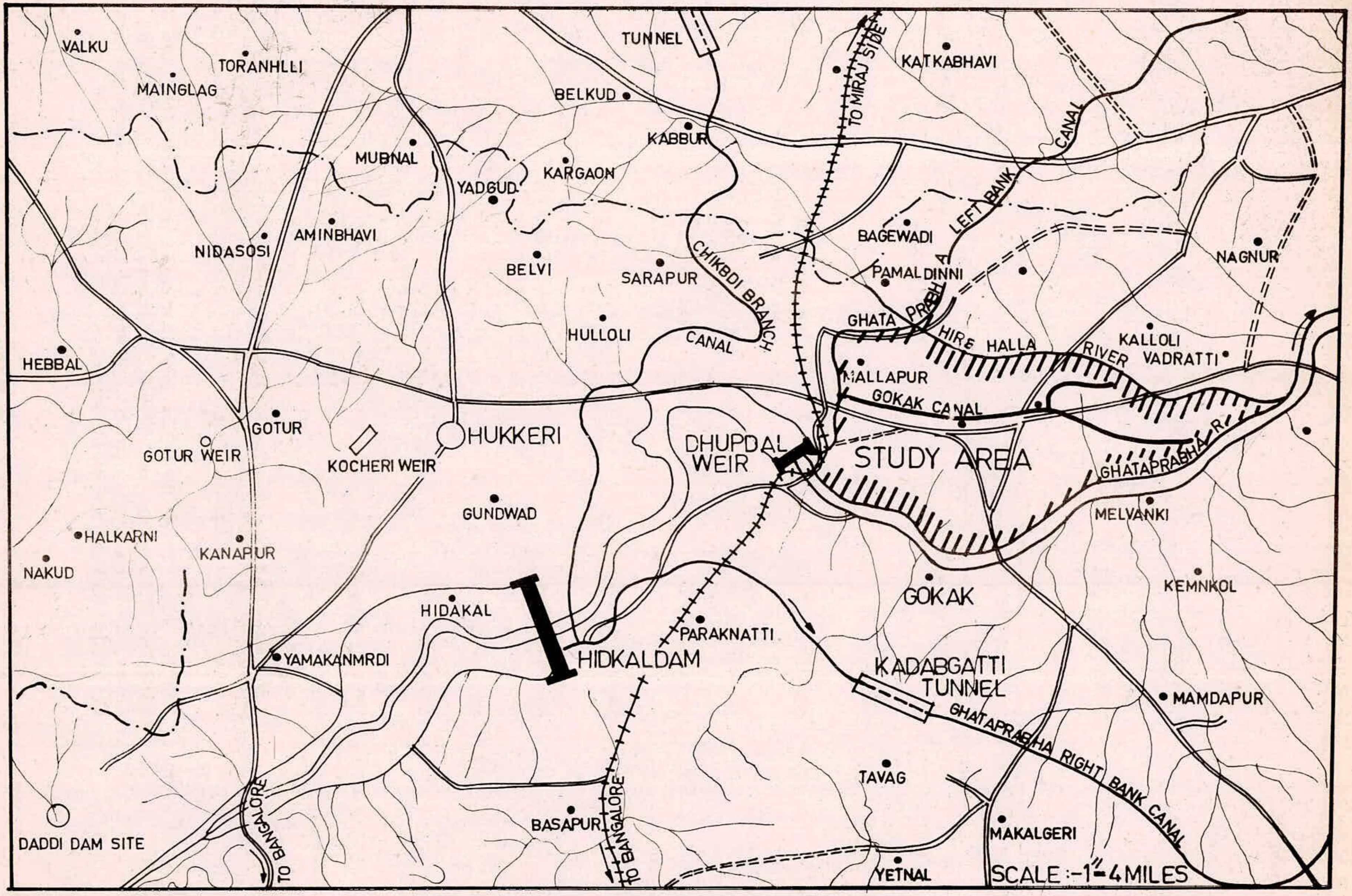

FIG.1 - INDEX MAP OF THE STUDY AREA

hottest month with a maximum temperature of 41°C and minimum of 35.5°C. The monthly average rainfall of Gokak for 66 years from 1921-86 is furnished in the following table:

Month	Average rainfall(mm)
January	0.80
February	1.03
March	5.88
April	33.62
May	59.80
June	64.74
July	72.55
August	62.73
September	102.83
October	103.81
November	31.15
December	4.46
	Annual = 543.40

The rainy season generally starts from June and continues upto Nov. The average annual rainfall for 66 years upto 1986 is 543.4mm. In the 66 years period the rainfall occurred above the average during 31 years and below the average for 35 years.

1.2.1 Land utilisation and agriculture

The main occupation of the people in the area is agriculture. There are two agricultural seasons, Khariff and Rabi in the year. The Khariff starts from June with harvest during October, and the Rabi starts from

September and October, and harvested during February and March. The principal crops are Jowar, Paddy, Maize, Sugarcane, Groundnut, Cotton, Chillies and Wheat.

The following table shows the land utilisation and related statistics of Gokak taluk:

Total area	154,308Ha	
Population	3,59,561	(1981)
Growth rate	3.18%	
Density	233/km^2	(1981)
Male population	1,82,762	(1981)
Female population	1,76,799	(1981)
Rural population	2,67,414	(1981)
Urban population	92,147	(1981)
Forest area	22,284 Ha	(1983-84)
Uncultivated land	11,540 Ha	(1983-84)
Fellow land	3,628 Ha	(1983-84)
Net irrigated area	32,744 Ha	(1983-84)
Net sown area	1,15,128 Ha	(1983-84)
Canal irrigated area	20,550 Ha	(1983-84)
Well irrigated area	8,434 Ha	(1983-84)
Tank irrigated area	Nil	
Others	3,755 Ha	(1983-84)
Agricultural holdings	44,087	(1980-81)
Area of agriculture	1,21,071	(1980-81)
Irrigation wells	6,740	(1984)
Paddy	850 Ha	(1983-84)
Jowar	28,880 Ha	(")
Ragi	38 Ha	(")
Bajra	13,000 Ha	(")
Wheat	9,250 Ha	(")
Suppl.crops	1,204 Ha	(")
Groundnut	18,325 Ha	(")
Cotton	227 Ha	(")
Tobaco	3,582 Ha	(")
Sugarcane	4,085 Ha	(")

Maize	-	16,113 Ha	(1983-84)
Tur dal	-	2,250 Ha	(")
Gram	-	4,634 Ha	(")
Other pulses	-	7,575 Ha	(")
Cattle population	-	60,342	(")
She buffelows	-	54,697	(")
Sheeps	-	65,492	(")
Goats	-	64,941	(")
Hens	-	95,603	(")

1.2.2 Soils in the study area

There are are two types of soils in the study area viz. (i) deep black soil and (ii) alluvial soil (Fig.2). The north half of the area is covered by medium to deep black soils. This soil has a high clay content and high water holding capacity. Hence there is excessive runoff and less infiltration (Govinda Gouda, 1972). Soil cover varies from few cms. to 3m. Irrigated crops are hybrid jowar, sugarcane, vegetables, cotton, and wheat. Rainfed crops are jowar, millets, oilseeds, cotton, wheat etc. The southern portion of the area is covered with alluvial soils which are shallow in thickness and are pale red to pale brown in colour. The thickness varies from few cms. to about 3m.

1.2.3 Hydrogeology

A major part of the area is underlain by a series of lava flows collectively known as Deccan traps. Sandstones, quartzites and Gneisses are exposed in the southern portion of the area near Arabhavi and Gokak(Fig.3). The order of superposition of the formation in the area is as follows:

i) Soil	Recent age
ii) Deccan traps	Cretaceous age
iii) Sandstone, shale, Limestone, and Conglomerates	Kaladgi (Precambrian)
iv) Granites and Gneisses	Archaean

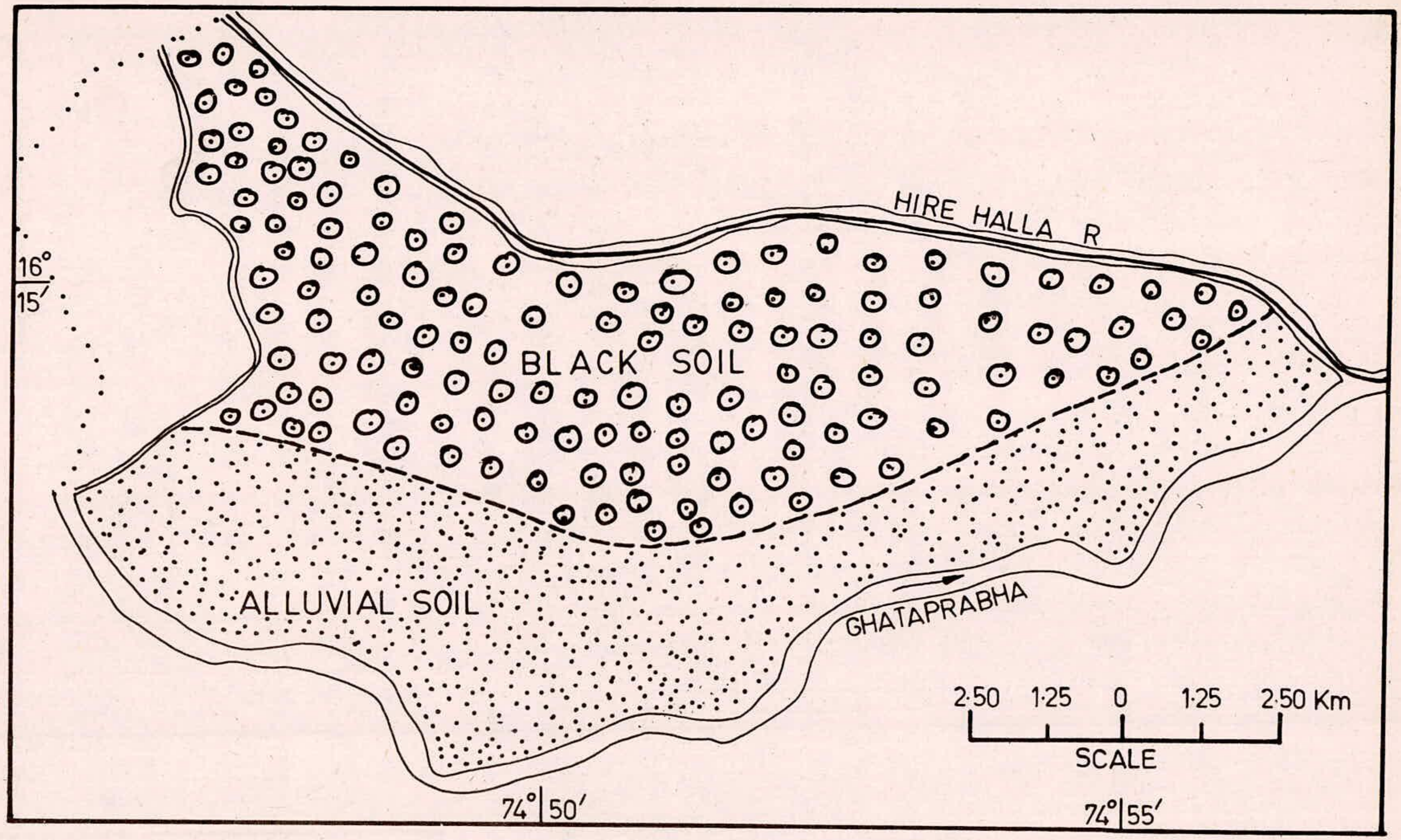

FIG.2 - SOIL MAP OF THE STUDY AREA

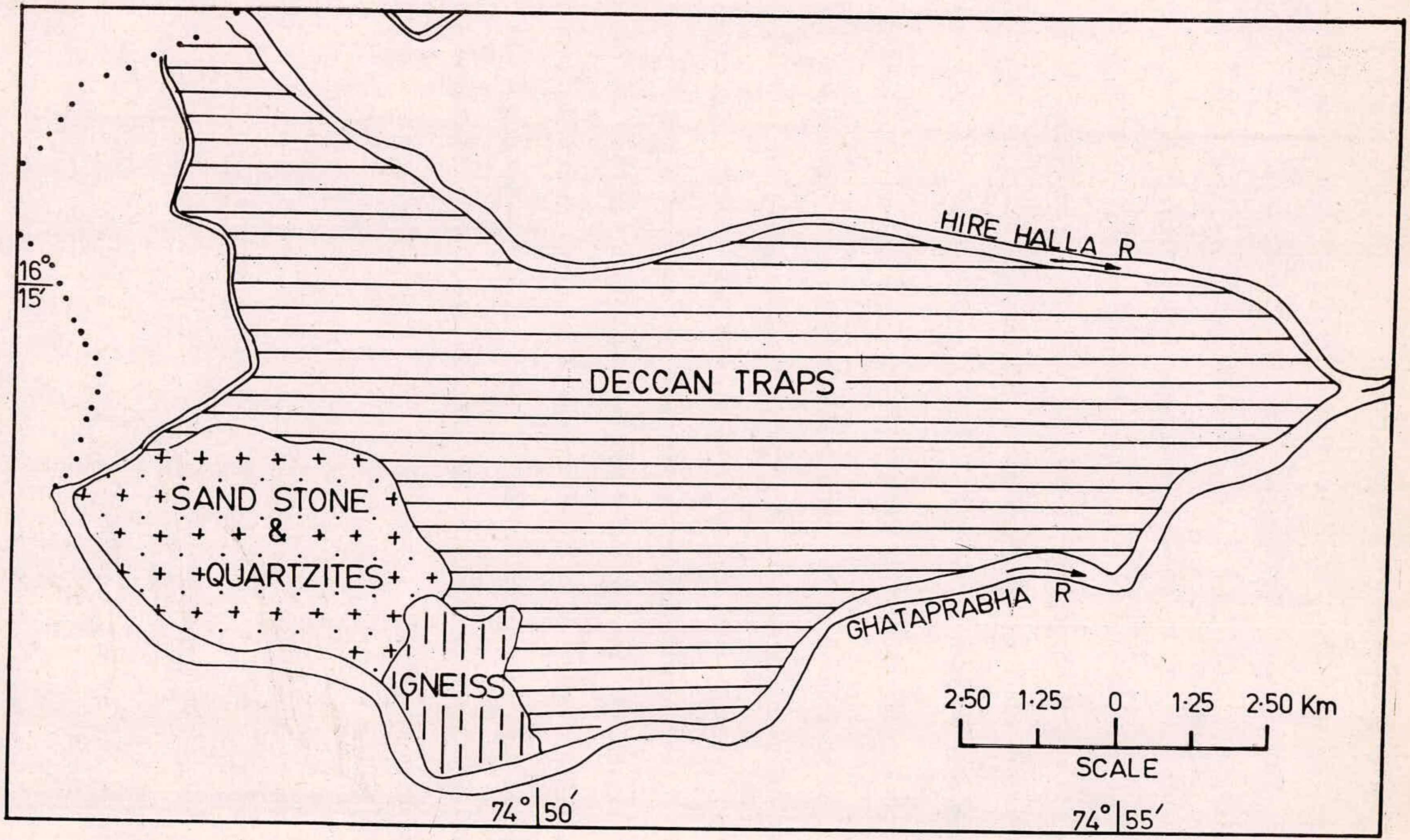

FIG.3 - GEOLOGICAL MAP OF THE STUDY AREA

The trap sequence is a succession of several lava flows that lie more or less horizontally. The flows largely consist of blocky and jointed lava of fine to medium grained texture. The common joint pattern are columnar, rectangular and sheeting. Rectangular blocks affected by spheroidal weathering are embedded in weathered rock matrix. The vesicles in the rock vary in shape from capillary to that of cavities which are generally filled with secondary minearals. Generally groundwater in the area occurs under water table conditions. The groundwater is recharged mostly through precipitation, return flow from irrigation and seepage from canals.

1.2.4 Groundwater potential estimation

The estimation of the various components of the groundwater recharge and discharge has been carried out with the data collected from secondary sources. Groundwater recharge is mainly through atmospheric precipitation and to a considerable extent through seepage from canals and return flow from irrigation. The procedure proposed by NABARD has been adopted for estimating groundwater potential in the study area. A computerised technique has been used to arrive at the water balance components. The computer output showing different water balance components and groundwater potential is shown in Table 1.2.

Table 1.2 GROUND WATER ASSESSMENT BASED ON WATER TABLE FLUCTUATION APPROACH FOR THE STUDY AREA (All units are in ham)

Recharge from canals		Recharge from S W Irrig.		Recharge from rainfall		Total Mon Recharge	Total NMon Recharge	Total Annual Recharge	Net Recharge
Mon	NMon	Mon	NMon	Mon	NMon				
1735.48	847.08	895.00	1190.00	676.48	139.49	3306.97	2176.57	5483.54	4661.01

S.No.	M.I.Works	Nos.	Unit Draft	Yearly Draft
1	Dugwells	300	0.52	156.00
2	Dugwells with PS	200	1.05	210.00
	Total Annual Draft			366.00
	Net Annual Draft			256.20

GROUND WATER BALANCE = 4404.81

PRESENT STAGE OF DEVELOPMENT = 5.50%

STAGE OF DEVELOPMENT 5 YEARS HENCE = 15.50%

CATEGORY OF BLOCK = WHITE

1.2.5 Surface water supply

There are no tank irrigation in the study area. Ghataprabha Left Bank Canal (GLBC) irrigates about 75% of the area. The study area is traversed by Gokak canal, Badigwad distributory and distributory nos.1 and 2. The canals are run from June 15 to Feb.15 for a period of about 250 days continuously for 24 hours. The monthly water that is supplied through all canals and distributories to the study area is shown in Table 1.3.

1.2.6 Cropping pattern and irrigation practices

The existing cropping pattern is 40% Kharif, 40% Rabi and 20% two seasonals. The irrigation practice is by flooding method. The weighted intensity of irrigation has been estimated to be 100% (NWDA,1986) in the area.

TABLE 1.3

ESTIMATION OF SURFACE WATER AVAILABILITY FOR GHATAPRABHA SUB BASIN (INCLUDES WATER RELEASED IN GOKAK BRANCH CANAL, BADIGWAD BRANCH CANAL, AND DIVERSION NO.1&2)

S.No	Month	Total volume of water available in Ha.m
1.	January	1312
2.	February(1-15)	664
3.	March	0
4.	April	0
5.	May	0
6.	June(15-30)	664
7.	July	1372
8.	August	1372
9.	September	1328
10.	October	1372
11.	November	1328
12.	December	1372
	Annual =	10784

2.0 REVIEW OF THE LITERATURE

Literature concerning the applications of systems analysis and optimization techniques to water resource problems has appeared only since 1960 and most of this literature deals with concepts and simple examples rather than with actual examples. Literature dealing with the concepts of conjunctive use of groundwater reservoirs and surface water facilities is more extensive and earlier. However, most of the literature dealing with conjunctive use has been of a qualitative nature and has dealt primarily of a local nature. Literature dealing with the management of groundwater supplies has been concerned primarily with the problems of groundwater depletion.

The complexities of the problem of conjunctive operation of ground and surface water facilities were explored by some early writers who recognised that the two resources were really a single system and that economic advantages could be had by operating the system as a complete unit (Banks, 1953 and Kazmann, 1951). Although these early writers have discussed the benefits of joint utilization of groundwater and surface water only recently have investigators begun to apply optimization methods to the problems of allocating groundwaters and surface waters.

Authors who have dealt with the problems of conjunctive use of groundwater and surface water systems such as Clendenen (1954), Thomas (1957), Macksoud (1961), and others, have discussed the economic advantages of such a combination and have pointed out its effectiveness in the conservation of sizeable volumes of water. When these authors have dealt with the problems of economic optimization, the methods of analysis are based upon investigation of a limited number of alternatives and the selection of the best one according to the benefit-cost ratio during the economic life of the project.

The work of these authors, however, has been concerned mainly with the engineering problems in the design and operation of the conjunctive use system.

Fowler (1964) has suggested that solving the engineering problems associated with the development of a conjunctive use system requires a thorough understanding and investigations of the geology of the groundwater basin, of the hydrology of surface and groundwaters, of the existing surface and groundwater facilities including storage and transmission characteristics, and of existing and expected water demands and the economics associated with meeting those demands. Fowler states that when groundwater basins can be operated in a fully integrated fashion with surface water supplies, then optimum use of water resources can be achieved. However, in order to achieve this integrated operation, new methods and institutions must be devised to coordinate and manage the operation.

Saunders (1967) states that in order to assess the value of planned conjunctive use in relation to a particular area or basin, it is necessary to look at the economic, hydrologic, and legal system as a whole. A planning procedure is then presented to enable a planning agency to determine, at minimum cost, the feasibility of planned conjunctive use. The procedure consists of determining system characteristics and is discussed in terms of systems analysis and linear programming.

Tyson and Weber (1964) use a computer simulation approach to formulate a "most economical plan' for operating groundwater basins in conjunction with surface facilities. The computational procedure involves two phases: 1) development and verification of the model, and 2) use of the model in predicting basin behaviour under imposed conditions. An electronic differential analyzer, or analog computer, is used for the first phase and a digital computer is used in the second phase. In order to develop the mathematical model of the groundwater system, the groundwater complex is replaced by a simplified model divided into small polygonal zones. Assumptions used in deriving the model are that the aquifer is unconfined, that there is no vertical variation in aquifer properties, and that the aquifer thickness is small in comparison to its lateral dimensions. Flow in the aquifer is defined by a single linear equation derived by combining the continuity equation with the Darcy equation. The time dependent flow rate in the aquifer is the algebraic sum of the several extraction and replenishment flows.

For modelling on the analog computer the flow equation is transformed to an equivalent system of difference-differential equations. The system is solved simultaneously on the analog computer to give the groundwater level at the node points of the polygonal zones. However, the solution of a system of difference-differential equations on the analog computer is subject to inherent instability which is difficult to overcome.

Once the model on the analog computer is verified by comparing computed water levels with historical data, the equations are modelled on the digital computer for operational studies of the basin. Alternative schemes for operation of the basin are studied by successive iterations using different inputs for aquifer replenishment and with-drawals. The system is gradually improved by choosing the best alternative tried on the model. Simulation of this type provides great detail concerning system operation but does not necessarily provide the optimum alternative.

A common procedure for identifying the most economical and feasible plan for integrated operation of groundwater and surface water system has been to choose a number of alternative solutions or plans, which engineering and economic judgement indicate should be desirable, and compare the costs and benefits of the alternative. In this approach, 'most economical' is usually loosely defined as least cost, which may not be an appropriate measure of the best solution in all cases.

Chun, Mitchell, and Mido (1964) present an approach of this nature for studying the conjunctive operation of groundwater basins with surface supplies. Their approach is applied to a regional water supply system supplying the Los Angeles basin. In this study alternative plans were formulated representing use of the groundwater basin in coordination with surface facilities in order to meet imposed demands on the system. Each alternative plan which was studied was presented in terms of groundwater basin operation. Each alternative plan of operation was a combination of four decision variables:
1) the areal pattern of groundwater extractions, 2) the methods of prevention of sea-water intrusion, 3) a schedule of spreading artificial recharge water in given locations, and 4) the pumping schedule for fixed locations. The design is based on the use of existing facilities and on a limited number of possible recharging areas. From the vast number of alternatives, the relatively few having practical importance were selected in a preliminary examination. For each practical alternative, analyses were carried out separately for the subsurface and surface systems. The subsurface system was simulated on an analog computer in order to develop the mathematical model of the subsurface system. Operational studies of the subsurface system were then carried out on a digital computer. In the analysis of the surface system, future water demands in the region were taken into account. The most economical subsurface and surface facilities were selected on the basis of the operation studies. The final optimum alternative combination of subsurface and surface facilities was selected according to the criterion of minimizing the total annual costs. Economic comparisons of alternative plans of operation are made on the basis of

converting these annual costs into total present worth. The plan chosen as the most economical one is the alternative having the least total present worth. The authors state that, "Because all plans were formulated to satisfy identical physical requirements, the plan with the least total present worth has the greatest benefit cost ratio."

Despite the wide scope and detailed analysis characterizing this work, no modern techniques of mathematical programming for solving the problem of economical optimization were used. This approach is actually a "trial and error" approach. Some have classified the approach as a steepest descent method of cost minimization. The final result is supposed to be the most economic approach to the problem. However, there is no way of determining whether the final solution is the "lowest point of the bowl" or just a low point on the side of the bowl. In other words, the result may be a "local" minimum cost, but it is not necessarily the global optimum value. Also, a cost minimizing procedure is not necessarily the "most economical" approach nor the proper measure of objectives for all situations.

Renshaw (1963) presents the argument that decisions regarding the use of groundwater resources should be based on the value of the groundwater resource. The basis of the argument is that water left in storage has economic worth. The economic returns from water left in the ground can be estimated by two methods presented by the author. In the first method the returns are based on reduced pumping costs due to reduced mining of groundwater. The second method is based on the economic returns on the capitalized value of water left in storage. Renshaw's arguments emphasize the value of not pumping groundwater.

Koenig (1963) presents the opposite view regarding the economics of groundwater development and use. Koenig's thesis is that the attitudes and practices of groundwater development in the nation as a whole are far too conservative, and he recommends a much greater use of groundwater resources. Koenig argues that extractions from groundwater reserves should be viewed in the same manner as extractions from other resource reserves such as oil or coal or natural gas. Without consideration of any further replenishment of groundwater reserves, the life of the current reserve of groundwater is more than 18 times greater than the corresponding life of any other nonreplenishable resource with the exception of bituminous coal. According to Koenig, if the present rate of depletion of groundwater storage is continued, the reserve life would be 7800 years. Alternatives to local storages of groundwater are reducing the level of the economy in the local area or importing water to the water-short areas from areas of abundance. The conservative attitude toward groundwater development cannot be justified economically, according to Koenig.

Domenico, Anderson, and Case (1968) present a mathematical expression relating the economic worth of groundwater mining to the remaining worth of a basin after it has been partially depleted. This expression permits the establishment of an optimal, one-time storage reserve that may justifiably be exploited. In this argument, sustained yields are taken as use rates determined by and limited to natural replenishment, and mining yields are volumes of nonrenewable water in storage independent of the rate of mining. The volume of mining yield may be mined rapidly or slowly, but the volume extracted is limited. Maximization of present worth is taken as the conventional management objective. Optimality is determined by conventional calculus methods.

2.1 System Approach for Conjunctive Use

The problem of selecting the best strategy for conjunctive use of surface and groundwaters in a complex system where conflicting interests compete for limited natural and financial resources can be solved by system approach. Therefore, the system approach is being increasingly used to solve various problems associated with conjunctive use planning more so with the advent of digital computers. Basically the problems have been solved in two frameworks: optimization and simulation. The optimization techniques which have been extensively used are linear programming and dynamic programming. Linear programming is one of the methods which has been used by various research workers for solving the problem of allocating the surface water and groundwater resources among competing users in an optimal manner. The principles and techniques of solving linear programming problems are well described in the literature (Hadley, 1962, Dantzig, 1963 and Gass, 1969). Hadley describes the general linear programming problem as follows: given a set of m linear inequalities or equations in r variables, it is aimed to find non-negative values of these variables which will maximize some linear function of the variable while satisfying the linear constraints. Once a conjunctive use problem has been cast into standard linear programming form it can be solved by the Simplex method.

Roger and Smith (1970) have developed a conjunctive use model which is based upon linear programming. The groundwater system was considered as lumped. The model envisaged by Roger and Smith for conjunctive use of surface and groundwaters is shown in Fig.4. Linear programming though numerically very elegant, is rather restrictive in the sense that it assumes the objective function and the associated constraints to be linear functions of decision variables. This is only employed because of its computational ease rather than its capability to represent the real system. In the model given by Roger and Smith, the nonlinear part of the objective function relating to water table elevation has been linearized by assuming lift independent cost of pumping. This model has been applied by Chandra and

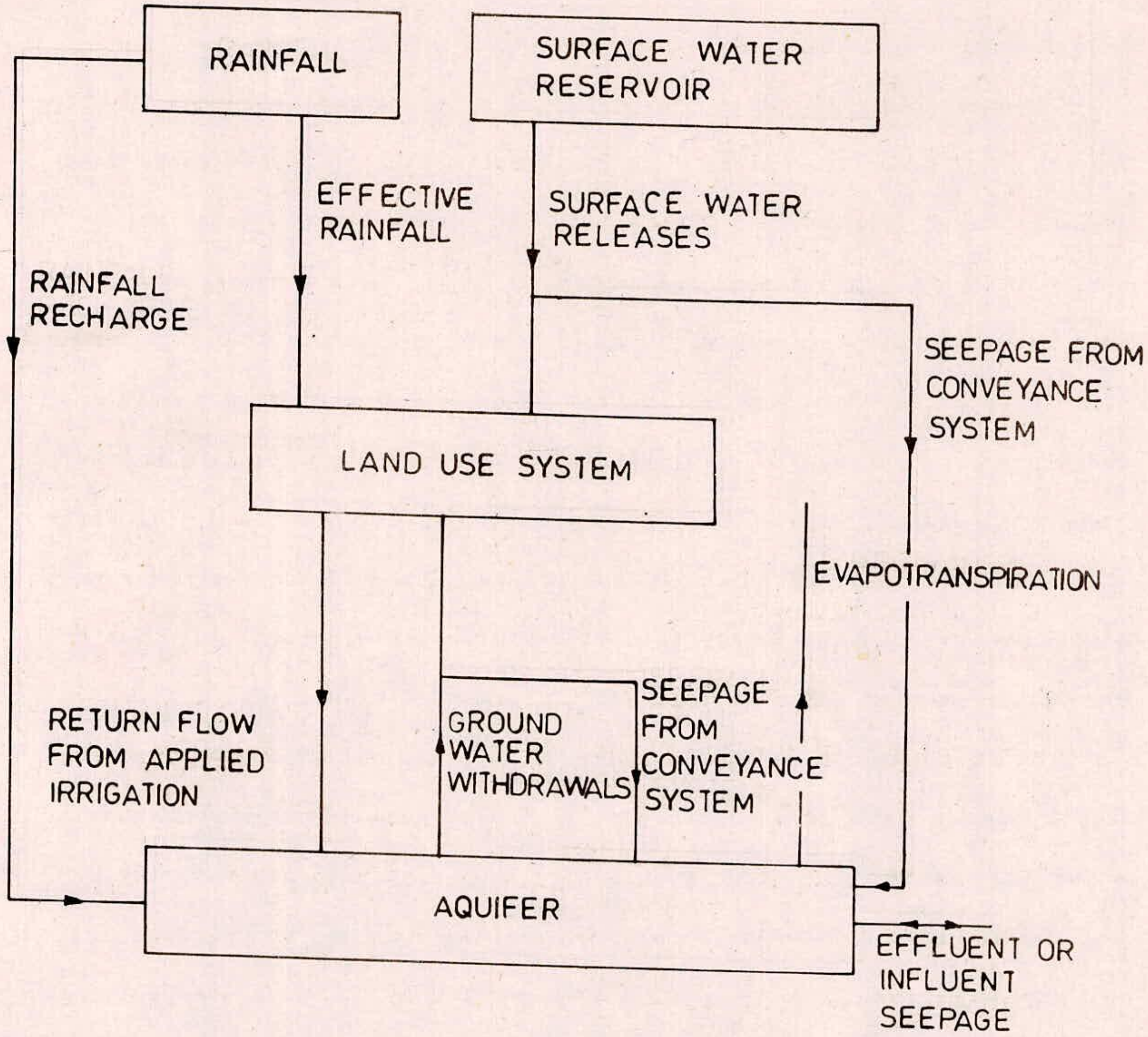

FIG.4 - CONJUNCTIVE USE OF SURFACE AND GROUND WATER

Pande (1975) for the study of conjunctive operation of surface and groundwater in the command area of upper Ganga Canal in U.P. The linear programming model has been used to get the optimal cropping pattern and schedule of releases for conjunctive operation after additional water supplies are available after the construction of Tehri Dam.

Dynamic programming is the most used optimization technique in water resources system. The Markovian and sequential nature of decisions that arise in water resource problems nicely fit into Bellman's principle of optimality on which dynamic programming is based. The dynamic programming is a mathematical procedure designed primarily to improve the computational efficiency of solving complex problems by decomposing them into smaller, and hence computationally simpler problems. Dynamic programming solves the problem in stages, with each stage involving exactly one optimizing variable. The computations at the different stages are linked through recursive computations in a manner that yields a feasible optimal solution to the entire problem when the last stage is reached (Taha, 1982).

Using dynamic programming, Buras (1963) has solved the conjunctive use problem. The system considered for investigation by him consisted of a surface reservoir of capacity Q and an aquifer of storage capacity G. The amount of water stored in the surface reservoir and underground aquifer at the beginning of i^{th} period were denoted by q_i and g_i respectively and during this period an inflow of amount y_i was assumed to enter in the surface reservoir. A recharge facility with an infiltration capacity of R units of water per season was also provided. During the i^{th} period, (x_i+r_i) amount of water was released from the surface reservoir out of which x_i was used for irrigation for adjoining agricultural area of A_s unit and remaining r_i unit was used for groundwater recharge. Besides an additional c_i units of water is recharged naturally as surface runoff and subsurface flow. The pumpage from the aquifer, π_i, was used to irrigate an agricultural area A_g. The aim of the formulation was to determine the size Q of surface reservoir, and the recharge works required for a recharge capacity R. It was also required to establish rules for water detention and release from surface and subsurface reservoirs. The basis for the development of water resources in the situation envisaged by Buras was maximization of the benefits derived from water supplied for irrigation and from prevention and attenuation of floods downstream from the two structures.

Buras adopted dynamic programming technique to optimize the operation of this system over N time periods. In the recurrence relationship, the returns obtained for any typical year were expressed by benefits obtained by releasing x units from surface reservoir and pumping out π units from aquifer added to the returns from the previous period. To compute net returns, capital investment for surface reservoir and recharge facility were deducted from the total benefits. A number of constraints were included to consider physical limitations such as non-exceedance of storages and continuity of mass.

Castle and Lindeborg (1961) define optimal allocation of water resources on the basis of maximizing beneficial use as determined by a linear programming model. Water is allocated from surface water and groundwater sources to two agricultural areas. A simplifying assumption is made regarding the production function for water that water users in the two agricultural areas would expand their inputs of other production factors in proportion to increases in the amounts of available water. This assumption allows the model to be formulated in the linear fashion required by the linear programming approach. Post-optimal analysis of the optimal solution is presented to indicate the stability of the solution to the allocation Problem.

3.0 STATEMENT OF THE PROBLEM

The Ghataprabha Project Authorities supply water for irrigating its command area for nearly 8 months in a year from later part of June to earlier part of February. This leaves a gap of four months when the surface water will not be available for irrigation. About 40 villages come under the Gokak canal irrigation which is the present study area. The continuous and uncontrolled supply of canal water has resulted in rising of the water table in the area. Water logging has tended increase in the salinity of the soil making the land unsuitable for cultivation. Therefore the main aim of the present study is to find the cropping pattern which can maximise the net yield while fully utilising all the available water potential of the area. The objective of the present study has been achieved using the linear programming approach.

3.1 Cropping Pattern Model

The cropping pattern model may be formulated to maximise the economic efficiency (i.e. annual net benefit) subject to resources and sociological constraints. The definition of cost and benefit depends on the context in which the model is framed. In a planning context, the benefit and the cost are to be computed as the national basis (social benefit cost) whereas the cost and benefit in a behavioural model may be in terms of the cost and benefit to individual farmers. The latter concept is used in formulating the following linear programming model:

$$\text{Max } Z = \sum_{i=1}^{m} A_i Y_i P_i - \sum_{i=1}^{m} A_i C_i - \sum_{i=1}^{m} \sum_{t=1}^{12} b_{it} A_i C_w \qquad (3.1)$$

subject to

$$\sum_{i=1}^{m} b_{it} A_i \leq WR_t \text{(for all } t=1,\ldots.12) \qquad (3.2)$$

$$\sum_{i=1}^{m} a_{it} A_i \leq A_t \text{ (for all } t=1,\ldots.12) \qquad (3.3)$$

$$A_i \geq 0 \quad i=1,2,\ldots.m \qquad (3.4)$$

where,

A_i = total area under i^{th} crop in hectares

P_i = selling price of i^{th} produce in Rupees/Quintal

C_i = cost of total input in Rupees/Hectare

b_{it} = water requirement of i^{th} crop in t^{th} season at saturation level (m)

C_w = unit cost of irrigation water in Rupees/Hectare metre

WR_t = available water for irrigation in the t^{th} season in Hectare metres

a_{it} = variable (0-1), equal to 1 if the i^{th} crop is grown in t^{th} season, zero otherwise

A_t = total area available for cultivation in t^{th} season in Hectares

Y_i = yield per hectare of i^{th} crop quital/ha

The subscripts are

i = stands for i^{th} crop

t = stands for t^{th} seasons

m = total number of crop activities

The model objective is to maximize net benefits from different crop activities. The benefit is computed as the value realised by selling the produce and the cost is computed as the cost of all inputs including water as paid by the farmer.

Equation (3.2) is a water constraint that the amount of irrigation water supplied in any season must be less than or equal to the amount of water available for irrigation in that season.

Equation (3.3) is the land availability constraint. It means the total area irrigated in any season must be less than or equal to the total available area for cropping in that season.

Implicit in the above formulation is the existence of production function of the form

$$Y_i = F(Q_1, Q_2, \ldots, Q_n) \tag{3.5}$$

where Y_i is the yield of i^{th} crop per unit area and $Q_1, Q_2, \ldots, Q_n$ are the resources including water that go into the production of the i^{th} crop. If all inputs are held at a constant level, the one dimensional production with reference to the water will be as shown in Figure (5), also shown in the figure are the definition of saturation depth of water and different levels of irrigation.

While all the variables and parameters used in the model are self explanatory, the b_{it} the water requirement of i^{th} crop in t^{th} season need some explanation. There are several methods available for computing crop water requirement. The method recommended by Ministry of Agriculture(1971) Government of India using pan evaporation and the crop coefficient is considered most suitable. The b_{it} is estimated as follows:

(i) The crop growing period, mid month, and maximum crop factor are used to calculate weighted monthly consumptive use coefficients on the basis of assumptions concerning the probable distribution of planting and harvesting over the respective periods.

(ii) These coefficients are multiplied by the class A pan evaporation figures for the region in question to give consumptive use in depth units.

(iii) Preplanting requirements are estimated and added to the appropriate months consumptive use. Similarly end of season soil moisture credit can also be estimated and deducted from the appropriate months consumptive use. (However the later part is usually neglected).

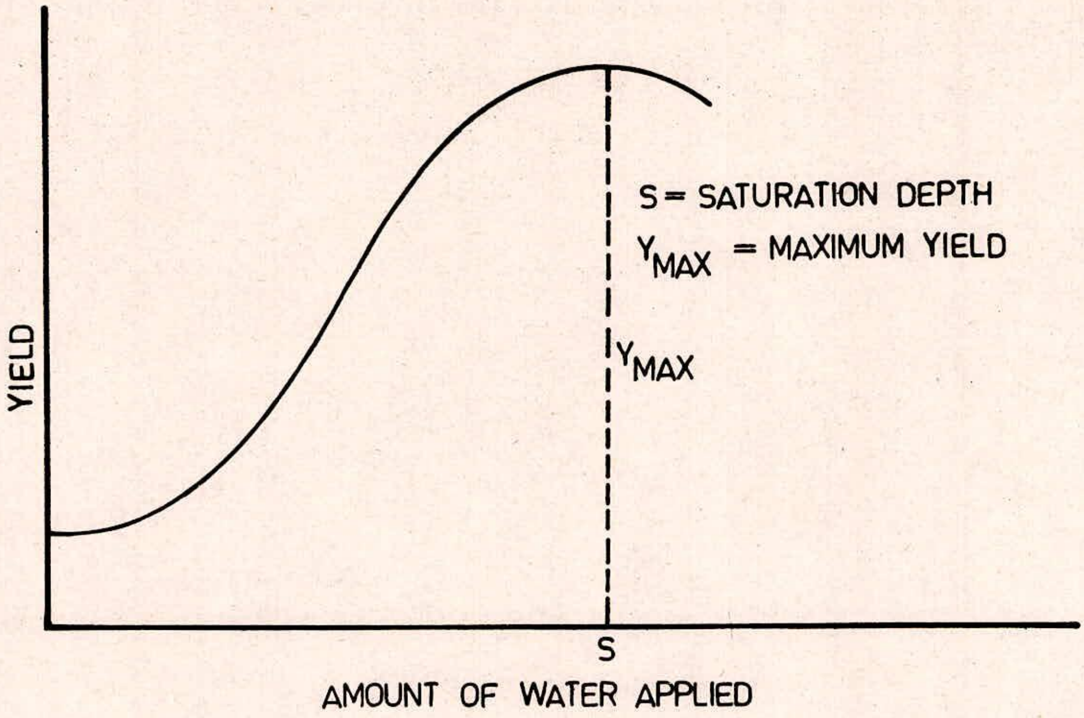

FIG.5 - PRODUCTION FUNCTION

(iv) If the resulting water requirement exceeds the effective rainfall, the net irrigation requirement is the difference between these two, otherwise it is equal to zero.

(v) The field irrigation requirement and the gross irrigation requirement are calculated by dividing the net irrigation requirement by field efficiency, and the field irrigation requirement by conveyance distribution efficiency respectively.

4.0 METHODOLOGY

The basic problem of water resources systems planning is the allocation of water from various sources to competing uses. Broadly speaking, mathematical programming problems deal with determining optimal allocations of limited resources to meet desired objectives. These problems are characterized by the large number of solutions which satisfy the basic conditions of each problem. The selection of a particular solution as the best solution depends on some overall objective implied in the statement of the problem. Thus the problem is a two-sided one concerned not only with the allocation of limited resources among those uses competing for them, but also with the influence that these allocations will exert upon the objective.

In this study the limited resources are the quantities of water available in the groundwater reservoirs and the local surface water. The surface water resource is to be managed optimally in conjunction with the groundwater resource to maximize the returns from irrigation.

4.1 Linear Programming

A linear programming problem differs from the general mathematical programming problem in that the mathematical model or description of the problem can be stated using relationships that are "straight-line" or linear. Mathematically these relationships are of the form

$$a_1x_1+a_2x_2 +...+a_jx_j+...+a_nx_n = b_1$$

where the a_j's are known coefficients, the b is the resource availablility, and the x_j's are decision variables. The complete mathematical statement of the linear programming problem includes a set of simultaneous linear equations which represent the conditions of the problem and a linear function which describes the objective of the problem. The mathematical statement of a general form of the linear programming problem is the following. Find $x_1, x_2, \ldots, x_n$ which maximize the linear objective function

$$Z = c_1x_1+c_2x_2+ \ldots +c_nx_n \qquad (4.1)$$

subject to the constraints,

$$\begin{aligned} &a_{11}x_1+a_{12}x_2+ \ldots +a_{1n}x_n \leq , = , \geq b_1 \\ &a_{21}x_1+a_{22}x_2+ \ldots +a_{2n}x_n \leq , = , \geq b_2 \qquad (4.2) \\ &\quad\vdots \\ &a_{m1}x_1+a_{m2}x_2+ \ldots +a_{mn}x_n \leq , = , \geq b_m \end{aligned}$$

and

$$x_1 \geq 0,\ x_2 \geq ,\ \ldots\ x_n \geq 0,$$

where the a_{ij}, b_i, and c_j are given constants. The x_j's are the decision variables. Written in matrix notation the problem statement becomes: Find X to maximize the objective function

$$Z = CX \qquad (4.3)$$

subject to the constraints

$$AX \{\leq , = , \geq \}B \qquad (4.4)$$

and

$$X \geq 0$$

where $A = a_{ij}$; $X = x_j$; $B = b_i$, and

$C = c_j$, and where

$j = 1,2, \ldots m,\ j = 1,2, \ldots n.$

In linear programming terminology any set of x_j's which satisfies the constraints is called a solution to the linear programming problem. A solution which also satisfies the non-negativity conditions is called a feasible solution. A feasible solution which optimizes the value of the objective function is called an optimal feasible solution (Hadley, 1962).

The linear constraints represent a set of hyperplanes dividing the space into a series of half spaces, the intersection of which forms a convex set. Only points in this set satisfy the constraints and become feasible solutions to the linear programming problem. The extreme points of this convex set of solutions are basic feasible solutions and if an optimal solution exists, at least one basic feasible solution will be optimal. If the optimal solution is not unique, points other than extreme points are also optimal.

All techniques actually used in obtaining an optimal solution to a linear programming problem are iterative. No method has been devised yet which will yield the optimal solution in a single step. The best known and most efficient method for solving linear programming problems is called the simplex method. This method is an algebraic iterative procedure or algorithm which will solve, exactly, any linear programming problem, properly formulated in a finite number of steps.

Briefly, the simplex algorithm can be described as a method which proceeds in systematic steps from an initial basic feasible solution to adjacent basic feasible solutions and finally in a finite number of steps to an optimal basic feasible solution. The value of the objective function at each step (iteration) is better (or at least not worse) than at the preceding step. Because the value of the objective function is improved (or at least not worsened) at each step, the number of iterations needed before an optimal solution is arrived at is, in general, small relative to the total number of existing basic solutions. In linear programming the basic feasible solutions are "corners" on the boundaries of the convex set. If there is an optimal solution, one of the extreme points is optimal. Thus in common terms, the simplex method involves moving along the edge of the region of feasible solutions from one corner to an adjacent one in such a manner that each step gives the maximum increase (or decrease) in the value of the objective function. At each corner the simplex method indicates whether the corner is optimal and if not which extreme point will be the next one examined in the iterative procedure.

If at any stage the simplex method comes to an extreme point which has an edge leading to infinity (unbounded convex set) and if the value of the objective function can be increased (or decreased)by moving along that line, an unbounded solution is indicated.

In formulating a linear programming problem for the simplex method of solution, slack variables are used to change the inequalities to equalities. Thus the problem is treated as a system of linear equations. The slack variables take on physical meaning in an applied problem, and their values represent the amount of the resource redundant to the optimal activities of the final solution.

4.2 Analysis of Data

Seven major crops have been identified for production sets on the basis of soil, climate, social requirements and the cropping pattern observed in the area. The existing cropping pattern in the area is 40% Kharif, 40% Rabi and 20% two seasonals. The weighted average intensity of irrigation is found to be 100 percent.

4.2.1 Hydrometeorological data

The hydrometeorological data that have been used in the present study have been supplied by the Karnataka State Irrigation Department. The mean monthly normal rainfall calculated using 66 years data (1921-1986) and the monthly average pan evaporation values are given in Table 4.1.

4.2.2 Calender of cultivation

The calender specifies the dates of planting the crops through its harvesting. The agricultural calender for the study area has been adopted from the existing agricultural practices. Table 4.2 gives the crop calender for the study area. Land use coefficients in the crop calender are mentioned monthwise. A land use coefficient of 1 against a crop in any month indicates

TABLE 4.1

MEAN MONTHLY NORMAL RAINFALL AND PAN EVAPORATION IN GHATAPRABHA SUB-BASIN

S.N.	Month	Normal Rainfall (mm)	Pan Evaporation (mm)
1.	January	0.80	148.80
2.	February	1.03	190.40
3.	March	3.88	279.00
4.	April	33.62	279.00
5.	May	59.80	266.60
6.	June	64.74	150.00
7.	July	72.55	121.00
8.	August	62.73	136.40
9.	September	102.83	162.00
10.	October	103.81	167.40
11.	November	31.15	129.00
12.	December	4.46	145.70
	Annual	543.40	2175.30

TABLE 4.2

CROP CALENDER FOR THE STUDY AREA

$$
\begin{array}{l|cccccccccc|}
 & A_1 & A_2 & A_3 & A_4 & A_5 & A_6 & A_7 & A_8 & A_9 & A_{10} \\
\hline
\textbf{Jan} & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\
\textbf{Feb} & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\
\textbf{Mar} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\
\textbf{Apr} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\
\textbf{May} & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\
\textbf{Jun} & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
\textbf{Jul} & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 \\
\textbf{Aug} & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 \\
\textbf{Sep} & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 \\
\textbf{Oct} & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\
\text{Nov} & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\
\textbf{Dec} & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\
\hline
\end{array}
\begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \\ A_7 \\ A_8 \\ A_9 \\ A_{10} \end{bmatrix}
\leq [A_T]
$$

A_1 = Paddy, A_2 = Groundnut

A_3 = Chillies, A_4 = Maize

A_5 = Wheat, A_6 = Cotton

A_7 = Sugarcane, A_8 = Moong

A_9 = Urad, A_{10} = Fodder

that the crop can be grown in that month and a zero indicates the possible occupancy of the land by the particular crop in that month.

4.2.3 Crop water requirement

This is calculated for each crop taking into consideration the crop calender. The method used for calculating the crop water requirement is that suggested by Ministry of Agriculture, Govt. of India (1971). There are seven major crops viz., Paddy, Groundnut, Chillies, Maize, Wheat, Cotton and Sugarcane which are grown in the area. Using the average pan evaporation and the normal monthly rainfall the consumptive use requirement for these 7 crops are calculated as follows:

Let

r_j = average rainfall in the j^{th} month in mm

p_j = pan evaporation in the j^{th} month in mm

K_{ij} = the crop coefficient of i^{th} crop in the j^{th} month

EP_{ij} = consumptive use or evapotranspiration in mm, = $p_j x K_{ij}$

R_{ij} = net water requirement in the j^{th} month for the i^{th} crop in mm.

The net water requirement R_{ij} in excess of effective rainfall for the i^{th} crop in j^{th} month can be written as

$$R_{ij} = EP_{ij} - e_{ij}$$

The crop coefficients given by the Ministry of Agriculture (1971) are used for calculating EP_{ij} (Table 4.3). The effective rainfall e_{ij}, is evaluated using the values prescribed by the Ministry of Agriculture (1971) as given in Table (4.4). The detailed calculations are shown in Table 4.5 through 4.11 and are summarised in Table 4.12.

TABLE 4.3

CONSUMPTIVE USE (EVAPO-TRANSPIRATION) COEFFICIENT K,TO BE MULTIPLIED BY ESTIMATED OR MEASURED CLASS A PAN EVAPORATION

%of crop growing season	wheat	maize	cotton	paddy	groundnut	sugar cane	chillies
0	0.30	0.40	0.22	1.00	0.30	0.34	0.22
5	0.40	0.42	0.22	1.02	0.30	0.37	0.22
10	0.51	0.47	0.23	1.03	0.32	0.40	0.23
15	0.62	0.54	0.24	1.05	0.35	0.44	0.24
20	0.73	0.63	0.26	1.07	0.40	0.50	0.26
25	0.84	0.75	0.35	1.09	0.49	0.60	0.35
30	0.92	0.85	0.58	1.11	0.60	0.72	0.58
35	0.96	0.96	0.80	1.13	0.69	0.86	0.80
40	1.10	1.04	0.95	1.16	0.78	0.93	0.95
45	1.10	1.07	1.03	1.18	0.85	0.98	1.03
50	1.00	1.09	1.08	1.20	0.90	1.02	1.08
55	0.91	1.10	1.08	1.21	0.94	1.05	1.08
60	0.80	1.11	1.07	1.22	0.96	1.07	1.07
65	0.65	1.10	1.05	1.22	0.95	1.10	1.05
70	0.51	1.07	1.00	1.21	0.94	1.13	1.00
75	0.40	1.04	0.93	1.19	0.91	1.16	0.93
80	0.30	1.00	0.85	1.16	0.86	1.19	0.85
85	0.20	0.97	0.73	1.10	0.79	1.20	0.73
90	0.12	0.89	0.62	1.03	0.72	1.20	0.62
95	0.10	0.81	0.50	0.96	0.64	1.19	0.50
100	0.10	0.70	0.40	0.86	0.55	1.19	0.40
Seasonal K	0.61	0.86	0.68	1.10	0.68	0.89	0.68

TABLE 4.4

NORMAL MONTHLY EFFECTIVE RAINFALL[1] AS RELATED TO NORMAL MONTHLY RAINFALL AND AVERAGE MONTHLY CONSUMPTIVE-USE.

MONTHLY NORMAL RAIN-FALL(rt) (mm).	AVERAGE MONTHLY CONSUMPTIVE USE IN MM.													
	25	50	75	100	125	150	175	200	225	250	275	300	325	350
	NORMAL MONTHLY EFFECTIVE RAINFALL (mm) re													
25	15	17	18	18	19	20	21	22	25	25	25	25	25	25
50	$\frac{25}{42}$	33	35	36	37	40	41	44	48	50	50	50	50	50
75		47	51	54	56	58	61	65	69	74	75	75	75	75
100		$\frac{50}{81}$	65	69	73	75	79	83	88	95	100	100	100	100
125			$\frac{75}{124}$	83	89	91	96	102	108	116	123	125	125	125
150				97	104	106	113	120	127	136	144	150	150	150
175				$\frac{100}{162}$	117	120	128	136	143	154	166	172	175	175
200					$\frac{125}{200}$	131	140	148	158	169	184	191	197	200
225						142	152	162	175	189	200	210	220	225
250						148	164	175	192	206	216	226	236	245
275						$\frac{150}{260}$	173	188	205	223	233	242	255	265
300							$\frac{175}{290}$	195	215	235	246	258	273	288
325								199	220	242	258	275	290	304
350								$\frac{200}{330}$	224	245	265	285	303	320
375									$\frac{225}{360}$	248	270	292	310	328
400										$\frac{250}{390}$	273	296	317	335
425											$\frac{275}{420}$	298	320	340
450												$\frac{300}{450}$	322	343
475													324	346
500													$\frac{325}{485}$	349
														$\frac{350}{520}$
525	25	50	75	100	125	150	175	200	225	250	275	300	325	

---

[1] Based on 75 millimeters net depth of application, for other net depths of application, multiply by the factors shown below.

Net Depth of Application.	25	38	50	63	75	100	125	150	175
Factor	0.77	0.86	0.93	0.99	1.00	1.02	1.04	1.06	1.07

TABLE 4.5

CALCULATION OF CROP WATER REQUIREMENT

Units:mm

Name of Crop: Paddy

Dates	Mid point	% Growing season	Pan evaporation E_p	K= E_t / E_p	C_u or E_t $=K.E_p$	Effective rainfall ($^*R_e$)	NIR $=C_u-R_e$	FIR $= \frac{NIk}{0.85}$	GIR $= \frac{FIR}{0.75}$
Jun 1-30	15	10	150.0	1.03	154.50	40	114.50	134.71	179.61
Jul 1-31	46	30	121.0	1.11	134.31	56	78.31	92.13	122.84
Aug 1-31	77	50	136.4	1.20	163.68	50	113.68	133.74	178.32
Sep 1-30	107	70	162.0	1.21	196.02	74	122.02	143.55	191.40
Oct 1-31	148	97	167.4	0.91	152.33	91	61.33	72.16	96.21

* 80% chances of rainfall occurrence and .75.mm net depth of application have been considered.
Crop growing period : ..153.. days

TABLE 4.6

CALCULATION OF CROP WATER REQUIREMENT

Name of Crop: Ground nut   Units:mm

Dates	Mid point	% Growing season	Pan evaporation E_p	K= E_t / E_p	C_u or E_t $=K.E_p$	Effective rainfall (*R_e)	NIR $=C_u - R_e$	FIR $= \frac{NIR}{0.85}$	GIR $= \frac{FIR}{0.75}$
Jun 15-30	8	6	150.0	0.30	45.0	33.0	12.0	14.00	18.80
Jul 1-31	31	25	121.0	0.49	59.3	49.0	10.3	12.10	16.16
Aug 1-31	62	51	136.4	0.90	122.8	46.6	76.2	89.65	119.53
Sept. 1-30	92	75	162.0	0.91	147.4	66.5	81.0	95.00	127.00
Oct 1-15	115	94	167.4	0.64	107.2	83.0	24.0	28.00	38.00

* 80% chances of rainfall occurrence and ..75..mm net depth of application have been considered.
Crop growing period: ..122. days

TABLE 4.7 CALCULATION OF CROP WATER REQUIREMENT

Name of Crop: Chillies

Units: mm

Dates	Mid point	% Growing season	Pan evaporation E_p	K= E_t / E_p	C_u or E_t $=K.E_p$	Effective rainfall (*R_e)	NIR $=C_u-R_e$	FIR $=\frac{NIR}{0.85}$	GIR $=\frac{FIR}{0.75}$
Jun 15-30	8	3	150.0	0.22	33	29.42	4.0	4.7	6.3
Jul 1-31	31	14	121.0	0.24	29	26.50	2.5	2.9	4.0
Aug 1-31	62	29	136.4	0.58	79	43.14	36.0	42	56.5
Sept 1-30	92	43	162.0	1.03	167	68.63	98.4	116	154.0
Oct 1-31	123	57	167.4	1.05	176	96.00	80.0	94	125.5
Nov 1-30	153	71	129.0	1.00	129	28.40	100.6	118	158.0
Dec 1-31	184	86	145.7	0.73	106	7.40	99.0	116	155.0
Jan 1-15	208	97	148.8	0.45	67	0.70	66.3	78	104.0

* 80% chances of rainfall occurrence and .75..mm net depth of application have been considered.
Crop growing period: ..215. days

TABLE 4.8

CALCULATION OF CROP WATER REQUIREMENT

Name of Crop: Maize

Units:mm

Dates	Mid point	% Growing season	Pan evaporation E_p	K= E_t / E_p	C_u or E_t $=K.E_p$	Effective rainfall ($*R_e$)	NIR $=C_u-R_e$	FIR $=\frac{NIR}{0.85}$	GIR $=\frac{FIR}{0.75}$
Oct 15-31	8	7	167.4	0.44	73.66	75.00	0	0	0
Nov 1-30	23	19	129.0	0.63	81.27	26.75	54.52	64.14	85.52
Dec 1-31	52	43	145.7	1.05	152.99	7.70	145.30	170.93	228.00
Jan 1-31	83	68	148.8	1.08	160.70	0.73	160.00	188.00	251.00
Feb 1-14	105	86	190.4	0.97	184.69	0.94	183.80	216.23	288.30

* 80% chances of rainfall occurrence and .75..mm net depth of application have been considered.
Crop growing period: .122.days

TABLE 4.9

CALCULATION OF CROP WATER REQUIREMENT

Units:mm

Name of Crop: Wheat

Dates	Mid point	% Growing season	Pan evaporation E_p	K= E_t / E_p	C_u or E_t $=K.E_p$	Effective rainfall ($^*R_e$)	NIR $=C_u-R_e$	FIR $=\frac{NIR}{0.85}$	GIR $=\frac{FIR}{0.75}$
Nov **1-30**	15	14	129.0	0.62	79.98	25.0	54.98	64.7	86.2
Dec 1-31	46	43	145.7	1.10	160.27	7.4	152.90	180.0	240.0
Jan 1-31	77	73	148.8	0.45	66.96	0.7	66.26	78.0	104.0
Feb 1-14	99	93	190.4	0.11	20.94	0.9	20.04	24.0	31.4

* 80% chances of rainfall occurrence and ..75.mm net depth of application have been considered.
Crop growing period: .106.. days

TABLE 4.10 CALCULATION OF CROP WATER REQUIREMENT

Name of Crop: Cotton

Units:mm

Dates	Mid point	% Growing season	Pan evaporation E_p	$K = E_t / E_p$	C_u or $E_t = K.E_p$	Effective rainfall (*R_e)	NIR $= C_u - R_e$	FIR $= \frac{NIR}{0.85}$	GIR $= \frac{FIR}{0.75}$
May 15-31	8	4	266.6	0.20	53.32	40	13.32	15.67	20.89
Jun 1-30	31	14	150.0	0.24	36.00	29	7.00	8.24	10.99
Jul 1-31	62	29	121.0	0.58	70.18	51	19.18	22.56	30.08
Aug 1-31	93	43	136.4	0.99	135.04	48	87.04	102.40	136.53
Sept 1-30	123	57	162.0	1.08	175.00	70	105.0	123.53	164.71
Oct 1-31	154	72	167.4	0.97	161.54	93	68.04	80.05	106.73
Nov 1-30	184	85	129.0	0.73	94.17	26	67.67	79.61	106.15
Dec 1-15	206	96	145.7	0.50	72.85	7	65.45	77.00	102.67

---

*80% chances of rainfall occurance and 75mm net depth of application have been considered.
Crop growing period: 215 days

TABLE 4.11

CALCULATION OF CROP WATER REQUIREMENT

Units:mm

Name of Crop: Sugar cane

Dates	Mid point	% Growing season	Pan evaporation E_p	K= $E_t = E_p$	C_u or E_t $=K.E_p$	Effective rainfall (*R_e)	NIR $=C_u - R_e$	FIR $= \frac{NIR}{0.85}$	GIR $= \frac{FIR}{0.75}$
Jan 1-31	199	55	148.8	1.05	156.24	0.70	155.54	183.0	244.0
Feb 1-28	228	62	190.4	1.08	205.63	0.90	204.70	241.0	321.0
Mar 1-31	258	70	279.0	1.13	315.27	7.80	307.40	362.0	482.0
Apr 1-30	289	79	279.0	1.18	329.22	37.55	291.40	343.0	457.0
May 1-31	319	87	266.6	1.20	319.92	62.60	257.30	303.0	404.0
Jun 1-30	350	96	150.0	1.19	178.50	40.00	138.50	163.0	213.7
Jul 1-31	15	4	121.0	0.35	42.35	37.70	4.65	550.0	733.3
Aug 1-31	46	12	136.4	0.42	57.29	41.50	15.79	18.6	24.8
Sept 1-30	77	21	162.0	0.51	82.62	59.80	22.82	26.8	35.8
Oct 1-31	107	29	167.4	0.72	120.53	88.80	31.73	37.7	50.0
Nov 1-30	137	37	129.0	0.89	114.81	27.50	87.30	103.0	137.0
Dec 1-31	168	46	145.7	0.98	142.79	7.50	135.80	159.0	212.0

*80% chances of rainfall occurrance and 75mm net depth of application have been considered.
Crop growing period: 365 days

TABLE 4.12

NET WATER REQUIREMENT OF CROPS (IN METERS)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Seasonal Total
Paddy	-	-	-	-	-	0.18	0.123	0.178	0.191	0.096	-	-	0.768
Groundnut	-	-	-	-	-	0.02	0.016	0.120	0.127	0.038	-	-	0.321
Chillies	0.104	-	-	-	-	0.006	0.004	0.057	0.154	0.126	0.158	0.158	0.764
Maize	0.251	0.288	-	-	-	-	-	-	-	0	0.086	0.228	0.853
Wheat	0.104	0.031	-	-	-	-	-	-	-	-	0.086	0.240	0.461
Cotton	-	-	-	-	0.021	0.011	0.031	0.137	0.165	0.107	0.106	0.103	0.681
Sugar Cane	0.244	0.321	0.482	0.457	0.404	0.217	0.007	0.025	0.036	0.050	0.137	0.212	2.592

1. Rabi crops: Maise, Wheat
   (June-Oct)
2. Kharif crops: Paddy, Groundnut
   (Oct-March)
3. Bi-seasonal crops: chillies, cotton
4. Annual crop: Sugar cane

4.2.4 Other inputs

For each crop standard inputs of labour and services have been defined. They range from land preparation and seeding through plant tending and application of chemical products (fertilizers and pesticides), to the harvest. The standard inputs per operation for each crop are assumed constant over the whole area under study.

Information on agricultural production costs typically comes in the form of estimates of total expenses per operation such as plowing, irrigation and fertilizer application. These estimates include cost of material, labour, draft animals and machinary services if any. The unit activity level for all crop activity is defined to be cultivation of one hectare and estimates of necessary inputs are taken in computing the net benefits per hectare of each cropping activity and these are shown in Tables 4.13 to 4.19 for the seven major crops. Table 4.20 provides a summary of the cost of cultivation, total income, net benefit, total water requirement per hectare-metre of water for the various crop options in the study area.

TABLE 4.13

Benefit Calculation of Crops/Ha-Crop-Rice

I. Cost of cultivation Rs/Ha

Input Breakup	Unit	Rate in Rs.	No.of units	Value in Rs.
1. Human labour	Day	6.00	102	612
2. Bullock labour	Day	20.00	20	400
3. Seeds	Kg.	1.5	30	45
4. Fertilizer				
a) Nitrogen N_2O	Kg.	2.0	150	300
b) Potassium KO	Kg.	0.9	60	54
c) Phosphorous P_2O	Kg.	0.8	40	32
d) F.Y.M.	Kg.			
5. Irrigation (FIR)				100
6. Nursery preparation				150
7. Special Operation		LS		100
8. Miscellaneous				
a) Rental value				
b) Plant Protection				
c) Overhead cost		LS		550
d) Implements				
Cost of cultivation				2343

II. Benefits/Ha	Qntl/ha	Rate Rs/Qntl	Amount
Main product	35	95.0	3325
By product	35	3.00	105
Gross Benefit/Ha			3430
Net benefit/Ha			1087

TABLE 4.14

Benefit Calculation of Crops/Ha-Crop-Groundnut

I. Cost of cultivation Rs/Ha

Input Breakup	Unit	Rate in Rs.	No.of units	Value in Rs.
1. Human labour	Day	6/-	100	600/-
2. Bullock labour	Day	20/-	20	400/-
3. Seeds	Rs.	2/-	120	240/-
4. **Fertilizer**				
a) Nitrogen N_2O	Kg.	2/-	100	200/-
b) Potassium KO				
c) Phosphorous P_2O				
d) F.Y.M.				
5. Irrigation (FIR)				60/-
6. Nursery preparation				100/-
7. Special Operation				
8. Miscellaneous				
a) Rentral value				
b) Plant Protection				550/-
c) Overhead cost				
d) Implements				
Cost of cultivation				2150/-

II. Benefits/Ha	Qntl/ha	Rate Rs/Qntl	Amount
Main product	12	230	2760
By product			
Gross Benefit/Ha			2760
Net benefit/Ha			610

TABLE 4.15

Benefit Calculation of Crops/Ha-Crop-Chillies

I. Cost of cultivation Rs/Ha

Input Breakup	Unit	Rate in Rs.	No.of units	Value in Rs.
1. Human labour	Day	6	57	345
2. Bullock labour	Day	20	5	100
3. Seeds	Kg.	2	50	100
4. Fertilizer		2	250	500
a) Nitrogen N_2O	Kg.			
b) Potassium KO	Kg.			
c) Phosphorous P_2O	Kg.			
d) F.Y.M.				100
5. Irrigation (FIR)				100
6. Nursery preparation				
7. Special Operation				
8. Miscellaneous				
a) Rentral value				
b) Plant Protection				
c) Overhead cost				
d) Implements				
Cost of cultivation				1,245

II. Benefits/Ha	Qntl/ha	Rate Rs/Qntl	Amount
Main product	15	1000	15,000
By product			
Gross Benefit/Ha			15,000
Net benefit/Ha			13,755

TABLE 4.16

Benefit Calculation of Crops/Ha-Crop-Maize

I. Cost of cultivation Rs/Ha

Input Breakup	Unit	Rate in Rs.	No.of units	Value in Rs.
1. Human labour	Day	6.00	93	558
2. Bullock labour	Day	20.00	30	600
3. Seeds	Kg.	1.50	30	45
4. Fertilizer				
a) Nitrogen N_2O	Kg.	2.00	60	120
b) Potassium KO	Kg.	0.90	30	27
c) Phosphorous P_2O	Kg.	0.80	20	16
d) F.Y.M.				
5. Irrigation (FIR)				
6. Nursery preparation				
7. Special Operation				
8. Miscellaneous				
a) Rentral value				
b) Plant Protection	LS			550
c) Overhead cost				
d) Implements				
Cost of cultivation				1976

II. Benefits/Ha	Qntl/ha	Rate Rs/Qntl	Amount
Main product	25	95	2375
By product			450
Gross Benefit/Ha			2825
Net benefit/Ha			849

TABLE 4.17

Benefit Calculation of Crops/Ha-Crop-Wheat

I. Cost of cultivation Rs/Ha

Input Breakup	Unit	Rate in Rs.	No.of units	Value in Rs.
1. Human labour	Day	5.00	125	625
2. Bullock labour	Day	20.00	45	900
3. Seeds	Kg.	2.00	80	160
4. Fertilizer				
a) Nitrogen N_2O		2.00	120	240
b) Potassium KO		0.9	60	54
c) Phosphorous P_2O		0.8	30	24
d) F.Y.M.				
5. Irrigation (FIR)		LS		100
6. Nursery preparation				
7. Special Operation				
8. Miscellaneous				
a) Rentral value				
b) Plant Protection		LS		550
c) Overhead cost				
d) Implements				
Cost of cultivation				2653

II. Benefits/Ha	Qntl/ha	Rate Rs/Qntl	Amount
Main product	35	115	4025
By product	35	0.6	21
Gross Benefit/Ha			4046
Net benefit/Ha			1393

TABLE 4.18

Benefit Calculation of Crops/Ha-Crop- Cotton

I. Cost of cultivation Rs/Ha

Input Breakup	Unit	Rate in Rs.	No.of units	Value in Rs.
1. Human labour	Day	6	57	345
2. Bullock labour	Day	20	5	100
3. Seeds	Kg.	2	50	100
4. Fertilizer		2	250	500
a) Nitrogen N_2O	Kg.			
b) Potassium KO	Kg.			
c) Phosphorous P_2O	Kg.			100
d) F.Y.M.				100
5. Irrigation (FIR)				
6. Nursery preparation				
7. Special Operation				
8. Miscellaneous				
a) Rental value				
b) Plant Protection				200
c) Overhead cost				
d) Implements				
Cost of cultivation				1445

II. Benefits/Ha	Qntl/ha	Rate Rs/Qntl	Amount
Main product	16	800	12,800
By product	5	100	500
Gross Benefit/Ha			13,300
Net benefit/Ha			11,855

TABLE 4.19

Benefit Calculation of Crops/Ha-Sugar cane

I. Cost of cultivation Rs/Ha

Input Breakup	Unit	Rate in Rs.	Crop(Ist year) No.of units	Value in Rs.	(2nd year)
1. Human labour	Day	6.00	300	1800	900
2. Bullock labour	Day	20.00	40	800	400
3. Seeds	Kg.	14.00	100	1400	
4. Fertilizer					
a) Nitrogen N_2O	Kg.	2.00	250	500	500
b) Potassium KO		0.9	80	72	72
c) Phosphorous P_2O	Kg.	0.8	400	320	320
d) F.Y.M.					
5. Irrigation (FIR)				200	200
6. Nursery preparation				400	400
7. Special Operation				600	600
8. Miscellaneous					
a) Rentral value					
b) Plant Protection		LS		550	550
c) Overhead cost					
d) Implements					
Cost of cultivation				6642	3942

II. Benefits/Ha	Qntl/ha	Rate Rs/Qntl	Amount	Qntl ha	Rate Rs/ha	Amount
Main product	400	20	8000			8000
By product			175			
Gross Benefit/Ha			8175			8000
Net benefit/Ha			1533			4058

Ist crop benefit = 1533
2nd crop benefit = 4058
Total benefit for two years = 5591

Average benefit = 2795/ha/year
Say 2800/-

TABLE 4.20

NET BENEFIT AND BENEFIT PER UNIT OF WATER FOR VARIOUS CROPS

S.No.	Name of Crop	Cost of cultivation (Rs/ha)	Total income (Rs/ha)	Net-benefit (Rs/ha)	Water req. per hectare (m)	Net benefit in Rs per Ha.m of water
1.	Paddy	2343	3430	1087	0.768	1,415
2.	Wheat	2653	4046	1393	0.461	3,022
3.	Sugar cane	5947	8175	2800	2.592	1,080
4.	Maize	1976	2825	849	0.853	995
5.	Ground nut	2150	2760	610	0.321	1,900
6.	Chillies	1245	15,000	13,755	0.764	18,004
7.	Cotton	1445	13,300	11,855	0.681	17,408

+ In calculating net income from Sugar cane 2 years net benefit is averaged, limiting the cost of labour and animal to 50% and cost of seed to be zero for the second year.

5.0 RESULTS AND DISCUSSIONS

Linear programming model has been formulated to allocate the optimal areas to different crops so that net benefits from the system are maximized. The optimized cropping pattern should satisfy the social needs, self sufficiency in food grain production and marketability of the produce. The physical constraints used in the model are for the availability of surface and groundwater in each month, land resources, and water requirements of the crops. The LP problem was solved on VAX 11/780 computer at National Institute of Hydrology. The results are discussed below:

First Trial

In this trial no constraints are put on any crop. The benefit are optimized for the physical constraints of available water and land. The results of this trial show that only two crops viz. Chillies and Cotton are entered in the solution. The net return is Rs.11.7 crore with cropping intensity of 69%. The surface water resources are not fully utilized in all the months except during the months of September, November and December. Groundwater is not used because these two crops are not grown during March to May when groundwater is scheduled to be used. This cropping pattern of growing only Chillies and Cotton is unacceptable as it does not satisfy the social needs, self sufficiency in food grains,marketability of the produce and soil characteristics in the area.

Second Trial

On small farm holdings, it is natural for the farmers to try to produce their consuption requirements on their farms. Therefore attempt has been made to establish the minimum needs of various crops based on the present level of consumption in this study area. These crop constraints have been included in this run and the benefits are optimized for the physical constraints of available water and land. The results of this trial are shown in Table 5.1. From the table it is observed that the surface and groundwaters are not fully utilized in all the months except during the months of February and June. Because of the scarcity of water availability during February and June the intensity of cropping is restricted to only 77%. It is also physically not possible to increase the surface water supply during February and June as the reservoir level during these months is very low. Therefore to utilize the remaining land and water resources three more additional crops viz., Moong, Urad and Fodder have been planned to be included in the third run.

Third Trial

In this trial total ten crops have been entered with their constraints and the benefits are optimized for the physical constraints of available land and water. The results of this run are shown in Table 5.2. It is observed that the net benefits are increased by about 0.44 crore as compared to the second trial where only seven crops were entered in the solution. Further there is an increased use of surface and groundwater in all the months. The annual crop intensity in this run is 110 percent while it was only 77 percent in the second run. The crop intensity can't be increased beyond 110 percent as there is 100 percent utilization of surface and groundwater during February, April and June months. Therefore the cropping pattern of this run can be adopted for growing in the area as it meets the socio-economic requirements of the population in the study area while maximizing the anuual net returns.

TABLE 5.1

COMPUTER RESULTS OF SECOND RUN

S.No.	Crop	Optimal area allocation (Ha)	% CGA	Water Utility		
				Month	Surface water %	Ground-water %
1.	Paddy	2760	22	Jan	56	-
2.	Groundnut	1300	10	Feb	100	-
3.	Chillies	650	5	Mar	-	19
4.	Maize	1371	10.5	Apr	-	18
5.	Wheat	1950	15	May	-	18
6.	Cotton	1300	10	Jun	100	-
7.	Sugarcane	650	5	Jul	30	-
				Aug	64	-
				Sep	78	-
				Oct	42	-
				Nov	46	-
				Dec	84	-

Net return = 3.14 crores (rupees)

Cropping intensity = 77.5% (annual)

TABLE 5.2

COMPUTER RESULTS OF THIRD RUN

S.No.	Crop	Optimal area allocation (Ha)	% CCA	Water Utility		
				Month	Surface water %	Ground-water %
1.	Paddy	2760	22	Jan	56	-
2.	Groundnut	1300	10	Feb	100	-
3.	Chillies	650	5	Mar	-	70
4.	Maize	1371	10.5	Apr	-	100
5.	Wheat	1950	15	May	-	66
6.	Cotton	1300	10	Jun	100	-
7.	Sugarcane	650	5	Jul	31	-
8.	Moong	1000	7.5	Aug	68	-
9.	Urad	1000	7.5	Sep	82	-
10.	Fodder	2329	18	Oct	48	-
				Nov	46	-
				Dec	84	-

Net return = 3.5 crores (rupees)

Cropping intensity = 110.5% (annual)

6.0 CONCLUSIONS

The crop planning for a particular region depend not only on the availability of water, but also, upon socio-economic factors, internal consumption needs, besides soil characteristics, topography, climatic conditions, marketability of produce etc. Planning the conjunctive use of surface and groundwaters calls for greater ingenuity so as to exploit the total available water resources to best advantage. In the present study the groundwater and surface water potentials are estimated to be 4404 and 10,784 ha.m respectively. The cultivable command area is 13,000 ha. The groundwater is utilized only during the summer months (March-May) when the canal water is not supplied. Using these physical constraints an optimal cropping pattern has been achieved. Ten crops are recommended for growing. The groundwater potential is used to a maximum possible extent and the surface potential has not been fully harnessed in each month due to other constraints. The annual cropping intensity is 110 percent and the net annual return is 3.5 crore rupees. The net return with the existing cropping pattern work out to be about 1.7 crore rupees. With the recommended cropping pattern the net return is doubled and cropping intensity is increased.

7.0 RECOMMENDATIONS

The cropping pattern as seen in the third and final run can be recommended for growing in the area which will maximize the net return and at the same time meets the socio-economic needs of the population in the area. To use the remaining water resources the cropping intensity should have to be increased beyond 110 percent. This requires that the groundwater should have to be pumped to augment the surface water during each month. To achieve this objective the LP model has to be reformulated and run using more refined and extensive data. The present study has been conducted with the help of the available data. It would be possible to evaluate the various water balance components to greater accuracy and refine the model if more detailed information in respect of seepage from canals, irrigation efficiency measurements of the fields, infiltration test data, meteorological data, field measurement of evapotranspiration, runoff, stages of rivers in the area, hydrogeological data, well lithologs, specific yield, water level fluctuations, and other parameters of the water table aquifer are available.

Novertheless, it is hoped that the recommended crop planning using the present distribution of surface and groundwaters would help planners and administrators for optimum development of the area and encourage to extend such studies to include the entire command area.

ACKNOWLEDGEMENTS

The authors are grateful to Dr.G.C.Mishra, Scientist F for his useful suggestions and discussion during the formulation and implementation of the linear programming model. The co-operation and help extended by the Department of Irrigation, Government of Karnataka, for collection of relevant data for the study has been sincerely acknowledged. Thanks are also due to the Department of Mines and Geology, Belgaum branch and National Water Development Agency, Belgaum circle for their useful suggestions and discussions.

REFERENCES

Banks, H.O.(1953), Utilization of underground storage reservoirs. Transactions , ASCE 118:220-234.

Buras, Nathan (1963), Conjucntive operation of dams and aquifers. Journal of the Hydraulics Division, ASCE. Vol.89, No.HY6, proc. paper 3697.

Clendenen, F.B. (1954), A comprehensive plan for the conjunctive utilization of a surface reservoir with underground storage for basin-wide water supply development. Solano Project, California. D.Eng. Thesis, University of California, Berkeley, California. 160p.

Chun, R.Y.D., Lewis R.Mitchell, and Kiyashi W. Mido.(1964), Groundwater management for the nation's future-optimum conjunctive operation of groundwater basins. Journal of the Hydraulics Division, ASCE. Vol.90, No.HY4, Proc.Paper 3965.

Castle, E.N., and K.H.Lindeborg. (1961), Economics of groundwater allocation. Agricultural Experiment Station Miscellaneous Paper 108. Oregon State University, Corvallis, Oregon.

Chandra, S., and P.K.Pande. (1975), Recharge Studies for a basin using mathematical model. Proc. Second World Congress IWRA, New Delhi.

Dantzig, G.B. (1963), Linear programming and extension, Princeton University Press.

Domenico, P.A., D.V. Anderson, and C.M. Case. (1968), Optimal groundwater mining. Water Resources Research 4(2):247-255.

Fowler, L.C. (1964), Groundwater management for the nation's future - groundwater basin operation. Journal of the Hydraulics Division, ASCE. Vol.90, No.HY4, Proc. Paper 3985.

Gass, Saul I.(1964), Linear programming. McGraw-Hill Book Company, Inc., New York. 280p.

Govinda Goudar, B.H. (1972), Groundwater resources of Gokak Taluk, Belgaum District. Groundwater studies, Dept.of Mines and Geology, Govt. of Karnataka, Bangalore, Report No.70.

Hadley, G.(1962), Linear programming. Addison-Wesley publishing company, Inc., Reading, Massachusetts. 520p.

Hillier, Frederick S., and Gorald J. Lieberman. (1967), Introduction to operations research. Holden-Day, Inc., San Francisco, California. 639p.

Irrigation Commission, (1972), Report. Ministry of Irrigation and power. New Delhi Vol.I and II.

Khosla, A.N. (1949), Appraisal of water resources: analysis and utilization data. Proc. the U.N. Scientific Conference on Conservation and Utilization of Resources, Lake Success, New York.

Kazmann, R.G. (1951), The role of aquifers in water supply. Transactions, AGU 32(2): 227-230.

Koenig, L. (1963), Economics of groundwater utilization. American Water Works Association Journal 55(1):59-66.

Ministry of Agriculture., (1971), A guide for estimating irrigation water requirement. Department of agriculture, water management division, New Delhi.

Macksoud, S.W. (1961), Dynamic project planning through integrating multistage groundwater development and controlled irrigation water uses. D. Eng. Thesis, University of California, Davis, California.

National Water Development Agency. (1986), Preliminary Water Balance Study of Ghataprabha sub-basin of Krishna basin. Technical Study No.17. New Delhi.

Roger, P. and Smith, D.V.(1970), An algorithm for planning irrigation projects. Bulletin of ICID., Jan. 1970.

Renshaw, E.F. (1963), The management of groundwater reservoirs. Journal of Farm Economics 45(2):285-295.

Saunders, Barry C. (1967), A procedure for determining the feasibility of planned conjucntive use of surface and groundwater. Utah University, Logan, Utah. 78p.

Tyson, H.N., and E.M. Weber. (1964), Computer simulation of groundwater basins. Journal of the Hydraulics Division, ASCE. Vol.90, No.HY4, Proc. Paper 3973.

Thomas, R.O. (1957), Groundwater development-a symposium. Transactions, ASCE 122:422-442.