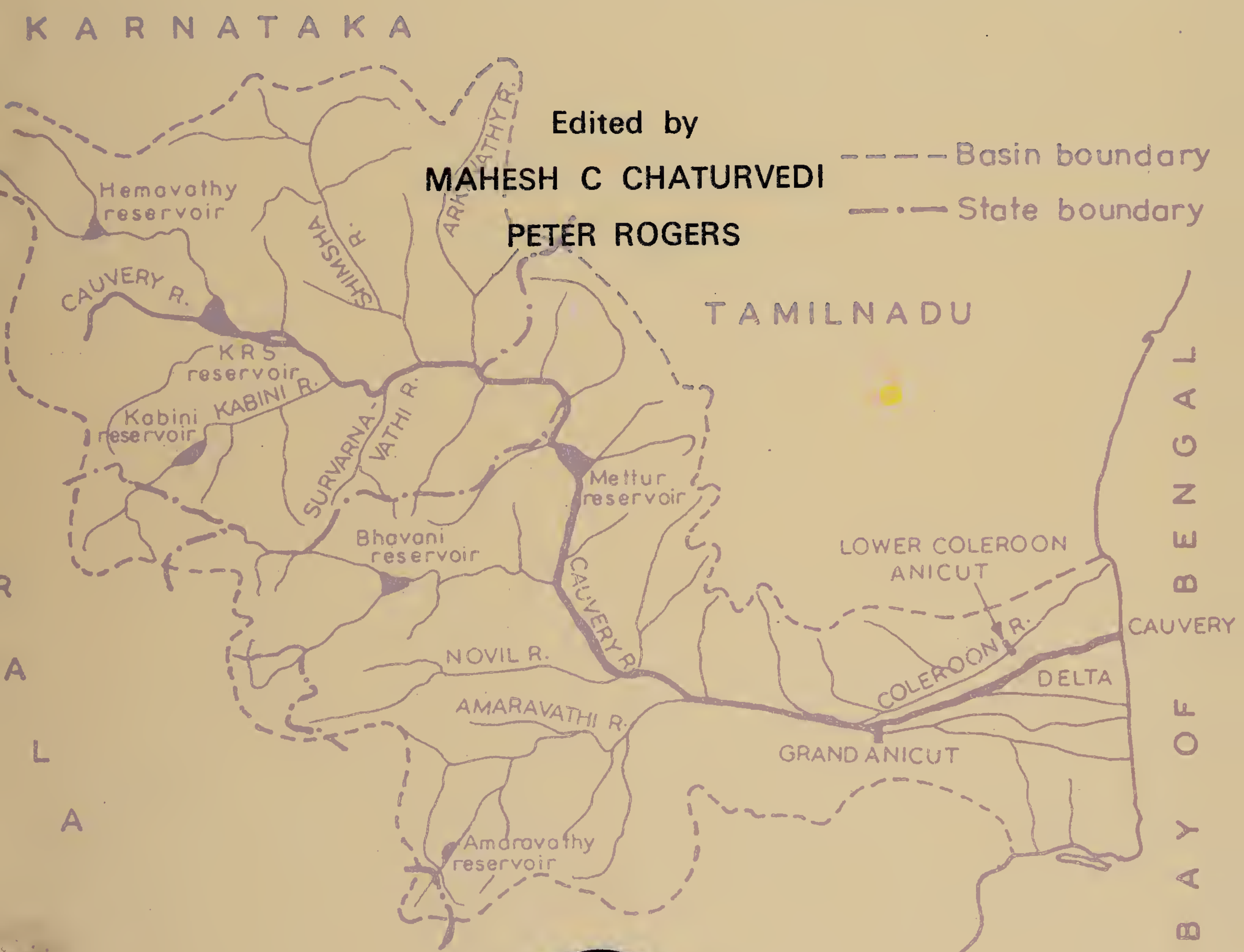
WATER RESOURCES SYSTEMS PLANNING

Some Case Studies for India



Edited by
MAHESH C CHATURVEDI
PETER ROGERS

INDIAN ACADEMY OF SCIENCES
Bangalore 560 080

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MAHESH C CHATURVEDI
Indian Institute of Technology, New Delhi

PETER ROGERS
Harvard University, U.S.A.

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The cover shows the plan of the Cauvery basin, from the paper by S. Vedula

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Foreword

Development of natural resources is, in many countries, a prerequisite for economic development. Two of these natural resources—land and water—play a key role in the earlier stages of development in view of the primacy of the agricultural sector in the overall economy. The development of water resources is particularly important in India in view of its arid-monsoon climate. This fact has been realized since time immemorial. Since Independence great emphasis has been laid on water resources development with almost 25 % of the current development budget being invested in this sector.

Ambitious plans have been drawn up by Government for rapid development of water resources within the next 25 years. The first step in achieving this task is Institutional modernization and development of well trained cadres of professionals who have the appropriate concepts, attitudes and capabilities. With the development of a systems approach to water management, it is now considered mandatory that modern development should be planned on these lines.

Realizing these needs, the Ford Foundation has been supporting the development of man-power in this sector. In view of the pioneering work done at Harvard University in this area, a programme was started there and Indian faculty and senior officials were invited to work with the Harvard faculty. We believe that the work done under that project should be made available and widely disseminated as this would be helpful in the ongoing efforts of development of manpower in systems planning. Hence this volume.

The importance of systems planning has also been emphasized independently by the Government of India. It was decided as far back as 1968 that a systems study of Ganga basin be undertaken. The decision was taken by the then Union Minister of Irrigation, Dr K L Rao, and a preliminary study of the Ganga basin was completed by one of the authors (Chaturvedi). In this context a short term programme of three months was organized at the Indian Institute of Technology (IIT)-Delhi with the support of the Ministry of Irrigation in March 1972, to train prospective engineering officers for the Ganga basin studies.

Efforts have continued since then to train personnel in the systems approach of water resources development. In the fourth five-year plan it was decided that the systems study of two river basins be carried out so that capability in the studies in this area could be developed. The Indian author was invited to carry out these studies in systems planning for the state of Punjab and for a project in Maharashtra under the auspices of the Planning Commission and the respective states. This effort was also supported by the Ford Foundation. Some of the relevant studies carried out by the Indian author independently of the Harvard-Ford Foundation programme have also been accordingly included in the volume.

The authors realize the shortcomings of the volume. It does not represent a single coordinated or integrated study to illustrate the application of systems approach to one river basin, but in totality several aspects of regional water resources development have been covered and we consider that it will be useful in the task of human

resources development required for the challenges facing India. We also believe that these studies will be helpful for other countries, both in the developing and the developed part of the world, and will also contribute to the art and science of large scale engineering-economic systems planning.

The work is essentially a collaborative activity of all the participants whose studies have been reported in the various papers. The work became possible only through the support of the Ford Foundation which is gratefully acknowledged. The support of the officers of the Ford Foundation, particularly Dr Sadik Toksaz and Dr Roberto R Lenton, who have been directly responsible for the project not only as Ford Foundation Administrators, but also as distinguished systems analysts is also gratefully acknowledged.

The work was carried out at Harvard in the Centre for Population Studies. Prof Roger Revelle, then Director of the Centre for Population Studies was an enthusiastic supporter and collaborator and thanks are specially due to him. Thanks are also due to other Harvard faculty who were involved in the programme. Some of the faculty who deserve special mention are Professors Joseph J Harrington, Myron Fiering, Harold Thomas Jr, Drs James Gavan, Richard Tabors and Samuel Liberman. Thanks are also due to the many undergraduate and graduate students who worked as research assistants and many of whom have moved on to distinguished careers in the area of resources management. Dr John Brisco was particularly helpful in this category Thanks are also due to the secretaries who provided office support so necessary for the completion of such a project, particularly Ms. Elizabeth Gibson and Ms. Kathie Macagy.

On the Indian side, the Indian Institute of Technology, Delhi has been generously supporting the work of the Indian author in this area. The work of two of his graduate students, Dr V K Srivastava and Dr D K Srivastava has also been reported and thanks are due to them for this collaboration. Thanks are also due to Mr B N Asthana, Executive Engineer, Irrigation Department, UP, currently leading the group working on the UP-Ford Foundation Project for helping the Indian author in the editing of these studies. Without his help these studies could not have seen the light of the day.

While we express our thanks to the people and institutions mentioned above we wish to make it absolutely clear that the views expressed in these papers are solely those of the authors and do not necessarily reflect the views of any of the people or institutions who supported our research.

MAHESH C CHATURVEDI
PETER ROGERS

Introduction

MAHESH C CHATURVEDI* and PETER ROGERS†

* Applied Mechanics Department, Indian Institute of Technology, New Delhi 110 016, India

† Department of Environmental Engineering, Pierce Hall, Harvard University, 121, Cambridge, MA 02138, USA

1. Background

Water, though a crucial component of the physical environment, is generally not available as and when required, and attempts have been made since time immemorial to make it available for man's varied use. Indeed, in view of the importance of water, its development has occupied a leading place in any society's efforts. The ancient civilizations of Egypt, Mesopotamia, India and China, show that making water available for domestic use, harnessing it for irrigation and controlling it for flood protection against floods were basic preoccupatons in these societies. Interestingly, the history of science and technology for quite some time was the history of mechanics, hydraulics and water resources development (Rouse & Ince 1957). Continued emphasis has been laid on this area, and in modern times, many impressive technological achievements have become possible.

Water development in India has occupied the highest importance in view of the arid monsoon climate and agrarian economy. There is evidence of canals, dams and dugwells from prehistoric times. Large canals were being constructed as early as 16 A.D. Many canals with a capacity of the order of 300 cumecs were constructed as far back as the middle of the 19th century. These developments attracted the attention of scientists from the United States, and engineers from US Bureau of Reclamation visited these works for guidance in their later works (Maddock T III 1977 personal communication). The Indian irrigation systems were one of the technological wonders of the world and, indeed, still are.

As increasing technological capability is developed, it is becoming clear to perceptive thinkers that technological activity, unless carefully planned can become a source of societal and environmental damage. Techno-economic-environmental-social interaction is extremely complex, but what is crucial is that technology be developed creatively and critically. Recent developments in several areas such as operations research, welfare economics and computer science and technology have led to the development of the new art and science of systems analysis to aid scientific technological planning. Concern with the scientific development of technology, increasingly careful analysis of its economic-social consequences and emphasis on the environmental-ecological implications of technological activity have become the leading concerns of post-industrial society.

As water is a crucial component of the resource-environmental vector, systems analysis has found extensive application in water resources planning. The origin of the activity may be said to be in the late 1950s in the United States, when the US Bureau of the Budget (now Office of Management and Budget, OMB) asked the major US governmental agency dealing with water projects, the US Army Corps of Engineers, to provide better estimates of the social and economic consequences of the water projects presented to the Budget Office for funding. In order to carry out this charge, the Corps of Engineers approached various academic institutions for help. One such group of engineers, economists and political scientists was at Harvard University. Pioneering work was done by this group and is reported in Maass *et al* (1962). Since then, the importance of systems planning has been increasingly recognized and continuous advances are being made. Systems planning of the Ganga Basin was proposed to be taken up by the Government of India at IIT Delhi in 1968, but the international dispute of the Ganga river led to the shelving of the proposal. In the Fourth Five Year Plan (1969–74) systems planning of water resources was stipulated to be required for future developments. Systems planning of Punjab was accordingly carried out by the Indian author.

In 1972 the Ford Foundation, New Delhi, approached the Harvard University to explore a collaborative venture in which the Harvard faculty would work with practising Indian academics and professionals in the field of Water Resources Planning to pursue the applicability of these new approaches to the Indian situation. The Indian author was particularly invited by the Harvard group to collaborate on this project. The papers contained in this volume are one result of this programme. Since 1973, several Indian academics, government employees and private consultants have participated in the programme. The participants in the programme worked alone or in groups on various projects, some of which are outlined here. Simultaneously, certain other studies have been carried out at IIT Delhi, and Harvard, some of which are also included. Basically, we believe that these new techniques are of substantial interest and use in the Indian context, and may contribute to this field in general.

2. Systems analysis: some general observations

Systems analysis embraces a body of concepts, approaches and mathematical techniques, aimed at assisting in the scientific and creative development of technology. Technological planning, basically, is a complex decision process, involving development of the optimal scheme for the transformation of environment, resources, energy, and information according to a society's or an individual's needs. The transformation has to satisfy two considerations. First, the physical laws must be satisfied. This gives the technological transformation or the production function. Second, the technological transformation has to be evaluated in the context of a set of interrelated evaluation criteria which may be classified as environmental, economic, political and social. Both these tasks have to be carried out in an integrated and hierarchical fashion. Technological planning is a very complex creative activity. Many of the issues or objectives are non-quantifiable. There are no set answers, and infinite alternatives or novel approaches are possible. The systems approach is an aid, typically using mathematical modelling, to examine the various issues over a wide and yet manageable range in a systematic manner. The models can be considered as 'thought experiments'. Systems planning is only an aid to and not a substitute for sound judgement.

Systems planning is particularly important for water resources, because of the complex interlinkages and socio-economic interactions involved. Water resources development transforms the spatial and temporal availability of waer, through a number of specific technological activities or projects, which are interrelated by hydrologic continuity and other technological interlinkages. For their optimal specification, capacity and location, and the operating policy, these technological interlinkages must be taken into account. Similarly, the complex socio-economic evaluation of the system and correspondingly of each project has to be carried out integrally. The complexity of the socio-economic interlinkages may be seen in the issues shown schematically in figure 1.

Another important aspect is the dynamic nature of the problem. Not only is the resource availability time-dependent but the demand changes as population grows and socio-economic development takes place. Since water resources development involves irreversible physiographic changes with associated socio-economic and environmental commitments, a long-term integrated view, despite all the difficulties and limitations, is essential.

The issues to be examined for water resources systems planning will depend upon the specific problem, but in general the following analysis will give an idea of the tasks to be carried out and the sequence of activities. Since technological planning relates to the transformation of resources according to societal demands constrained by availability, the issues may be studied under three headings: (i) water availability, (ii) water demand, (iii) techno-economic planning. The study of water availability requires

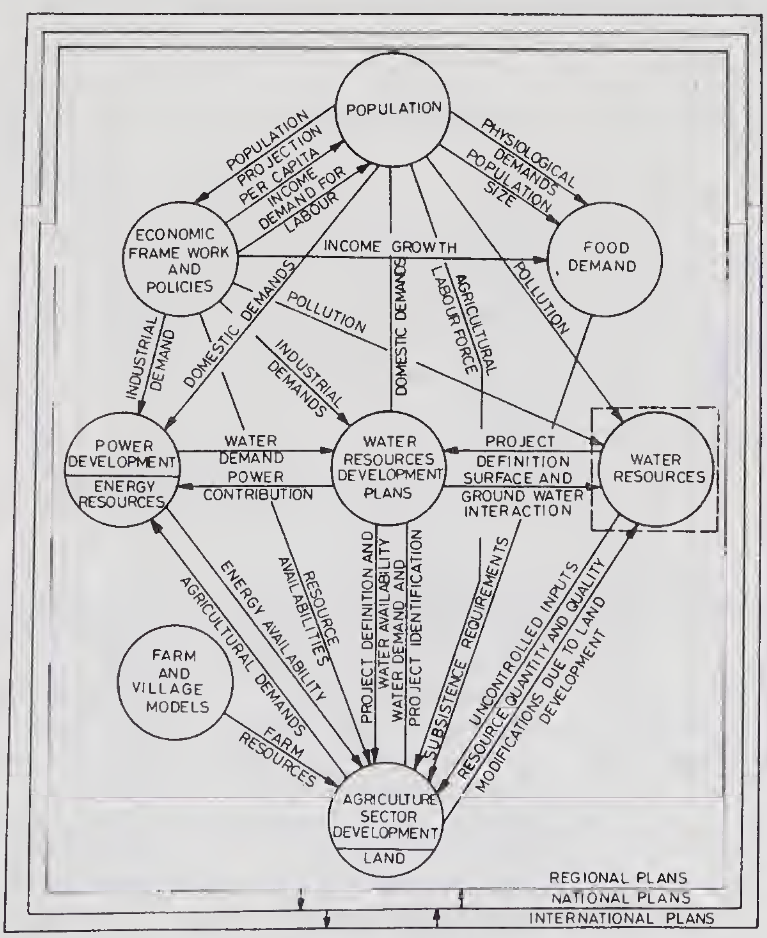


Figure 1. Resource and policies interactions in water resources development

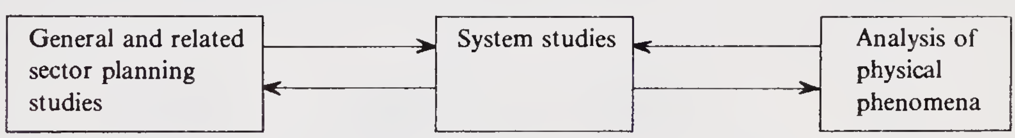
sophisticated analysis of physical phenomena. The demand analysis similarly requires refined engineering-economic analysis, such as developmental strategies, resources availability and social evaluation of key resources, loss function and risk criteria, and project selection criteria. Techno-economic systems studies start by assessing supply and demand and then developing policies of optimal allocation of water resources over planning regions leading to optimal development. It is a hierarchial-iterative activity, which has to be carried out creatively on the basis of judgement with the help of models depicting a large number of complex issues involving physical processes, environmental-economic-social evaluation and analysis of technological activity.

Some of the issues under the above three headings and the appropriate models are listed in table 1. A design morphology has to be suitably developed for the specific study. For physical and technological systems studies the likely sequence is shown in figures 2 and 3. The scope of the models and the state-of-art have been discussed elsewhere (Chaturvedi 1984) and the approach may be only briefly mentioned here. Starting with the estimate of water availability and water demand, a developmental policy is outlined and a systems investigation model, termed the first coordination model, is developed. The objectives of this model are to (i) scan the total system

Table 1. Relevant issues and models

Issues

Socio-economic studies	Water and allied resources studies	



1. Development strategies 2. Social evaluation of key resources 3. Resources availabilities 4. Evaluation of loss function and risk criteria 5. Project selection criteria	1. Regional optimal allocation of water resources 2. Optimal development constrained by economic and physical resources 3. Project evaluation and selection	1. Description of physical phenomena 2. Analysis and simulation of physical phenomena

Models

1. Intersectoral resource allocation model 2. Population studies 3. Food demand models 4. Agricultural sectoral model 5. Technology-efficiency-equity models	1. Preliminary system formulation model 2. Subsystem and system analysis (deterministic model) 3. Subsystem and system analysis (stochasic model) 4. System simulation models 5. Simulation of crop activities 6. Power sector models 7. Space structuring models 8. System environmental models	1. Hydrologic models 2. Hydrogeologic exploration models 3. Surface-ground water simulation model 4. Ground water recharge models 5. Crop-water fertiliser response models 6. Water quality models

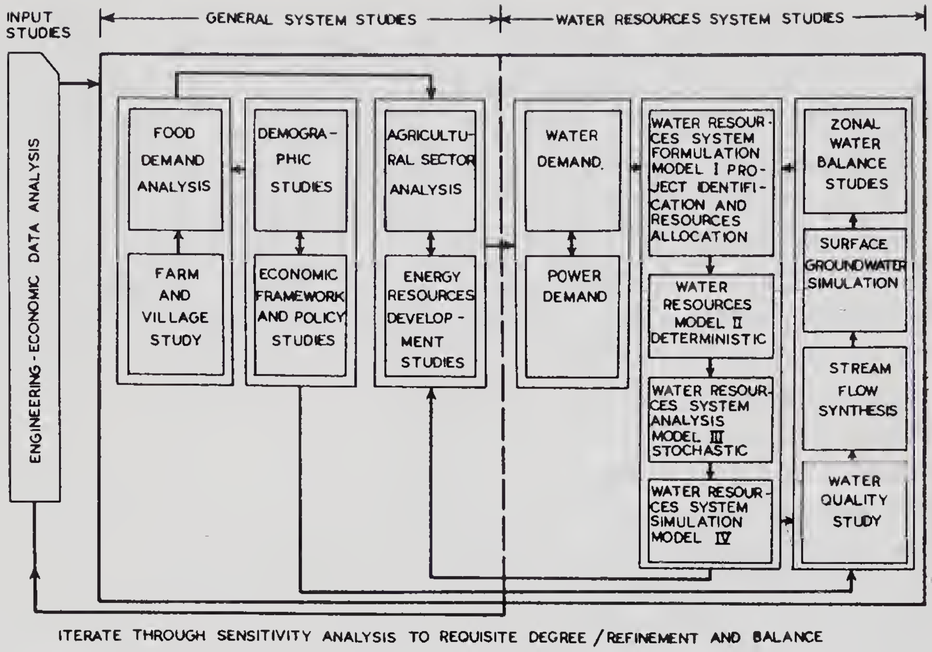


Figure 2. Water resources systems analysis modelling morphology

performance and then to determine the limits of interlinkage of various systems elements which may be examined in greater detail, (ii) identify the sensitivity of the decision to physical processes and parameters in terms of which data collection and physical processes modelling may be carried out and (iii) identify the socio-economic evaluation studies for a correspondingly more refined analysis. Progressively and

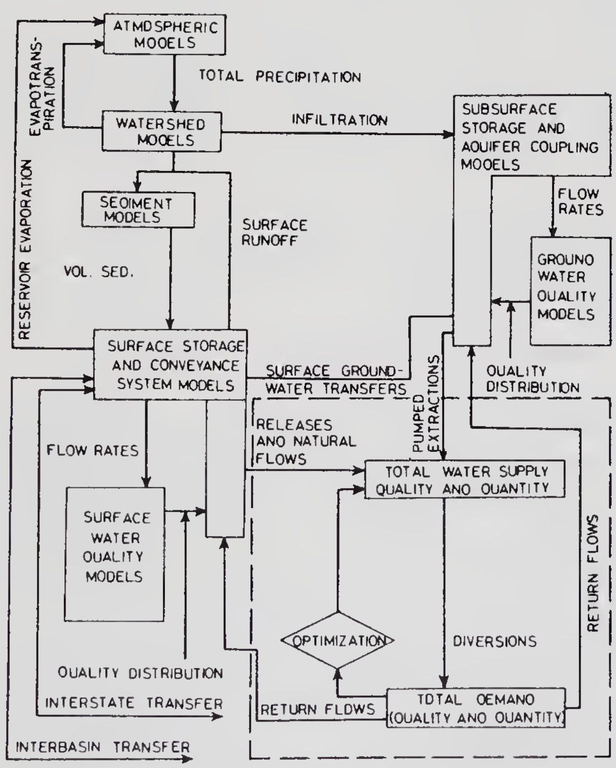


Figure 3. Water-resource system (after Ackermann 1969)

integrally each of these three activities may be refined. For instance, watershed modelling coupled with groundwater simulation may be carried out to quantify surface and groundwater availability and their dynamical interlinkage as man-made engineering activities are proposed. In this, both quantity and quality analyses are involved. Stream-flow synthesis studies may be carried out to arrive at a better understanding of regional temporal availability, with consequent refinement of the capacity and operating policy of the individual projects. Several other studies may be mentioned.

On the socio-economic side, the problem may be that instead of being limited to partial equilibrium analysis, a general equilibrium analysis may have to be carried out because of the large investments that go into water resources development in India. Appropriate economic-environmental objectives may have to be developed and quantified. For example, according to latest policies, employment generation is an important objective in Indian developmental planning. An appropriate cropping pattern for the project, embedded in a dynamic cropping pattern policy for the country may have to be determined. It is not necessary that optimum water to meet physiologic crop-requirements be provided. A lower amount, according to optimal marginal contribution to production may be more advisable. Further, the differential impact of irrigation on farms of different sizes creates problems. Issues of institutional, organizational and technological planning in terms of the multiobjectives of economic efficiency and equity, and expected value and risk may have to be examined. Several other issues may be mentioned.

As these studies of physical processes and evaluation continue, technological systems studies get refined. Each subsystem may be studied for short time intervals to determine the optimal capacity and operating policy. After deterministic analysis, stochastic studies may be carried out. Algebraic technologic functions for each subsystem may be developed and finally through the coordinating model, an optimal system plan may be developed. In the final analysis, simulation of the system may be carried out.

Water resources development is so basic to India that its planning may involve simultaneous consideration of systems planning in other areas, such as land, energy, or transportation. Although difficulties are introduced when such an integrated planning is envisaged, the interactions may make it mandatory in planning for many large river basins. For example, at present, about 50% of electric power in the Ganges Basin is hydro-electric and its future potential is at least as important as other modes of energy. Or canals may be developed as inland waterways and thereby integrated planning with the transportation system may be advisable. Or, since transportation crossings are economic sites for diversion works, it may be desirable to have integrated planning of the two areas.

Systems planning involves the collection of data and techno-economic analysis. Any systems analysis is only as good as the data: hydrologic, economic and technological. However, there are two basic issues. First, systems studies shed valuable light on the sensitivity of the decision to various parameters and at all stages of study, through sensitivity analysis, are mandatory for data collection and techno-economic analysis. Secondly, at each stage, the central issue is judicious balance in the level of sophistication of the techno-economic analysis, study of physical phenomena and analysis of techno-economic-environmental evaluation, in terms of the value of their contribution to decision issues. Indeed, it is on this principle that continuous progress in refinement is made and studies are iterated and finally terminated.

Large-scale water resources systems planning is thus an integrated-hierarchial-sequential activity. It calls for creative macro-modelling supported by adequate micro studies. It is far removed from professional *adhoc* project-by-project analysis or academic systems-analysis exercises Even the recent examples of modelling or integrated planning, though contributing significantly in this area, fall short of the task, particularly in developing countries because of undeveloped economic and technological systems. What is needed is continued application of recent systems-analysis approaches and techniques to real-life problems, leading to generalizations from the experience thus gained. The studies presented in this and other papers in this volume seek to contribute to this end.

3. Overview

The present studies were carried out independently and cover a wide field of subjects relating to a number of river basins. For convenience, these have been grouped into two parts, one relating to the Ganga Basin and the second, relating to other river basins. The river basins of India and those studied are shown in figure 4 and table 2 respectively.

After giving a background of the studies in this paper, the water resources of India are briefly reviewed in another paper in this volume (Chaturvedi 1985a). Following it in another article, the issues, developmental policy and programmes, and the planning approach are discussed (Chaturvedi 1985b). It will be seen that much of the development has taken place without any systematic policy analysis and the continued *adhoc* project-by-project development that is taking place may lead to the most serious resource depletion and environmental degradation. As the first step in systems analysis, the issues, objectives and planning approach for the development of water resources have to be decided. It may be necessary to have an all-India overview and to identify a policy and trajectory of development, according to which hierarchial-iterative macro- and micro-systems planning may be carried out.

The planning approach for the Ganga Basin, which is typical of a very large basin is illustrated through a series of eight studies. First, the salient features of

Table 2. River basin and study area

River basin	Study area	River basin	Study area
Ganga Basin	B5*	Narmada	B8
Brahmaputra	A	Tapi including Kim	
Barak and other rivers		Godavari	
East flowing rivers between Ganga and Mahanadi	B6	Krishna	
Mahanadi		Pennar and other east flowing rivers between Krishna and Cauvery	
East flowing rivers between Mahanadi and Godavari		Cauvery	B3
Indus	B1 + 2 B4	East flowing rivers below Cauvery	
Luni and others of Saurashtra and Kutch	B7	West flowing rivers below Tapi	
Sabarmati and Mahi			

* Covers only Damodar river basin

Figure 4. River basins and study areas (for A, B1 ... B8, see table 2). 1) Ganga, 2) Brahmaputra 3) Barak & others, 4) Between Ganga & Mahanadi (east-flow), 5) Mahanadi, 6) Between Mahanadi & Godavari (east-flow), 7) Indus, 8) Luni & others, 9) Sabarmati & Mahi, 10) Narmada, 11) Tapi, 12) Godavari, 13) Krishna, 14) Pennar & others, 15) Cauvery, 16) Below Cauvery (east-flow), 17) Below Tapi (west-flow)

the Ganga Basin and a tentative developmental policy is outlined (Chaturvedi 1985c). Next an approach for planning the development of a large river basin through a so-called 'coordinating-screening model', has been developed (Chaturvedi *et al* 1985). A study of the likely developments in surface water, groundwater, and hydro-electricity considering the interlinkage and multi-objectives of energy and irrigation in various projects, is carried out.The analysis is a prelude to a detailed analysis of each sub-basin, giving an idea of the range of decomposition of each subsystem. The decomposition can be carried out for a river basin, as in the study (Rogers & Kung 1985) or in political units as in the study (Karady & Rogers 1985).

Review of water demand and supply (as contemplated through conventional technology) shows that water resources are seriously inadequate. A novel approach to (ground water recharge is proposed (Revelle & Lakshminarayan 1985). Analysis of the problem requires that numerical-techniques be used. Groundwater-stream interaction through finite-difference approach has been developed and three schemes of groundwater recharge-surface development have been examined (Chaturvedi & Srivastava 1985b).

Several other related issues have been examined in the following studies. In one of the earliest papers on the subject, Rogers applies the game theory to demonstrate the use of analytical tools to analyse problems of conflict. The paper was referred to Chaturvedi, for independent study by the Indian Government as far back as 1968, and forms the beginning of the collaborative project between the two authors.

Regional water resources development usually focusses attention on the land region, neglecting the river-ocean interaction particularly as upstream developments take place. It is important that the implications of these developments are studied conjunctively. The implications of upstream development on flooding and saline penetration have been carried out by Rogers (unpublished).

It must be reiterated that systems planning is an adjunct to real-life planning demanding detailed technological and engineering-economic data and analysis. These studies are only concerned with an approach to analysis and the results are only indicative. We hope these studies will lead to detailed real-life systems planning of the water resources of India, which is long overdue. Systems planning of one large region, the Uttar Pradesh part of the Ganga Basin, is being carried out by Chaturvedi, but much requires to be done.

Further, systems studies of several river basins which also cover various other aspects of water resources planning, are presented. In the first of two studies, some problems of the Indus Basin are studied (Rao & Ramaseshan 1985a). The operation of Bhakra has been studied. It is shown that through multi-objective analysis and planning for conjunctive surface and groundwater development through a linear programming model, substantive improvements in returns and reliability could be obtained, both for energy and irrigation. The studies are extended for the operation of the Sutlej and the Beas (Rao & Ramaseshan 1985b) instead of only the Sutlej, in the second study.

The problem of optional operation of a number of reservoirs taking into account the varying storage in flow characteristics of each and the possibility of obtaining the optimum cropping pattern, is studied by Vedula (1985). The study relates specifically to the Cauvery Basin. The issue of cropping patterns is extended by Verma (1985) by studying, in addition and conjunctively, (i) the issues of the level of technology (high, medium, and low crop yields), and (ii) levels of irrigation technology (sprinkler and furrow irrigations). The area of interest is Rajasthan, a very arid region of the country, and the project studied is the Rajasthan Canal, having a capacity of 530 cumecs, one of the biggest canals in the world. Several policy issues are examined and significant modification in existing policy are suggested by Verma (1985).

Techno-economic systems planning of two river basins in the eastern parts of India—the Damodar Valley and the Subernarekha river is undertaken in two studies by Sinha & Rao (1985), and Sinha *et al* (1985) respectively. Both deal with complex large-scale systems and through mathematical modelling, incorporating multi-objective analysis and considering the possibility of optimal cropping patterns, an optimal development policy is attempted.

The study of the issue of irrigation policy, particularly important in arid areas with scarce water resources such as Rajasthan studied by Verma earlier is continued for an adjoining arid area of Gujarat by Basu D N, Gopinath C & Karady G (unpublished). One of the major issues in planning for investment of irrigation water is its allocation amongst crops and regions. Some of the issues are (i) inter-seasonal allocation (ii) inter-regional allocation, (iii) extensive *versus* intensive irrigation and (iv) implications of reliability of irrigation. Investigating (i) economic efficiency, (ii) calorific value and (iii) employment generation objectives, the policies of allocation among the different crops, seasons, regions and technologies have been examined through multi-objective analysis.

Additional technological systems planning issues with application to another major river basin are examined by Chaturvedi & Srivastava (1985a). The focus of interest is the Narmada river, in central India, significant from many considerations. The basin provides one of the most economical development options, perhaps in the world, and is yet almost totally undeveloped. According to the policy analysis carried out earlier, it can be an integral component in the national policy of water resources development. The issues examined in the paper are naturally limited. A procedure of analysis has been developed and has been applied to the Narmada system. It is proposed that for a complex system, a screening model has to be used in the first stage to identify the range of interlinkage for detailed subsystem analysis through decomposition. It is proposed that a programming—simulation approach could be used for examining the stochastic nonlinear nature of the problem.

The studies reported are isolated studies and are not related to the totality of real-life systems. While they do contribute to the science of planning, and in certain cases to specific issues, much remains to be done to apply them to real life problems. The issue of systems planning of river basins, with insights obtained from the foregoing studies is discussed in the concluding Overview and Reflections by the authors.

Systems planning of technology requires capability in design as well as in planning. Very often, scientists working in these two activity areas work in isolation, the professionals concentrating more on detailed design and project planning often from narrow techno-economic considerations and the academics concentrating on sophistications of systems analysis. There is a correlation between resolution level of data, engineering-economic analysis and systems analysis in terms of value in decision-making. Both for real-life utility and advances in the science of systems analysis, it is necessary that academics and professionals work together on real-life problems. Unfortunately, as the review of water resources development in the USA reveals, scientific planning though accepted as important, has generally not been followed (Schwarz 1979). One of the impediments is the lack of appreciation for the need and value of systems planning. We hope we have been able to make some contribution towards understanding and appreciating this need.

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Water resources of India—an overview

M C CHATURVEDI,
Applied Mechanics Department, Indian Institute of Technology, New Delhi 110016, India

1. Introduction

Specific physiographic, climatic and hydrologic characteristics along with economic and demographic features of a region determine the development of water resources. These are briefly described in the case of India as a prelude to the systems studies described later. A historical and quantitative perspective of developments is also given briefly. For details reference may be made to Rao (1976), Irrigation Commission Reports (1972), Chaturvedi (1976) and National Commission on Agriculture Reports (1976).

2. Physiographic features

The land mass which forms the subcontinent of India is a large peninsula, covering an area of 328 million hectares (mha), and supporting a population of 658 million (1981). It lies between 8° 4′ and 37° 6′ North latitude and 68° 7′ and 97° 25′ East longitude. With a land frontier of 15,200 km, much of which is bordered by very high mountains and a coastline 5,700 km long, it is the seventh largest country in the world. The location and the characteristics—a large peninsula with high mountains on the North—create a unique hydrologic-climatic environment.

Physiographically, India can be divided into seven divisions and twenty subdivisions (figure 1): (a) the Northern Mountains (b) the Great Plains (c) the Central Highlands (d) the Peninsular Plateau (e) the East Coast Belt (f) the West Coast Belt and (g) the Islands. We shall only confine ourselves to the coterminous subcontinent.

The northern Himalayan mountains stretch in a virtually unbroken chain, 2,500 km in length and 250 to 400 km in width, as a series of more or less parallel, though sometimes converging, ranges from the Indus in the west to the Brahmaputra in the east. In the north, there are three distinct ranges known as the Greater and the Middle Himalayas and the Lower Siwaliks. The average heights of these ranges are 6,000, 4,000 and 1,000 m respectively. They have some of the highest peaks of the world, and large areas above 5,000 m elevation are permanently snowclad. They contribute an annual snow melt of 5 million hectare metres (m ha m). They are geologically very young and, being formed of sedimentary rocks with steep slopes, contribute to high sediment charge to surface runoff. This is mitigated only by the fact that they are heavily covered with forests. As human and livestock populations grow, increasing soil erosion poses a serious problem.

Stretching at their feet and built up from the rivers flowing from the Himalayas, are the great Indo-Gangetic Plains. The alluvium forming the plains was laid down in

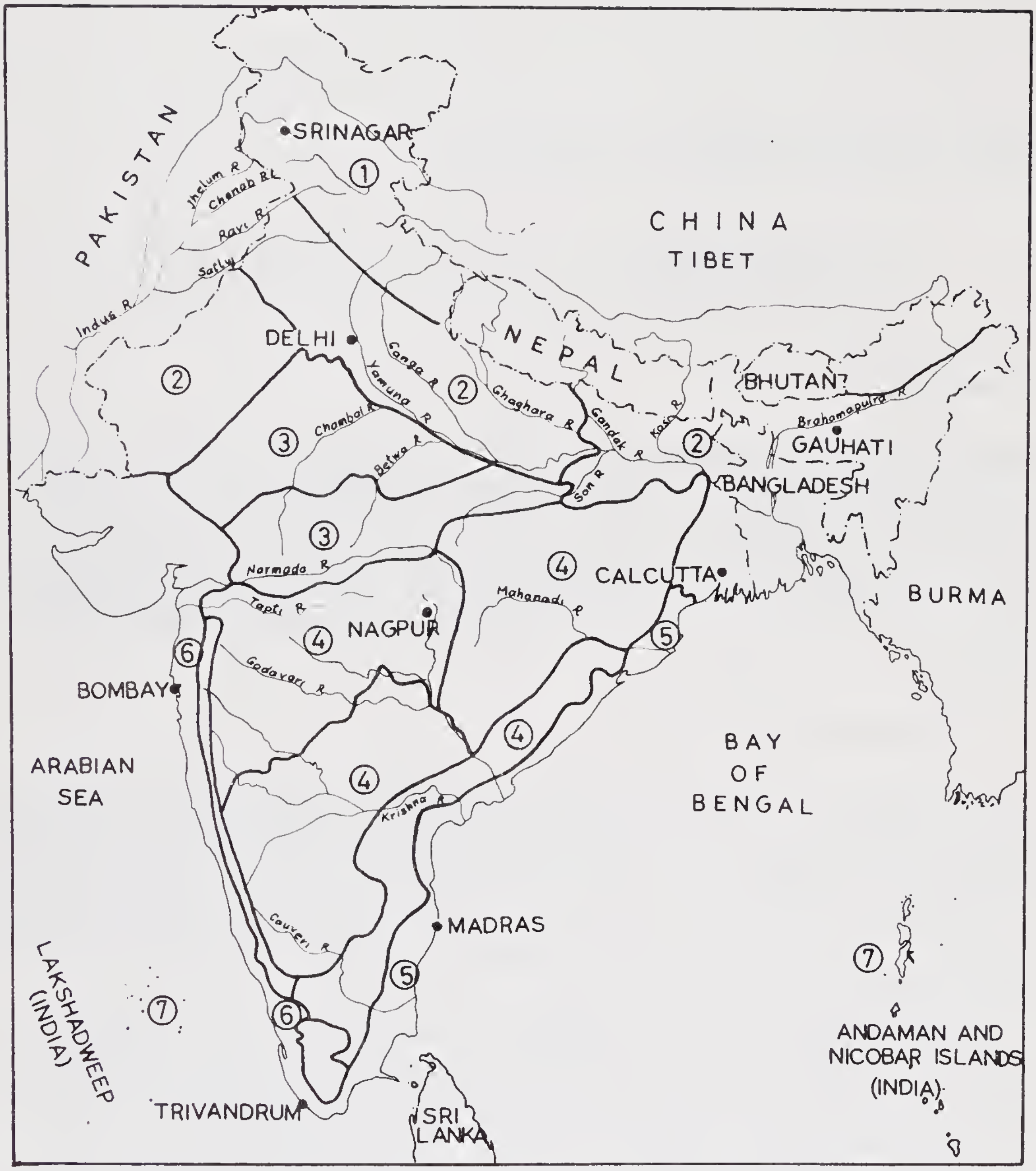

Figure 1. India physiographic map. International boundary–·–, regional boundary– – –. (source: Chaturvedi 1976)

successive geological eras and have depths of thousands of metres. The plains, with an area of 652,000 km^2, account for about 25% of the total land area of India. The surface of the great plains is at tide level near the sea but is well over 200 m above sea level in the Punjab plains.

Further south, are the Central Highlands, consisting of a compact block of mountains, hills and plateaus intersected by valleys and basins covered by forests, accounting for one-sixth of the total land area.

The triangular peninsula plateau, ranging in elevation from 300 to 900 m constitutes about 35% of the land. The surface sometimes consists of extensive plains. It is well-drained by a number of rivers flowing from west to east.

Of the two coast belts, the eastern is wider with a width of 100–300 km with a number of river deltas. The western belt is only 10–25 km wide between the Western Ghats and the sea.

The land is served by a number of large rivers. They can be divided into two groups; *viz* the perennial rivers of the Himalayan region which are snow fed, and the peninsular rivers. The maximum monthly discharge variation of the former is of the order of 50:1 while that of the latter is of the order of 1000:1. These can also be classified in three groups in terms of their catchment areas, as discussed later.

India can be divided into 17 river basins as shown in figure 2. The Ganga basin is the

Figure 2. India—: river basins 1) Ganga, 2) Brahmaputra, 3) Barak & others 4) Between Ganga & Mahanadi (east-flow), 5) Mahanadi, 6) Between Mahanadi & Godavari (east-flow), 7) Indus, 8) Luni & others, 9) Sabarmati & Mahi, 10) Narmada, 11) Tapi, 12) Godavari, 13) Krishna, 14) Pennar & others, 15) Cauvery, 16) Below Cauvery (east-flow), 17) Below Tapi (west-flow). International boundary–·–, river basin boundary– – – (source: Chaturvedi 1976)

Table 1. Salient water, land and population statistics

		Land						Water		
									Utilizable	
		Catchment area (inside India)	Culturable area (% of 1)	Net sown area (% of 2)	Cropping intensity	Precipitation	Evaporation	Annual runoff	Annual ground water recharge	Surface runoff (% of 7)	Utilizable ground water (% of 7)
		m.ha	%	%	%	cm	cm	mhm	mhm	%	%
Sl. No.	River basin	1	2	3	4	5	6	7	8	9	10
1	Ganga	86·15	70·0	76·5	125	116	212	55·01	14·62	33·6	18·9
2	Brahmaputra	18·71	64·9	22.7	118	122	125	42·2	3·97	2·1	4·5
3	Barak and others	7·82	14·3	66·5	124	286	150	17·5	1·60	2·12	3·7
4	Between Ganga and Manahadi (East flow)	8·10	63·0	65·1	114	147	175	4·35	1·63	94·0	16·0
5	Mahanadi	14·16	56·5	70·3	125	146	200	7·07	2·13	93·7	15·0
6	Between Mahanadi and Godavari (East flow)	4·97	54·4	66·7	124	111	200	1·72	0·73	93·5	23·6
7	Indus	32·13	30·0	72·3	133	56	200	7·69	2·90	64·2	14·8
8	Luni and others	32·18	72·8	60·3	105	38	305	1·23	0·80	74·0	48·2
9	Sabarmati and Mahi	5·93	62·8	77·6	111·5	159	320	1·55	0·62	73·35	21·0
10	Narmada	9·88	59·8	76·2	106	121	245	4·01	1·24	73·0	17·8
11	Tapi	6·69	66·0	88·6	104	78	305	1·97	0·61	71·0	20·1
12	Godavari	31·28	60·5	76·5	107	110	235	11·54	3·31	73·8	17·2
13	Krishna	25·90	78·4	76·6	105	81	290	6·28	2·65	83·5	31·5
14	Pennar and others	14·49	65·0	59·5	116	82	230	2·53	1·82	73·3	41·5
15	Cauvery	8·79	66·0	64·5	115	99	225	1·86	1·23	96·4	26·0
16	Below Cauvery East flowing	3·51	75·0	62·8	111	91	270	0·95	0·54	36·9	12·2
17	West flowing below Tapi	11·21	56·0	69·0	119	279	200	2·79	2·01	13·2	5·0
	Total	321·87	59·7	67·7	115·4	124·8	228	188·8	42·41	35·4	13·8

Utilized % of utilizable: Surface	Utilized % of utilizable: Ground water	Total utilized % of utilizable	People: Population	People: % of total population	People: Density/Km^2	Unit figures: Culturable land/capita	Unit figures: Water/capita	Unit figures: Water/culturable land	Unit figures: % gross sown area irrigated
%	%	%	m	%	persons/km^2	ha	cu.m	cms	%
11	12	13	14	15	16	17	18	19	20
71·0	39·4	59·1	221·19	41.20	256	0.32	3140	116	28·3
70·0	1·1	23·6	17·65	3·28	94	0·69	25700	375	21·3
27·0	11·3	10·0	5·33	0·99	68	0·21	36000	171	13·0
15·18	3·1	13·3	13·70	2·55	169	0·37	4370	117.2	16·8
33·60	2·8	27·1	17·80	3·39	126	0·45	5160	115·1	18·3
54·60	5·0	45·0	9·44	1·76	190	0·29	2600	90·6	35·4
93·40	71·2	90·0	24·63	4·58	77	0·39	4300	110	50·6
41·70	41·8	42·1	21·82	4·25	68	1·08	930	8·64	8·23
50·2	31·5	40·0	10·38	1·96	184·5	0·76	4060	54·5	11·6
9·46	19·8	11·1	10·60	1·97	107	0·56	4950	89	4·48
37·0	40·0	37·4	9·14	1·76	137	0·49	2820	58·4	6.10
38·4	28·2	37·5	35·46	6·69	113	0·29	2600	90·6	13·0
90·5	36·9	77·3	38·50	7·16	149	0·53	2190	41·6	12·9
81·0	45·0	71·6	30·28	5·18	209	0·31	1435	46·3	37·6
86·9	52·0	80·0	21·60	4·02	246	0·27	1430	53·3	36·5
82·1	10·4	83·1	9·48	1·77	270	0·28	1570	56·6	42·10
44·15	7·7	34·6	40·55	7·55	362	0·16	5850	379·0	17·0
47·1	30·0	50·1	537·55	100·06	166·2	0·43	4280	116·0	20·6

largest, covering almost one-fourth of the total geographical area. It has considerable variations in physiography, climate and allied characteristics and is, therefore, sub-divided into eight sub-basins. Some vital statistics, regarding water, land and people of the seventeen river basins are given in Table 1.

While our description of the system is primarily in terms of physical characteristics, the States are the administrative units and reference may have to be made to them. The country is divided into 22 states and 9 centrally administered union territories as shown in figure 3.

3. Climate and rainfall

The distinguishing characteristics of India are a tropical climate and the monsoons. Literally, the word monsoon means a wind system which undergoes a seasonal 180° reversal of direction. Many regions of the world experience the monsoons, but in India, two factors make them unique. One is the continuous and high mountain mass in the north which forms an effective barrier to the air movement across them and also contributes to the formation of a low pressure zone favourable to the monsoon across

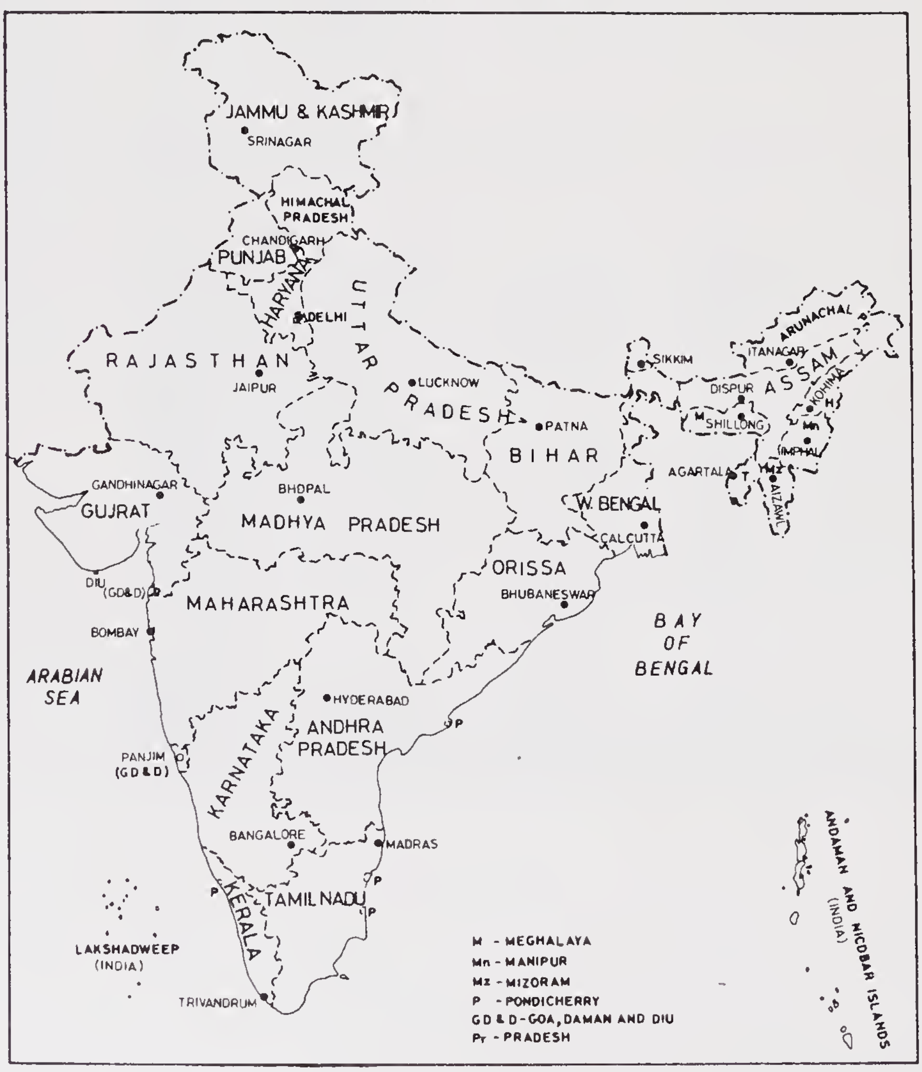

Figure 3. India—political map (source: Chaturvedi 1976)

India. The second is the peninsular shape of the subcontinent with the close proximity of the land to the ocean, thereby providing a rich source of moisture. India has a diversity and variety of climate and an even greater variety of weather conditions. The climate varies from continental to oceanic, from extremes of heat to extremes of cold, from extreme aridity and negligible rainfall to excessive humidity and torrential rainfall. Thus, generalizations cannot be made, but for convenience, it is possible to demarcate five broad regions with more or less similar patterns of climate and weather: (a) north-west India comprising West Rajasthan, Punjab and Kashmir, (b) central India comprising East Rajasthan, Gujarat, the northern districts of Madhya Pradesh, Uttar Pradesh and Bihar (c) the plateau region (d) Eastern India comprising West Bengal, Orissa and Assam and (e) the peninsular coastal lands and plains.

The average temperature with seasonal patterns is shown in figure 4. During the winter season, from November to February, the temperature decreases from the south to the north from about 24–29°C in the south to about 5–18°C in the north. From March to May the temperature rises sharply in northern India and the maximum may be above 40°C. Evaporation closely follows the march of the monsoon (figure 5). The potential evapo-transpiration (PE) which may be assumed to be the same as the evaporation, ranges between 140 and 350 cm.

Rainfall is primarily dependent on the monsoons and to a certain extent on shallow cyclonic depressions and disturbances. Only a fraction of the more than $3{\cdot}87 \times 10^8$ m ha m of atmosphere moisture moving over India reaches the ground as rain or snow. Evaporation from the oceans provides about 80 percent of this precipitation. The summer monsoon, coming from the southwest, bursts on the Malabar coast in the first week of June and establishes itself over most of the country by the end of the month. Coming from over the sea, it provides about 80–90% of the total annual rainfall. In view of the orographical features, the monsoons travel up *via* the Indus plain on the Arabian side and up the Gangetic plain on the Bay of Bengal side. The strength of the monsoon current increases from June to July, remains more or less steady in August and begins to weaken in north India in September, when there is a rapid decrease in rainfall towards the end of that month. Prior to the monsoons in the early part of the year, disturbances continue to enter India, bringing some rain to the north-west part of the country and a reasonable amount in West Bengal and Assam.

By the middle of October, the low pressure is transferred to the centre of the Bay of Bengal and the direction of the winds becomes north-easterly. They cause occasional showers on the mid east coast. Cyclonic storms from the Bay of Bengal, during October and November, are mainly responsible for the rainfall in the Deccan Plateau and Tamil Nadu. In the winter, from December to February, a shallow but extensive low pressure system moves across northern India from west to east. There is heavy precipitation in the form of snow in the higher ranges of the Himalayan system and moderate rain over the lower and outer ranges.

It has been estimated that during the four rainy months of June through September, the Arabian sea branch of the monsoon carries moisture amounting to about 770 m ha m and the Bay of Bengal branch about 340 m ha m of the monsoon moisture, 25 to 30% precipitating in the form of natural rainfall. During the remaining eight months also, there is a substantial amount of moisture over the country and it constitutes a precipitation of the order of 100 m ha m, a small portion of it being in the form of snowfall.

The annual rainfall and its seasonal distribution is shown in figure 6. It is upto 250 cm

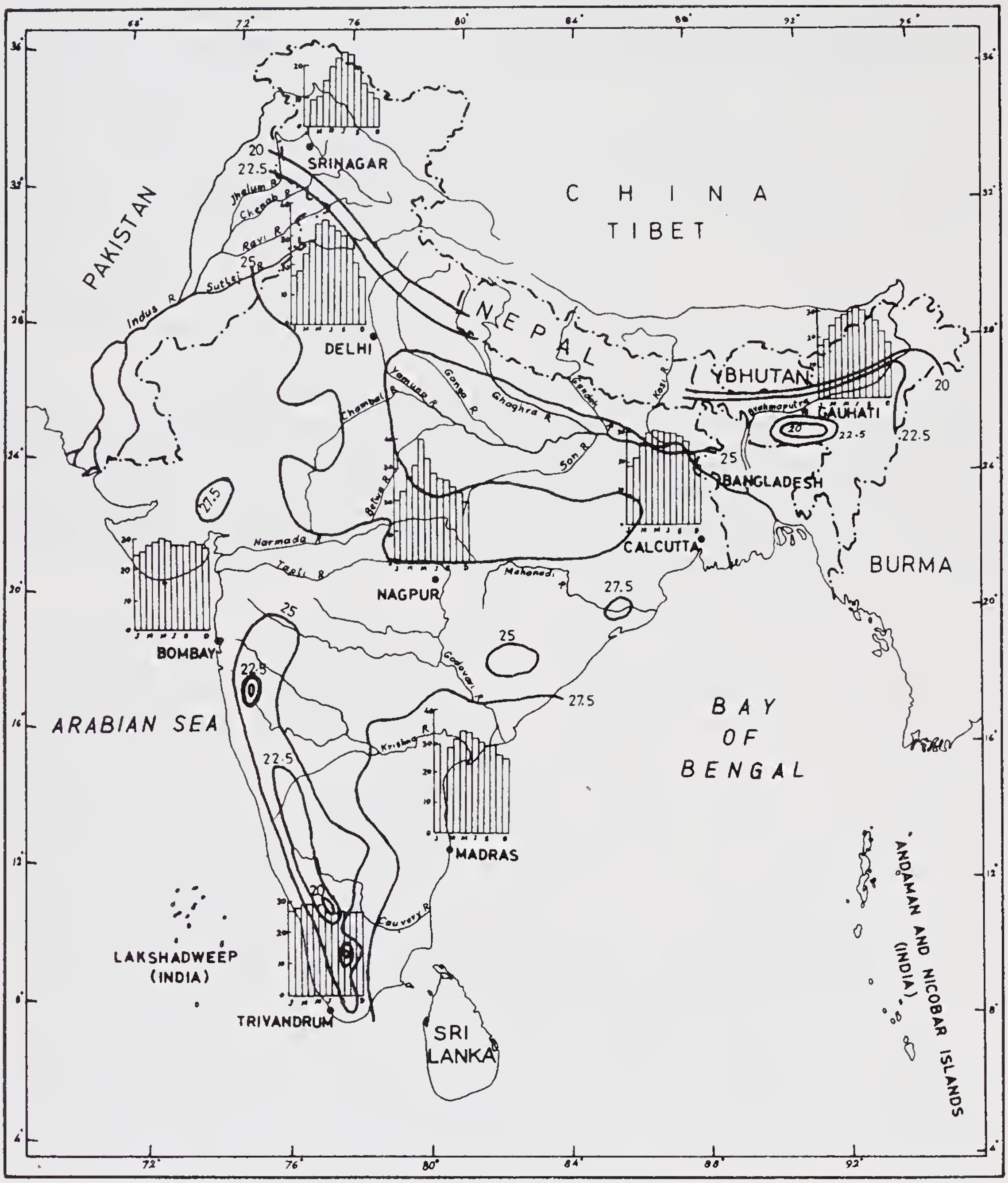

Figure 4. India—temperature variation (source: Chaturvedi 1976)

along almost the entire West coast and Western ghats and over most of Assam and sub-Himalayan West Bengal. West of the isohyetal joining Porbandar to Delhi and thence to Ferozpur it diminishes rapidly from 50 cm to less than 15 cm at the extreme west. The peninsula has an elongated area of less than 60 cm of rainfall. The normal annual precipitation over the country of 119·4 cm (National Commission on Agriculture 1976) is slightly more than the global mean of 99·1 cm. The point to be noted is the extreme spatial and temporal variation. Cherrapunji in the extreme east records a rainfall of the order of 1142 cm in a year and as much as 104 cm in a day, which are some of the highest figures in the world. In the west, in the Rajasthan desert some of the driest spots on earth can be located.

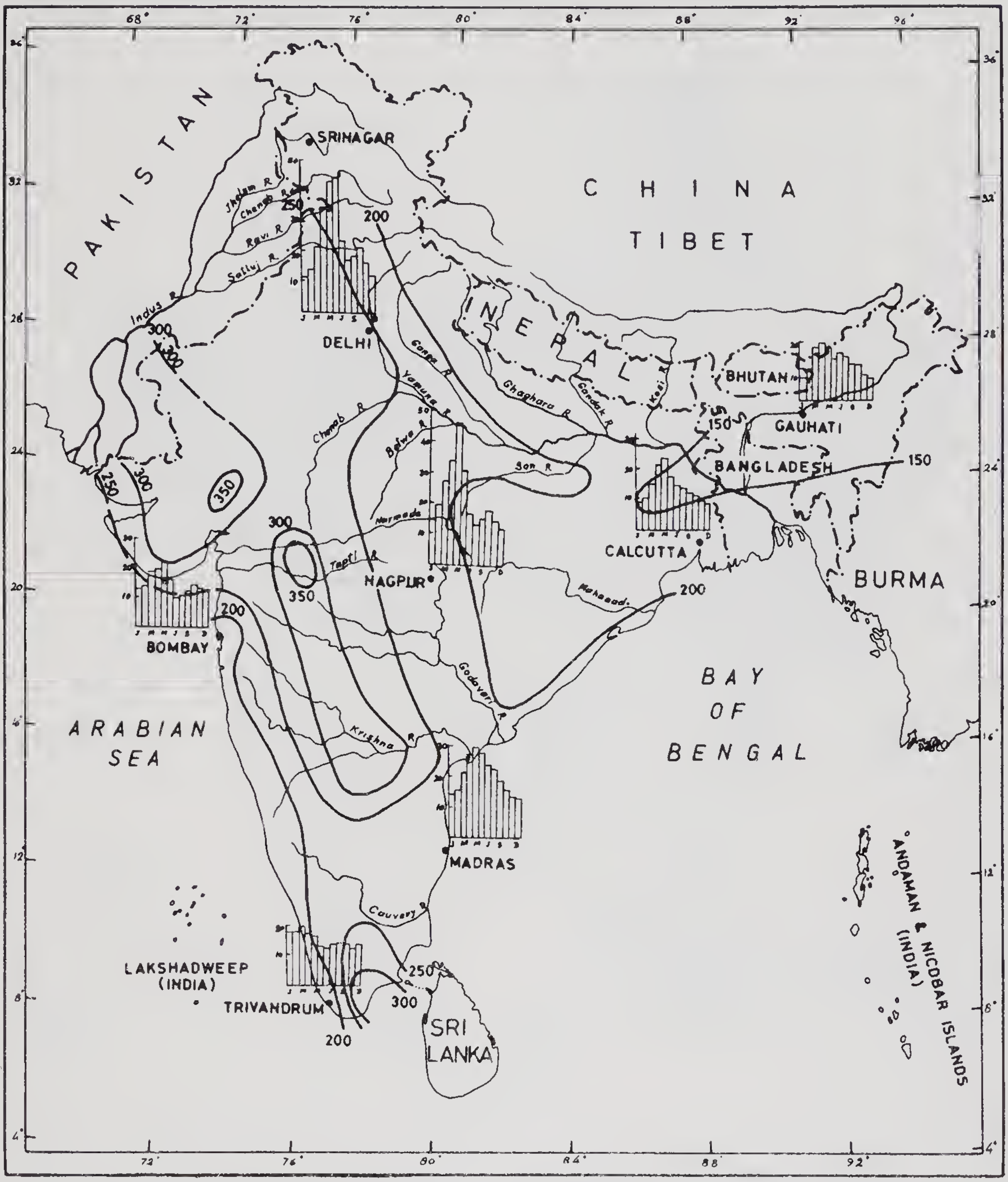

Figure 5. India—pan evaporation contours (source: Chaturvedi 1976)

The extreme spatial variation is further demonstrated in terms of annual water surplus and deficits, shown in figures 7 and 8. The values are computed by subtracting values of potential evapotranspiration from the average precipitation and adding up the annual surplus or deficit separately. The figures show that on the whole there is a net deficit all over the country. Even in the monsoon months, when there is general surplus, some regions are eternally drought-stricken. The figures are only indicative, as even in areas of annual water surplus, there are often seasonal or short-term periods of deficiency. The variability of available water resources is extremely important as deficiencies during critical periods of crop growth can be disastrous. Besides the considerable geographical and seasonal variation, the rainfall even during the monsoon

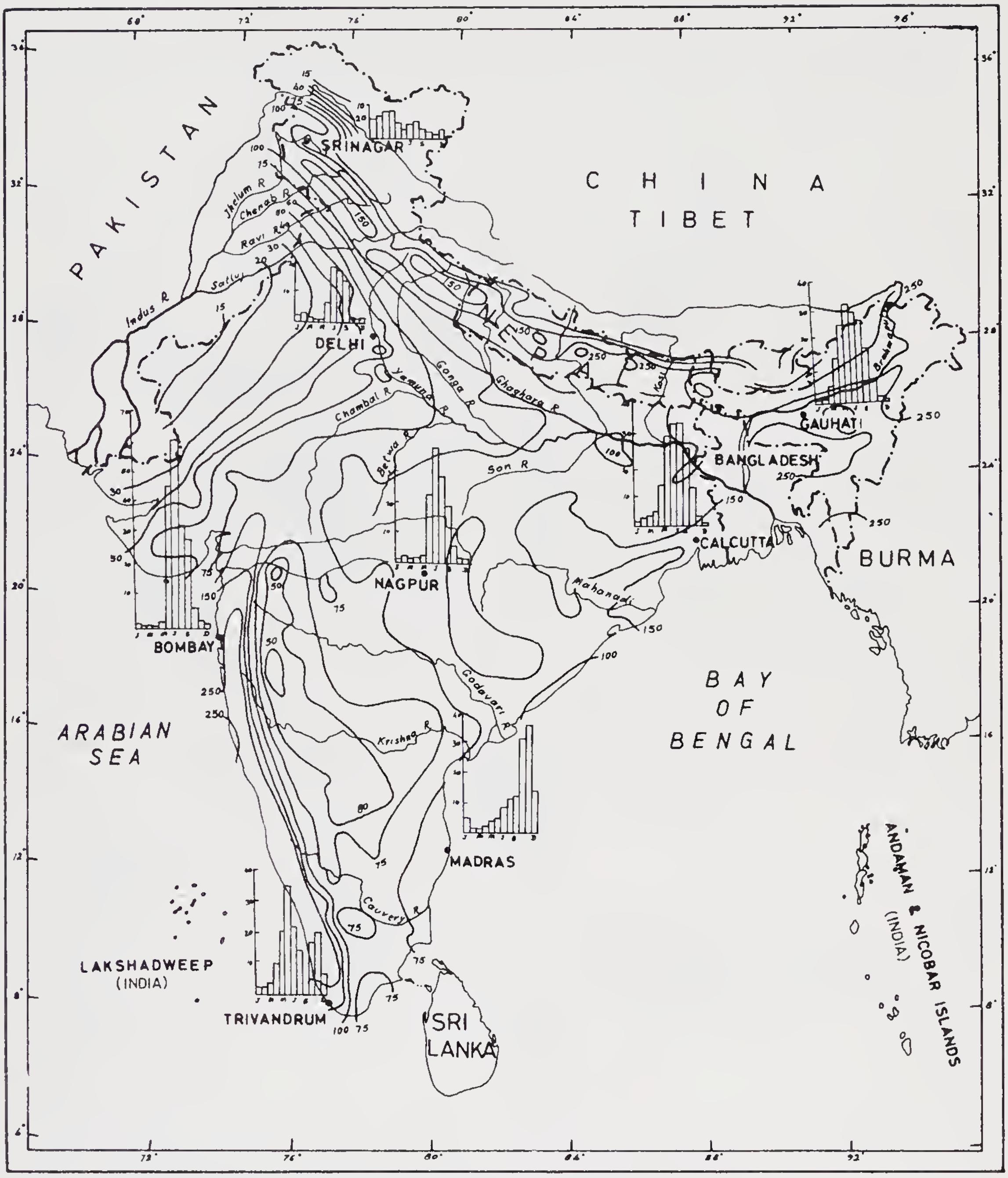

Figure 6. India—Isohyetes (source: Chaturvedi 1976)

is most uncertain. There are alternating periods of heavy to moderate rains and partial and general breaks when there are no rains.

The annual variation is, however, much less. The annual coefficients of variations are shown in figure 9. These present the percent plus or minus variation from the mean for 70% of the year. It generally varies between 15 to 30 taking the year as a whole. Along the West Coast near Mangalore, the coefficient of variation is less than 15%. The isoline of 30% runs through Bengal, Orissa, the Bihar Plateau and Assam, the north-eastern part of Assam having less than 15% variability. Over Gujarat and Rajasthan this coefficient is higher than 40%.

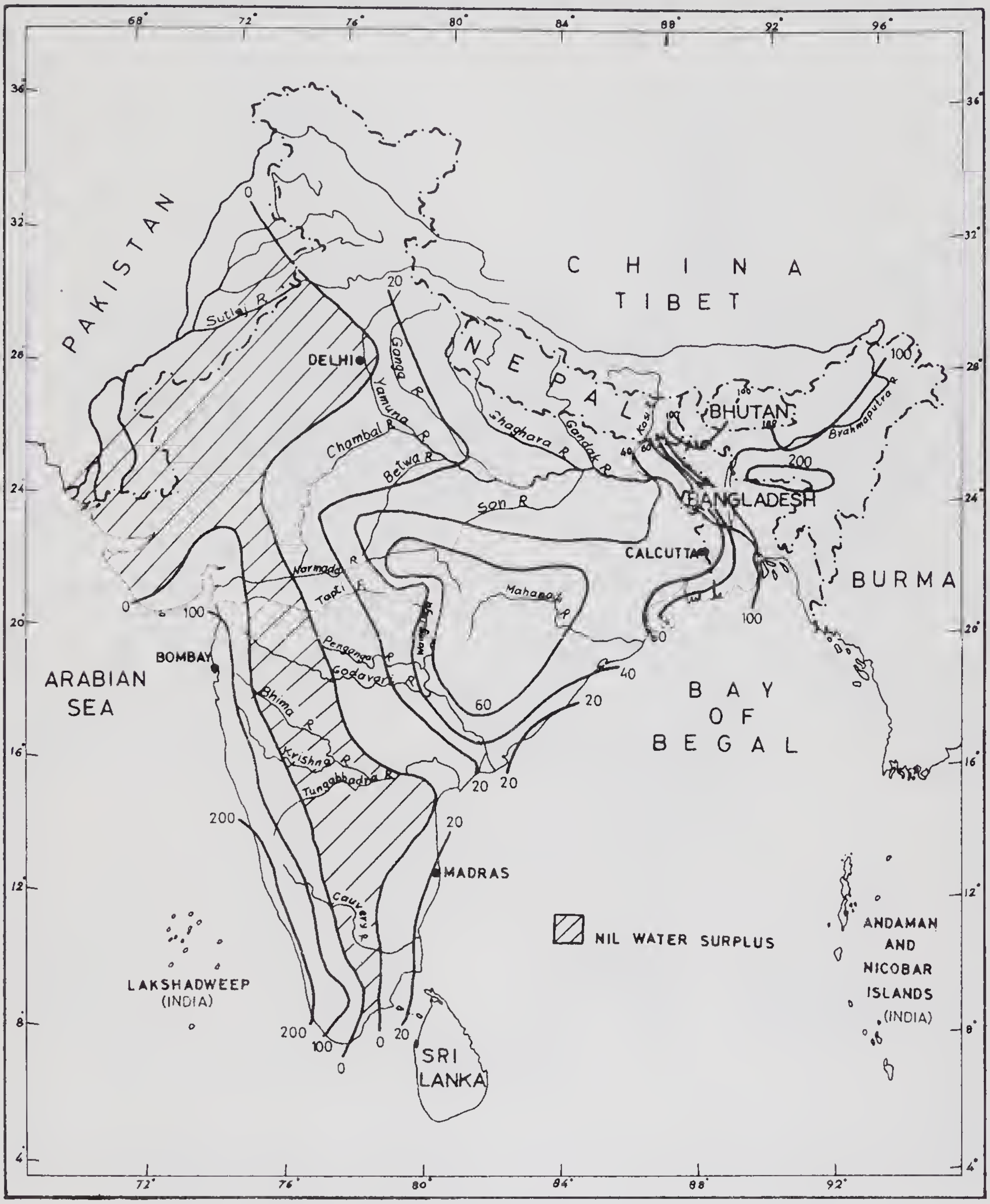

Figure 7. India—water surplus regions (source: Chaturvedi 1976)

4. Hydrological cycle and water balance

A correct assessment of the surface runoff is not possible as yet, as long-term and reliable discharge measurements have not been carried out at sufficient locations. The earliest attempt at estimating these was based on an empirical correlation with rainfall and temperature. Later, studies were made by several agencies on the basis of actual measurements and empirical studies. The figures currently in common use are given in

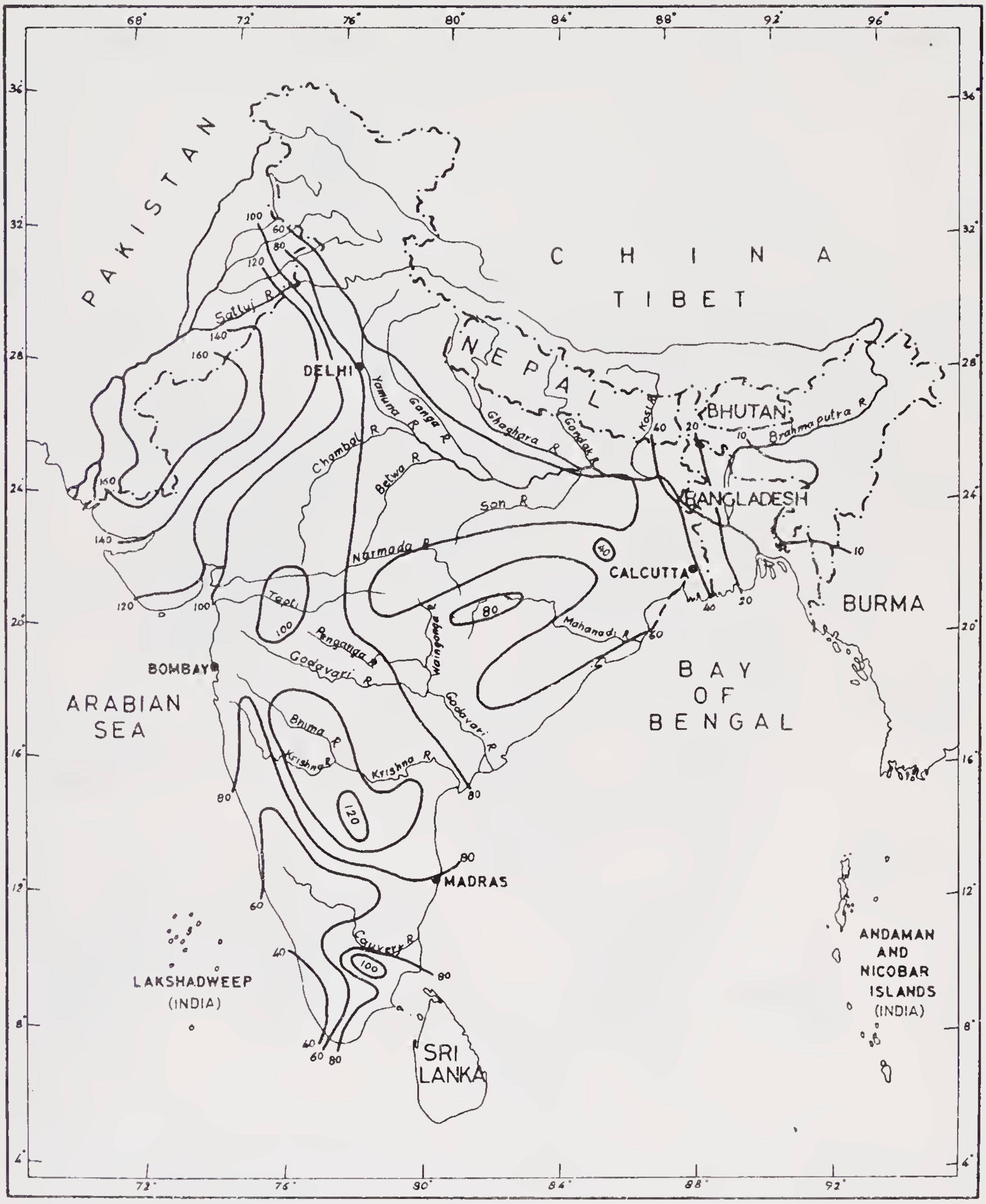

Figure 8. India—water deficit regions (source: Chaturvedi 1976)

table 1. These give the total runoff. Mean monthly and maximum monthly runoffs of some major rivers at some measuring sites are shown in figure 10.

Natural runoff is the annual flow of water that would appear in surface streams if there were no upstream development. In areas of surface water-groundwater continuity, the natural runoff includes the perennial recharge yield of groundwater aquifers. According to the Irrigation Commission Reports (1972), some estimates are as follows.

The mean annual natural runoff which leads to surface flows and groundwater recharge is estimated to be 188·12 m ha m. Of this, 42·41 m ha m is estimated to be the

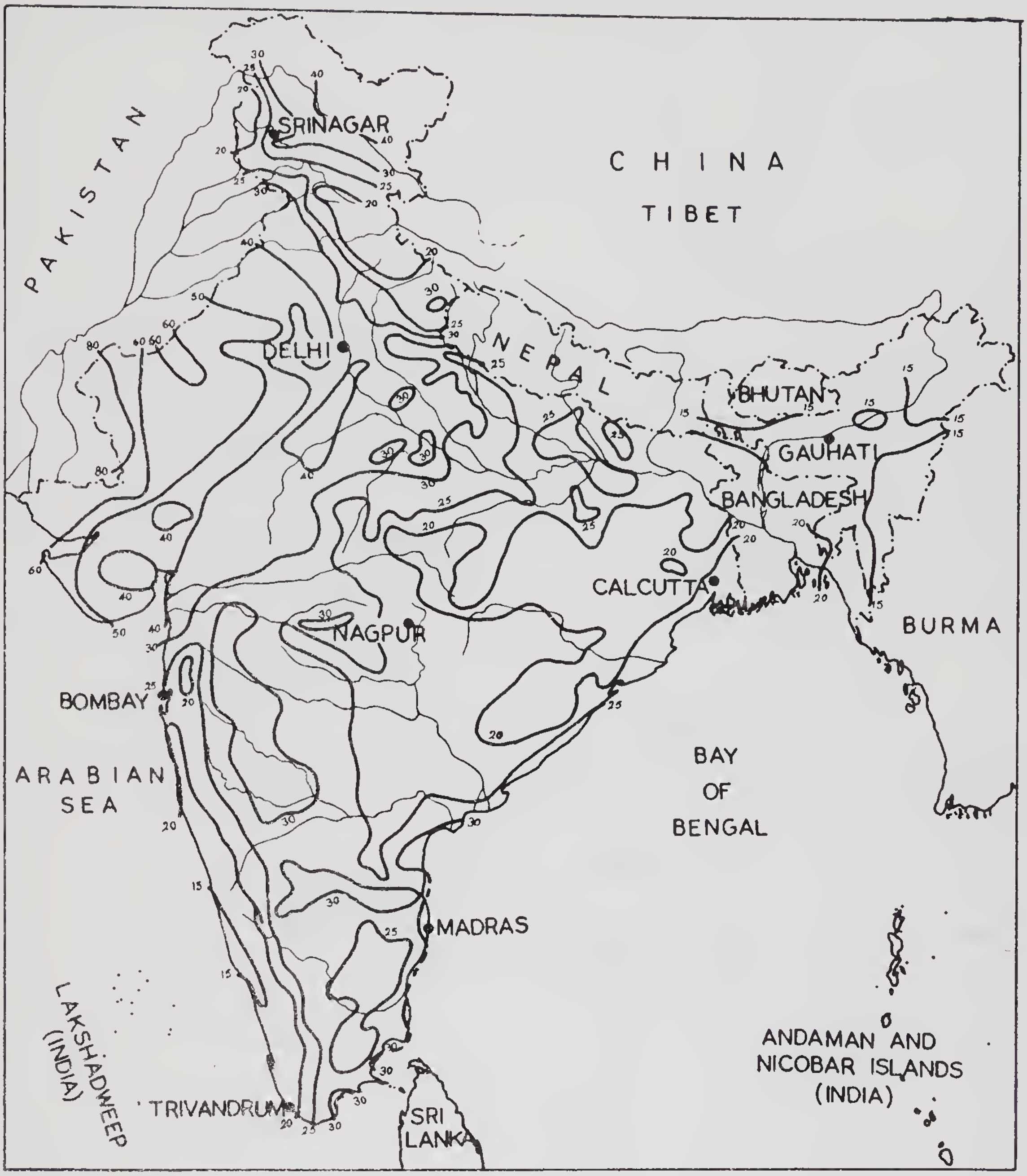

Figure 9. India—annual rainfall variation (source: Chaturvedi 1976)

mean annual groundwater recharge. The total surface flows which are considered to be utilisable are estimated to be 66·6 m ha m. In addition, 26·1 m ha m of groundwater is expected to be utilisable leading to a total utilisable resource of 92·7 m ha m. These figures are still tentative and approximate. There are vast disparities from river basin to river basin. For instance, the total utilisable water resource per unit of land is 116 cm in the Ganga basin, while the corresponding figure in the Cauvery basin is only 43·3 cm.

Assessment of groundwater is even more difficult and incomplete. Measurements of water balance, annual recharge and groundwater levels have to be made. The distribution of precipitation into surface runoff and groundwater recharge depends upon site conditions. The potential for groundwater is shown in figure 11 and the

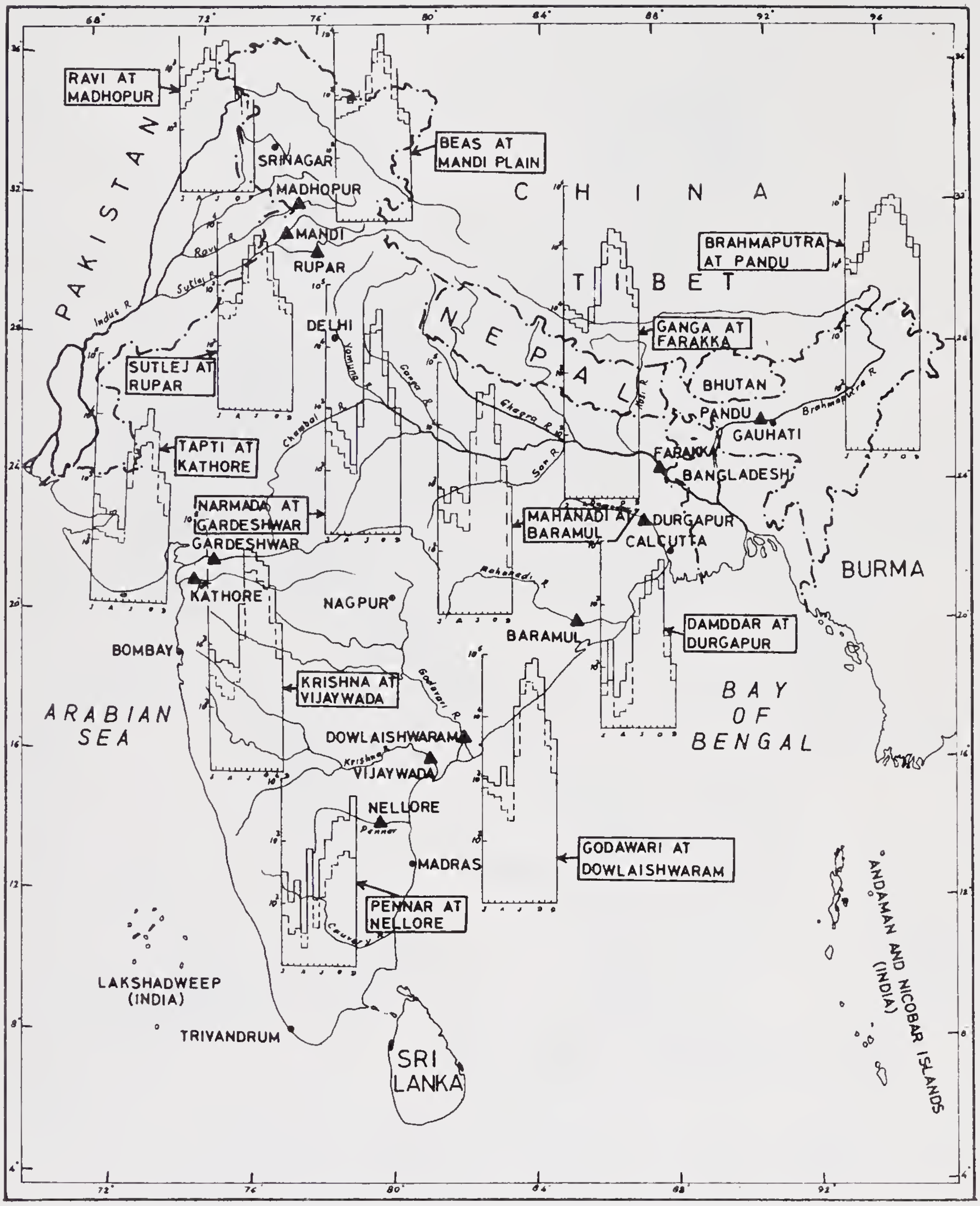

Figure 10. India—maximum and monthly mean river discharges in cumecs (source: Chaturvedi 1976)

pertinent data on annual ground-water recharge is given in table 1. The figures although not accurate are the best estimate on the basis of currently available data. As estimated earlier, out of the total of 42·41 m ha m, 26·1 m ha m are considered utilisable. The availability is even more nonuniform spatially as brought out in figure 11, as about 70% of the land surface is covered by hard rocks. Besides the annual recharge, a vast amount of nonrenewable groundwater resources are available which could be mined. This, however, creates many problems. As the groundwater table is lowered, a new equilibrium between surface runoff and annual recharge is established and contri-

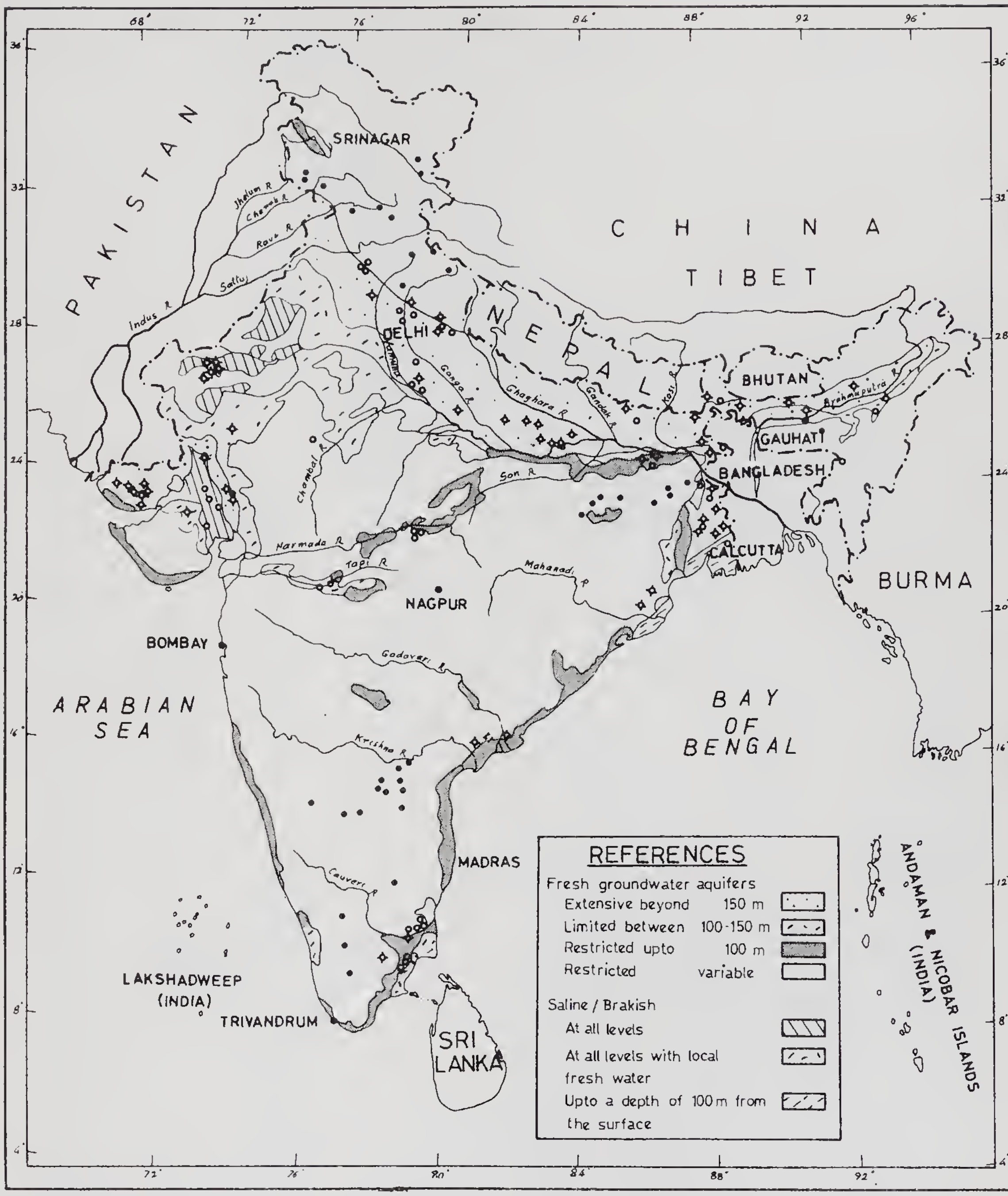

Figure 11. India—depth of aquifers and quality of groundwater (source: Chaturvedi 1976)

bution to surface runoff from groundwater will be reduced. There would be in-perpetuity costs of pumping from the reduced levels, and the resources developed would be nonrenewable.

Recently, water balance has again been estimated by the National Commission on Agriculture (1976). The water balance as estimated in 1975 and the likely position in the years 2000 and 2025 is shown in figure 12. The country's average annual rainfall is about 119·4 cm and the country's total average annual precipitation is estimated to be 394 m ha m. This may be rounded off to 400 m ha m including snowfall which is not yet

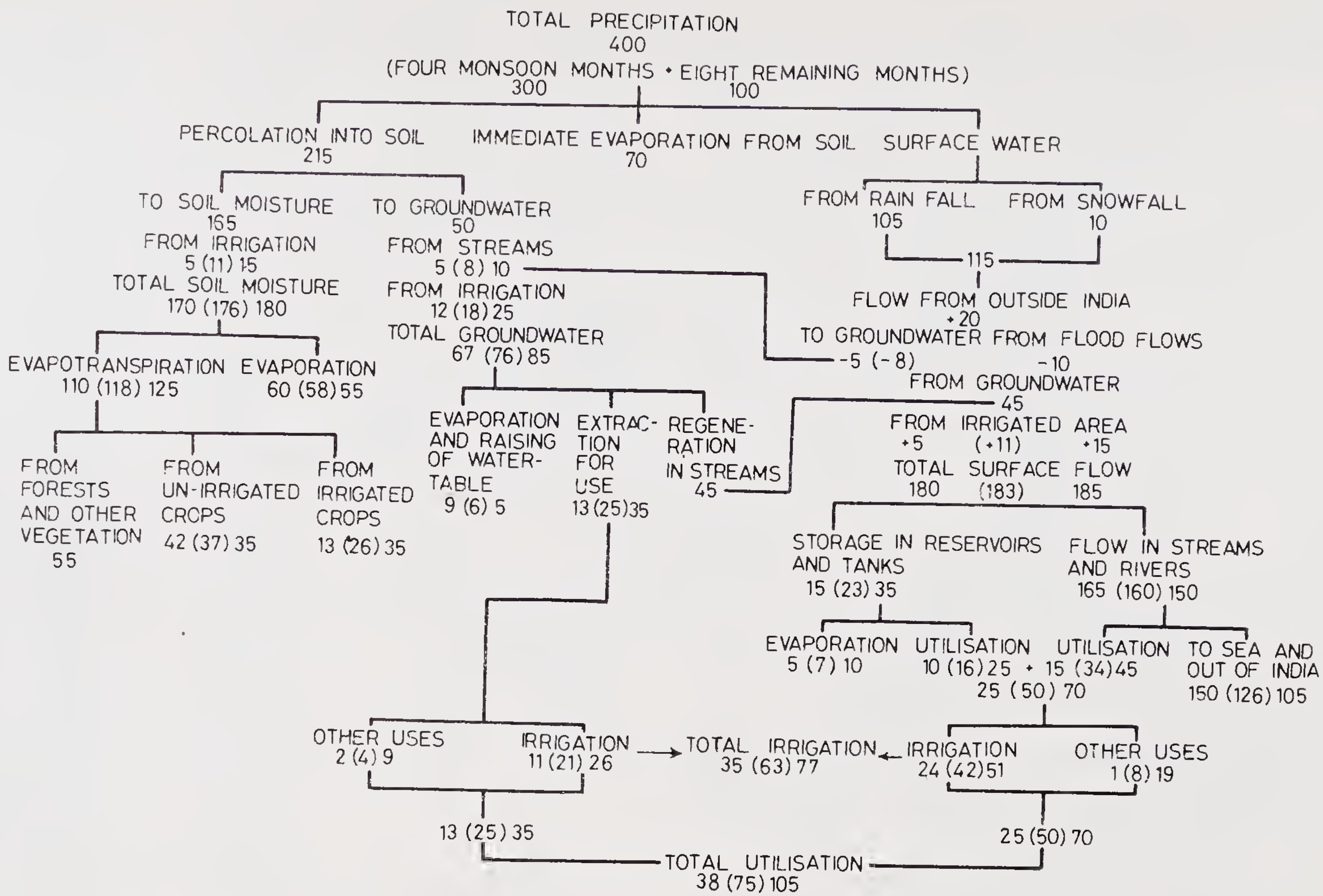

Figure 12. India—approximate distribution of average annual water resources as in 1974, 2000, and 2025 AD (m ha m). The numbers in brackets are those for the year 2000 (source: National Commission on Agriculture)

fully recorded. Out of the 400 m ha m, about 70 m ha m is estimated to be lost to the atmosphere by evaporation. Of the remaining 330 m ha m, about 115 m ha m becomes surface runoff and the remaining 215 m ha m soaks into the ground as soil moisture and groundwater recharge. Of this, about 45 m ha m regenerates as surface flows. An additional 20 m ha m is brought in by streams and rivers from catchments lying outside the country in Nepal and Tibet, and thus the total surface flows have been estimated to be 180 m ha m. Of the total surface water of 180 m ha m available in the country in an average year, about 15 m ha m is stored in various reservoirs and tanks of which about 5 m ha m is lost by evaporation. A considerable portion of the storage is in tanks constructed over long periods in the past. With future construction of projects, storage is ultimately expected to be about 35 m ha m and the loss about 10 m ha m. Of the 165 m ha m of water that flows in the river annually at present without any storage facility, the utilization through diversion works and direct pumping aggregates to 15 m ha m, which is more than that from the storage works. The remaining river flow of 150 m ha m goes to the sea and some adjoining countries. On full development, the use of water through diversion works or direct pumping is expected to increase to 45 m ha m. The balance of 105 m ha m would continue to flow to the sea and outside the country.

Of the 215 m ha m percolating into soil, about 50 m ha m, *i.e.* about 12·5% of the total precipitation is estimated to percolate as groundwater and the rest is retained in the soil as soil moisture. No significant change is expected in this according to present thinking and policy, although as we will argue later, the groundwater recharge has to be and can be substantially increased. Infiltration and contribution to groundwater also takes place from the irrigation works themselves. In the alluvial plain of north India, about 45% of the water that is let in at the head of an unlined canal system is lost from channels through seepage. Of the remaining 55% which reaches the field, another 30% is lost. Thus, it is estimated that only about 40% of the water let into an unlined canal system is actually utilised. It is estimated that at present about 5 m ha m is retained in the soil as soil-moisture and about 12 m ha m is added to the groundwater. On full development of irrigation in the country, the contribution to soil moisture and groundwater is expected to be about 15 m ha m and 25 m ha m respectively. Similarly, contribution to groundwater from streams is estimated to be 5 m ha m currently and is expected to be increased to 10 m ha m by developing schemes of induced groundwater. With the addition of 5 m ha m from flood flows and 12 m ha m from the irrigation system to the 50 m ha m from precipitation, the total groundwater, excluding soil moisture comes to 67 m ha m. It is estimated that at present, of the total groundwater amounting to 67 m ha m replenished on an average annually, 13 m ha m is extracted for various uses, about 45 m ha m regenerates into rivers and the remaining 9 m ha m is accounted for by evapotranspiration and raising of the water table. On the near full-development of water resources, the extraction is estimated to rise to 35 m ha m, evapotranspiration reduced to 5 m ha m, and the remaining 45 m ha m regenerates to rivers as at present.

Currently, the transpiration is estimated to be about 110 m ha m, 13 m ha m from irrigated crops, 42 m ha m from unirrigated crops, and 55 m ha m from forests and other vegetation. On full development, the total transpiration is estimated to become 125 m ha m, the component figures being 35, 35 and 55 m ha m, respectively.

Evaporation is a major item of the hydrological cycle. Of the total precipitation of 400 m ha m, 70 m ha m is lost directly. Of the 215 m ha m percolating into the soil, another 10 m ha m is estimated to be non-beneficial evaporation. These figures are estimated to change only marginally with development.

In terms of estimated utilisable resources and their development, it is seen that 180 m ha m of surface flows (which includes 45 m ha m of contribution from groundwater) is available. After almost complete development, these figures are estimated to change to 185 m ha m, the groundwater contribution to surface runoff remaining the same. Currently, 13 m ha m of groundwater and 25 m ha m of surface water have been developed, totalling 38 m ha m. These figures are estimated to change to 35, 70 and 105 m ha m at almost full utilisation—almost a three-fold increase. It is estimated that currently 150 m ha m of natural runoff, mostly in the form of surface runoff is flowing to the sea or out of India. This figure is anticipated to change to 105 m ha m.

5. Floods

The extreme seasonal and spatial variability of water resources in India is dramatically yet catastrophically exemplified by the occurrence of droughts and floods in different parts of the country almost at the same time every monsoon. The damage by floods depends upon the use characteristics and land shapes of the flood plains. All river basins are prone to floods in view of the extreme variability of the monsoons but the Brahmaputra and the lower Ganga river basins are subject to serious floods every year. (National Commission on Floods, 1980).

A total area of 40 m ha is estimated to be prone to floods of which 32 m ha can be protected though by 1980 only 10 m ha had been protected. During the period 1970 to 1978, the flood affected area worked out to 11·9 m ha in respect of total area affected and 5·4 m ha for cropped area. The former constituted 3·9 % of the reporting area in the country while the cropped area affected constituted 7·8 % of the total net sown area. For major flood-prone states, relevant figures for the seventies are much higher *e.g.* 12 % and 10 % for Bihar, 10 % each for UP and 15 and 9 % for West Bengal.

Besides crop losses, floods cause considerable damage to houses and property as also loss of human and cattle lives. On an average 0·93 million houses were damaged every year during the last 25 years, and 1240 human lives and 77,000 head of cattle were lost. Railways, roads, communication lines, public utilities etc. also suffer considerable damage during high floods.

Average figures, however, conceal large year-to-year variations. For instance, in the case of the total area, while in 1965 only a million hectares were affected, the spread was many times more during the three years 1976 to 1978 being over 17 m ha. About 3,500 people lost their lives in 1968 as against only 34 in 1953. The picture would be similar in the case of other losses also. Besides the direct losses floods destabilize economic activity. For instance, the annual rate of agricultural activity during the period 1962–63 to 1970–73 was 1.94 % for the country as a whole. The rates recorded for most of the flood-prone districts of eastern UP was only in the range of 0·1 to 0·9 %.

6. Drought

Droughts are extended periods of subnormal precipitation. The effect of drought, however, depends on climate and man's adaptation to his environment. Thus in arid areas where man customarily depends on surface and ground water for irrigation and supply, the lack of rainfall for a few months may not be noted, but in humid areas where man relies more on water from current rainfall, lack of rain for a few months could be disasterous.

Agricultural drought occurs when the soil moisture is so depleted that the normal yields are reduced resulting in substantial economic loss. Water supply drought, on the other hand, is related to general nonavailability of water. While the definition of drought is thus arbitrary we define drought areas as follows. We first define arid and semi-arid zones as those where the difference between precipitation received and potential evapotranspiration is, less than 33 cm, and between 33 and 66 cm, respectively. The drought areas are those which have an adverse water balance and 20% probability of rainfall departure of more than 25% from normal. If this probability is 40% then the area is called a chronically affected drought area. The drought areas are shown in figure 13. In order that the area may tide over the drought, 30% or more of the area should be irrigated. The total drought prone area comprises about 16% of the total geographical area of the country and directly affects about 11% of the population.

7. Water quality

Water quality is defined by a variety of physical and chemical parameters and pertains to suitability for a particular use. It is determined by the geological and hydrological influences present in a basin and also by such man-made influences as regulation of flow, discharge of waters and accelerated soil erosion. Studies of water quality in India are very scarce and we may analyse the basic factors to come to a general assessment.

Sedimentary rocks contribute much more suspended material than igneous rocks. Significant concentrations of dissolved materials, such as sodium, calcium, magnesium, chloride and sulphate ions are commonly associated with sedimentary rocks retaining brine from former marine environments. Areas of heavy precipitation and runoff, in otherwise similar situations, reduce dissolved chemical content but have little effect on sediment loads and concentrations. Groundwater is usually more mineralized than surface water owing to its longer and more intimate contact with weathered rocks and soils. The management of watershed land has profound effects on the quality, and considerable improvement could occur with the use of proper practices. By the above considerations, the quality of natural water can be judged from the geohydrological map of figure 11.

Pollution problems start when water is withdrawn from its natural place of occurrence, put to domestic, agricultural or industrial use, and this impaired water returned to a water course. With proposed large scale diversion of water for irrigation, and simultaneous increase in population and industrial activity, the problem is particularly serious, as discussed later.

8. Related land resources

The total geographical area of the country is 328 m ha. Of this, only 305·5 m ha are accounted for in land use statistics (1967–68). The difference of 22·5 m ha largely consists of mountains, deserts and forests in inaccessible areas. Regionwise details of land resources are given in table 1. The overall position is shown in table 2.

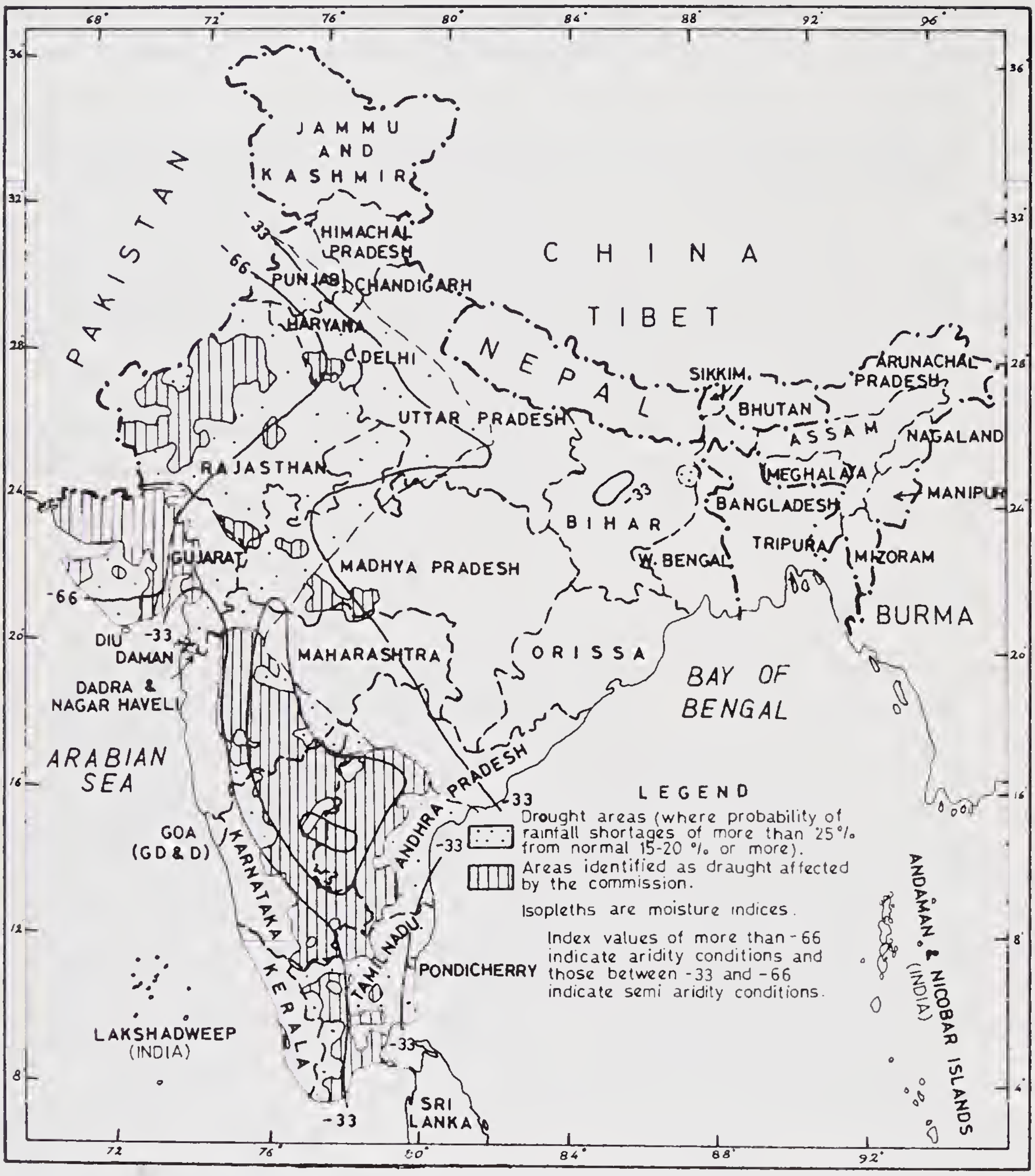

Figure 13. India—drought prone areas (source: Chaturvedi 1976)

According to the latest estimates (1972–73), the total arable area is estimated to be 175 m ha, of which 142 m ha would be under cultivation by the end of the Fourth Plan. The gross cropped area would be 169 m ha. According to present estimates 97 m ha of land or 55% of the gross cropped area can be ultimately irrigated both by surface and groundwater sources, their contribution being 72 and 25 m ha respectively. The concept of irrigation in these estimates, is, however, that of the marginal irrigation being provided as at present.

The percentage of the total land under cultivation in India is one of the highest in the world amongst the large countries. The percentage figures are: World 11·3; USSR 10·8; USA 16·2; China 11·5; India 49·7; Pakistan 30; Japan 15·5.

Table 2. Land resource statistics and projections (million hectares)

Classification	1970–71	2000	2025	% of total (2025)
Geographical area	328	328	328	100
Reporting area	305	318	318	96·95
Forests	66	70	70	21·34
Area under non-agricultural use	16	26	36	10·98
Barren and uncultural land (mountains, deserts and areas which can be brought under cultural use at high cost)	29	30	24	7·32
Miscellaneous trees, crops and groves not included in net sown area (thatching grass, casurina trees, bamboo bushes and other groves and trees for fuel etc,)	5	5	6	1·83
Culturable waste (not cultivated at present for the last 5 years or more)	16	9	4	1·22
Fallow lands other than current fallows (out of cultivation for 1 to 5 years)	9	5	3	0·91
Current fallows (not cultivated within one year for some reason)	11	8	5	1·52
Net area sown	140	150	155	47·26
Total cropped area	165	200	210	64·03

Source: National Commission on Agriculture, Part V, 1978.

9. Water resources development

Water resources development has received the highest importance in India right from prehistoric times down to the present. References to irrigation exist in folklore and ancient literature. Historical records bear testimony to the existence of a number of old works in different parts of the country. The characteristics of these were largely conditioned by the physiographic features of the area in which they were located. In the arid and semi-arid flat plains of North India, perennial rivers like the Indus and the Ganges made it relatively easy to direct flood flows through inundation channels. In the peninsula where the land is undulating but surface waters are not perennial, the practice of trapping stormwater in large tanks for domestic and agricultural purposes was widespread. In areas where a high groundwater table permitted lift irrigation, wells were common. These works were also of varied size. On the one hand, there were millions of small wells, on the other there were a few big canals, impressive for their times. The Grand Anicut near Tanjore built as far back as the 2nd century AD, irrigated 24,000 hectares in the beginning of the 19th century. The western and eastern Yamuna Canals and the Hasli Canal on the river Ravi were dug during the 14th to the 18th century, the latter irrigating 12,500 hectares in 1849.

Irrigation development under British rule began with the renovation, improvement and extension of existing works, like the ones mentioned above. When enough experience and confidence had been gained, new projects like the Upper Ganga canal, the Upper Bari Doab Canal, the Krishna Delta System and the Godavari Delta System were undertaken. These were major river diversion works, of the capacity of the order of 300 m^3/s. Very often, these were undertaken to stabilize the irrigation in the wake of famines from political and financial considerations. All these works were constructed during the period 1836 to 1866, but then there was a slackening after this period for a couple of decades.

Attracted by the profitability of these schemes, two private companies planned grandiose schemes to construct transcountry link canals, but they failed. All that was achieved was a series of disconnected waterways. However, two decisions followed from these activities. It was decided that in future, irrigation development would be undertaken exclusively by the government. Second, in accordance with the policy of private companies, finances were developed by public loans and works were undertaken only if they promised a minimum net return.

Not much activity was witnessed in the second half of the 19th century. However, following the great famine of 1876–78, the Famine Commission of 1880 recommended emphasis on irrigation, though no action was taken. The two great famines of 1897–98 and 1899–1900 however led to the appointment of an Irrigation Commission in 1901. Policy recommendations about financial criteria were developed and several schemes were proposed for public irrigation works. Emphasis was also laid on development of private irrigation works like wells and tanks, through higher outlays on comparatively easier terms. Much activity ensued, particularly on productive works and particularly in the area of Punjab in the context of the colonization of First World War soldiers. By 1920–21, the total irrigated area in undivided India (India and Pakistan) was 22·6 m ha.

Much of the irrigation development upto 1930 was in terms of diversion canals. There was little development in groundwater or even wells. The area irrigated by wells in British India was 4·68 m ha in 1902–03 and only 4·73 m ha in 1925–26. In 1930, hydroelectric development was undertaken in Uttar Pradesh by tapping the falls in the Ganga Canal and tubewell construction was started.

By the time of Independence, about 28·2 m ha of land, almost 24% of the cultivated land, was under irrigation. Source-wise, 54% of the area was irrigated by canals (mostly Government-owned), 23% by wells, 12% by tanks and the remaining 11% by miscellaneous sources. Much of the canal-irrigated area was, however, in what constitutes Pakistan now, and after independence, the irrigated area in India was reduced to 19·7% of the net sown-area against the earlier figure of 24·1% of undivided India.

Table 3. Irrigation potential (in m ha) (gross)

Period	Major and medium	Minor irrigation: Ground	Minor irrigation: Surface	Minor irrigation: Total	Total irrigation	Percentage of ultimate potential
1. Pre-Plan (1950–51)	9·70	6·50	6·40	12·90	22·60	19·9
2. End of 1st Plan (1956–58)	12·19	7·63	6·43	14·06	26·25	23·3
3. End of 2nd Plan (1960–61)	14·33	8·30	6·45	14·75	29·08	25·7
4. End of 3rd Plan (1965–66)	16·56	10·52	6·48	17·00	33·56	29·6
5. End of Annual Plans (1968–69)	18·10	12·50	6·50	19·00	37·10	32·7
6. End of 4th Plan (1973–74)	20·70	16·50	7·00	23·50	44·20	38·9
7. End of 5th Plan (1974–78)	24·77	19·80	7·50	27·30	52·25	46·0
8. Addl. target (1978–79)	26·12	20·85	7·75	28·60	54·90	48·4
9. Addl. target (1979–80)	27·22	22·10	8·00	30·10	57·50	50·7
10. Target 6th Plan (1980–85)	33·72	29·10	9·50	38·60	72·60	64·0
11. Ultimate feasible by conventional	58·60	40·00	15·00	55·00	113·50	100·0
12. Additional through national prospectives	25·00	10·00	—	10·00	148·00	—

Water resources development received the highest importance after Independence. Many impressive storage works, like the Bhakra Dam, the Rihand Dam, and the Earth and Rockfill Ramganga Dam to name a few, were constructed to augment irrigation facilities and hydropower generation. Equally important is the groundwater development particularly through private tubewells. This has unfortunately been limited to the arid areas of northwest India, particularly in Punjab.

The development of irrigation is shown in tables 3 and 4 and figure 14. Table 3 gives the development of irrigation source-wise and table 4 gives the net area sown, net area irrigated and the percentage of net area sown. The growth of irrigation is also shown in figure 14. The area irrigated crop-wise is given in table 5.

The achievements vary from State to State. Rainfall irrigation and sources of irrigation state-wise are given in figure 15.

Table 4. Development and future of irrigation in India

Year	Net area sown (m ha)	Net area irrigated (m ha)	% of net sown area irrigated
1950–51	110·75	20·85	17·56
1955–56	129·16	22·76	17·62
1960–61	133·20	24·66	18·51
1967–68	139·70	27·52	19·70
1973–74	142·71	32·60	22·85
1977–78	149·93	40·00	26·68
1982–83	155·17	52·40	33·77

Source: Irrigation Commission Report (1972); Sixth Five Year Plan. Figures for 1982–83 are estimates

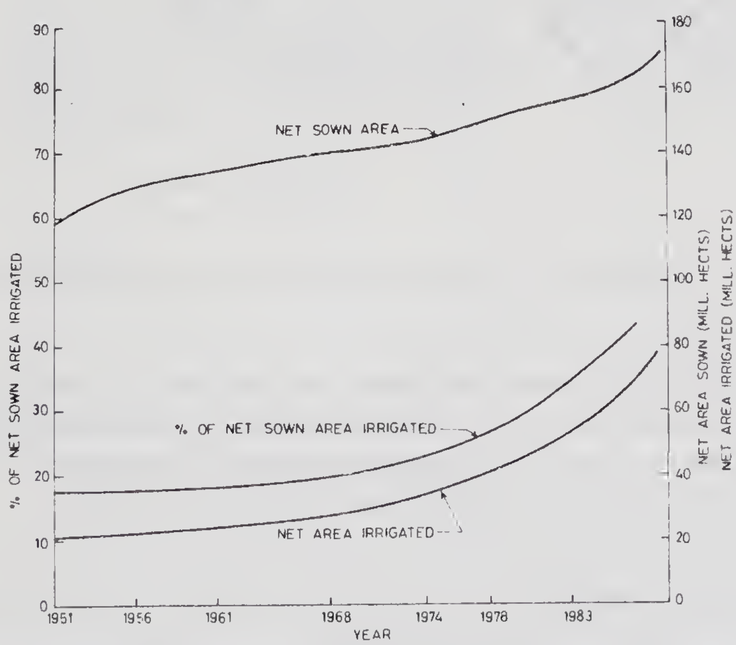

Figure 14. India—development of irrigation (source: Singh 1980)

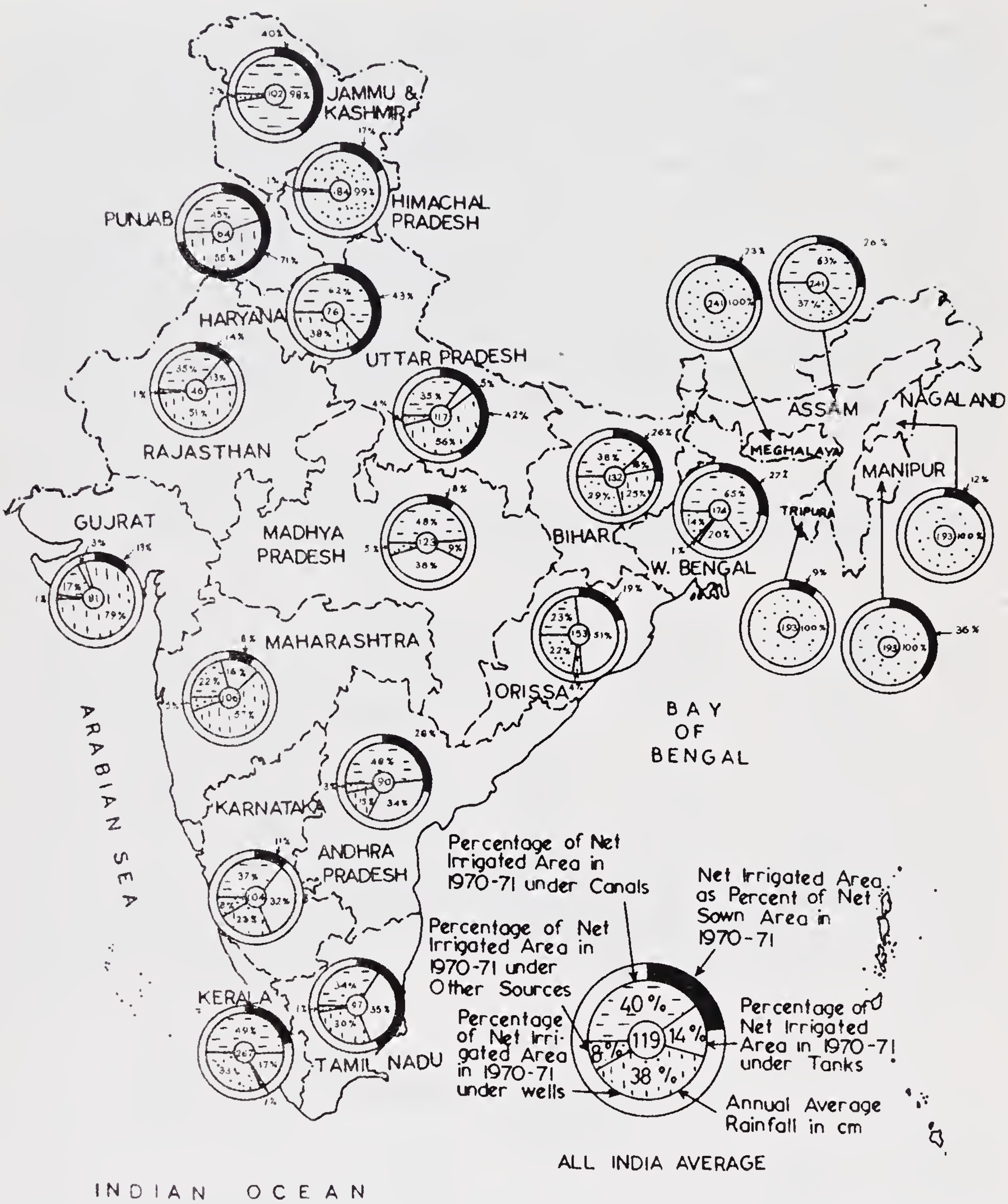

Figure 15. Rainfall, irrigation and sources of irrigation (source: Commerce Annual Number 1976)

Besides the quantitative increase, qualitative changes have also taken place. In addition to surface diversion works, several large dam and considerable groundwater development have also taken place. In addition, schemes of command area development for field-level distribution and application have been taken up.

10. Hydroelectric development

The hydropower potential of India is quite rich and is still largely untapped. The country's economically exploitable hydropower resources have been estimated at

Table 5. Irrigated area under principal crops

Crops	1970–71	1985	2000 AD
Rice	14·93	21·50	24·00
Wheat	9·84	14·00	14·90
Other cereals	3·80	5·76	6·99
Total cereals	28·57	41·26	45·89
Pulses	1·99	4·30	5·37
Total foodgrains	30·56	45·56	51·26
Oilseeds	1·02	2·80	5·10
Cotton	1·29	4·00	7·50
Sugarcane	1·90	3·25	5·00
Tobacco	0·10	0·25	0·40
Other crops	3·63	5·14	14·74
Total non-foodgrains	7·94	15·44	32·74
Total irrigated area	38·50	61·00	84·00

Table 6. Basin-wise abstract of hydropower potential and development in India (*MW*)

Name of river basin	Power potential*	Installed capacity	Effective capacity	Balance to be exploited
Indus	7,000	3,039	2,370	4,630
Ganga	5,000	1,899	1,127	3,873
Brahmaputra	12,000	276	152	11,848
Sabarmati	Nil	Nil	—	—
Mahi	100	Nil	—	100
Narmada	1,000	Nil	—	1,000
Tapi	300	300	115	185
Subarnarekha	100	130	26	74
Brahmani	1,000	Nil	Nil	1,000
Mahanadi	1,000	270	200	800
Godavari	6,000	1,355	662	5,338
Krishna	1,500	1,893	1,096	404
Pennar	Nil	Nil	—	—
Cauvery	1,000	940	586	414
Medium and Minor Basins	5,000	3,881	2,987	2,013

Source: Rao (1976)
* These are earlier figures. The present potential is estimated to be 75,400 W.

41,000 MW at about 60% load factor of which only about 10% is utilised at present (Sixth Five Year Plan 1980). In addition, the potential of Nepal is 85,000 MW of which none has been exploited. It is further considered that these estimates are on the low side and the actual potential may be almost twice as much. For instance according to a more recent estimate, the potential in India has been put at about 75,400 MW.

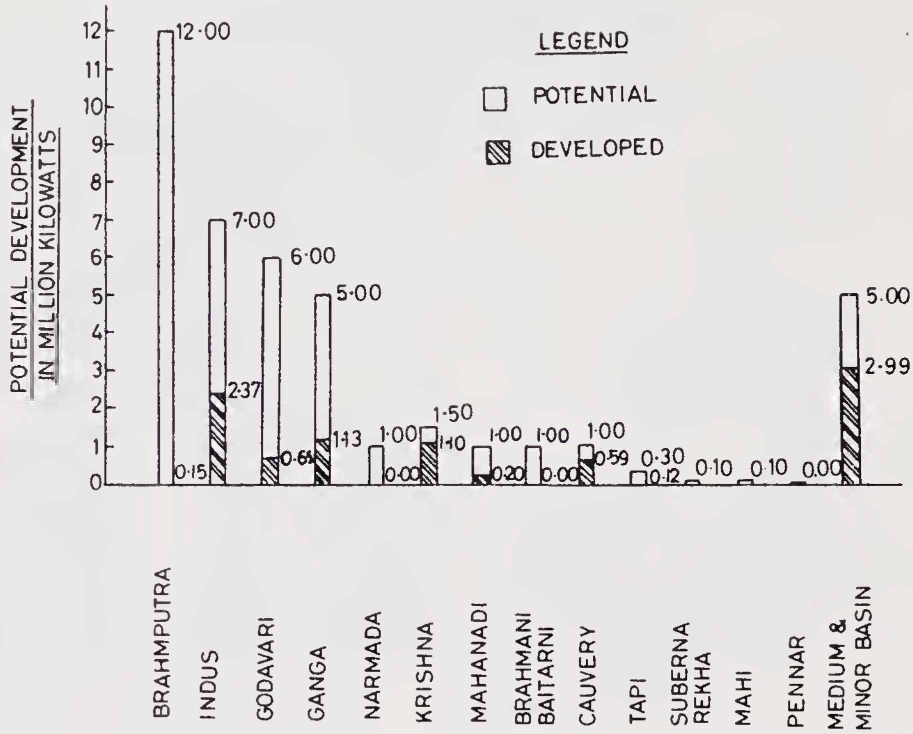

Figure 16. Hydropower potential and development in India (source: Rao 1976)

A basin-wise abstract of the hydropower potential and development in India is shown in table 6 and figure 16.

11. Conclusion

India is rich in natural resources, land and water, which however, have to be developed to improve their productivity. With the rising population and efforts on economic development, the problem is extremely important and urgent.

Development of water resources is central in this context as water is generally not available where and when required. India's arid-monsoon climate and geographical features lead to extreme seasonal and spatial variations. Efforts in this direction have been made since time immemorial, but as the overview shows, we have a long way to go.

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Water in India's development: Issues, developmental policy and programmes, and planning approach

MAHESH C CHATURVEDI

Applied Mechanics Department, Indian Institute of Technology, New Delhi 110016, India

Abstract. The importance of water resources development for sustaining life and the agrarian economy under the conditions prevalent in India is brought out. The inadequacy of drinking water and irrigation facilities inspite of large investments under the various Plans is very disappointing, as also the poor development of the hydroelectric potential. Despite the rich environmental and natural resources of India, there has been very little developmental work due to various reasons, chief of them being non-involvement by specialized technologists in the areas where they matter most. The need for a scientific policy and a planned approach is emphasized so that higher employment generation and rapid economic growth can be achieved.

Keywords. Water resources development; developmental policy; technological planning.

1. Introduction

From legendary accounts down to latest planning documents, development of water resources has been considered to be of the greatest importance in India. This is understandable in view of its crucial importance for sustaining life and the agrarian economy under the characteristic climatic and hydrologic conditions of India. Yet even till the beginning of the Sixth Five Year Plan (1981) this development could not be described as satisfactory. For instance only 10% of the rural population had been supplied with safe drinking water and only about 30% of the cultivated land had been irrigated (Sixth Five Year Plan 1981). The reliability and quantity of water supplied for irrigation is also inadequate and is reflected in low yields. As stated in the Sixth Plan Document, "Inspite of the large investment made in the irrigation sector and the phenomenal growth of irrigation during the past 30 years, the returns for the investment both in terms of yield as well as finance are very disappointing". Against this achievement one may note, to give an example, the achievement of 67·7% of irrigated land in China even by 1968 and correspondingly a much more stable agricultural base (Leeden 1975; Swamy 1973).

A review of other sectors reveals a similar picture. Out of the hydroelectric potential of 75,400 MW, only 10% had been developed and out of 40 MHA of the flood-prone area, only 10 MHA had been provided with protection till 1981 (Sixth Five Year Plan 1981).

This sad state is particularly poignant in view of the fact that India is rich in environmental and natural resources—land, water and sunshine, as can be seen from some salient statistics given in table 1. These are only indicative figures and have to be interpreted with care. For instance, in large parts of the world, unlike India, only one crop can be had per year, while on the other water resources may be available such that, again unlike India or China, that these could be readily used without much human

Table 1. Some salient statistics of land, water and population

Region	Cultivable land/ total geographical area (%)	Utilizable water/unit land (m)	Population density (/km²)
India	43	0·3	166
China	11	0·17	75
Northwestern Europe	26	0·49	91
Southern Europe	64	0·2	81
U.S.A.	19	1·4	22

Source: Calculated from Leeden (1975) and de Mare (1977)

intervention. For instance, only 6·8 % of the total cultivated area in Europe and 9·6 % in USA have to be irrigated.

To a large extent, our colonial history may be said to be responsible for this sorry state of affairs. For instance, the net irrigation intensity (net irrigated area/net cultivated area) was only about 17 % in 1947 at the time of Independence. Impressive technological achievements can be noted since then and the irrigation intensity has been almost doubled. Yet a critical study of the policy documents indicates that it has not been possible to break from the past heritage of colonial concepts, policies and institutional framework. An *ad hoc*, technologically-oriented planning and bureaucratically-managed development by officers rather than by specialised professional engineers continues. It will be argued that all this needs to be changed as otherwise it will not be possible to break the crawling agricultural growth rate of about 2·13 % of the past. Besides, a serious resource depletion and environmental dilemma will also be encountered very soon. It will be shown that much higher employment generation, rapid economic growth with regional and local equity can be achieved and the spectre of resource depravation and environmental destruction can be avoided if a scientific policy and planned approach is adopted. This will require, first and foremost, institutional modernization, which is also briefly discussed.

2. Developmental policy

For the sake of convenience the developmental policy may be divided into two phases: (a) pre-Independence and (b) post-Independence phase. The reason for this is the scale of development and technology rather than, as will be emphasised later, modernisation of policy.

2.1 *Pre-Independence phase*

Efforts have been made in India since time immemorial, consistent with the techno-economic capability of the people, to develop tanks, wells and small canals for the development of water resources for drinking water and irrigation. It is important to note that a considerable portion of the current water resources development is due to these historical efforts. The reliability of water supply from these historic sources was inadequate and naturally these could not lift the population out of sustenance agriculture or even meet the demands of the growing population triggered off in the last century.

During the early British period, little heed was paid to the development of water resources. Detailed studies of policy have not been carried out but it appears reasonable to conclude that the foreign government was primarily interested in maintaining law and order and undertaking only financially remunerative activities (Irrigation Commission 1972; Cautley 1860; Lieftink *et al* 1969). As Cobden stated in the British Parliament in 1855 "The single city of Manchester in the supply of its inhabitants with the single article of water has spent a larger sum of money than the East India Company has spent in the 14 years from 1834 to 1848 in public works of every kind throughout the whole of its vast dominions" (Clairmonte 1961).

The increasing population and exploitary policy of the foreign government created increasing strain on the economy and famines became more frequent and intense (Bhatia 1967). Irrigation had, therefore, to be developed to avoid politically disturbing phenomena. It is significant to note that many important irrigation works, such as the Eastern Yamuna Canal in 1820, the Eastern Yamuna and Upper Ganga Canal during 1830–1854, the Upper Bari Doab Canal in 1851, the Godavari and Krishna anicuts in 1850, the Agra Canal in 1873, to name a few, were constructed for increasing revenue and averting famines. It may be noted that irrigation activities were undertaken not where there are easily developable facilities, such as eastern Uttar Pradesh (UP) and Bihar but in the arid western and border areas. The reason was that these were more famine-prone and politically sensitive. The socio-political objective of irrigation was thus only to stabilize the sustenance agriculture for which extensive irrigation became the logical policy (Irrigation Commission 1972). Technological, economic and financial considerations also supported this policy. Groundwater control was not known at that time, the only technology known being surface diversion which cannot provide dependable and adequate water supplies. Fear of water-logging indicated extensive irrigation through diversion of the low flows. The poor paying capacity of the farmers and lack of technological capability to give assured supplies also pointed in the same direction. Similarly nonavailability of modern agricultural inputs also did not put pressure for dependable and adequate supplies.

Besides irrigation, other uses of water resources *viz*., navigation, flood control, drainage, hydroelectric development or even water supply for drinking purposes did not get any importance. Even irrigation got low priority compared to railways as the latter were considered essential for the maintenance of law and order. It may be noted that navigation canals were an outstanding financial investment for transport purposes in the growing economy of Europe at the beginning of the industrial revolution (Lansing 1966). The financial attraction encouraged water resources development for this purpose and even led to some private ventures in India, but it turned out to be a failure because corresponding industrial development was not taking place. Even for irrigation, the colonial government was content with supplying water up to canal outlets, leaving the rest of the task of conveyance and distribution to the farmers themselves. Activities such as land-levelling, drainage, lining of water courses etc., which demanded public participation were also not considered possible by a foreign government. These were not within the capability of the poor peasantry and were, therefore, neglected. Thus, in short, a policy of inefficient extensive irrigation through low flow diversions to stabilize the sustenance agriculture evolved from a convergence of social, political, economic, technological and financial considerations. It is significant

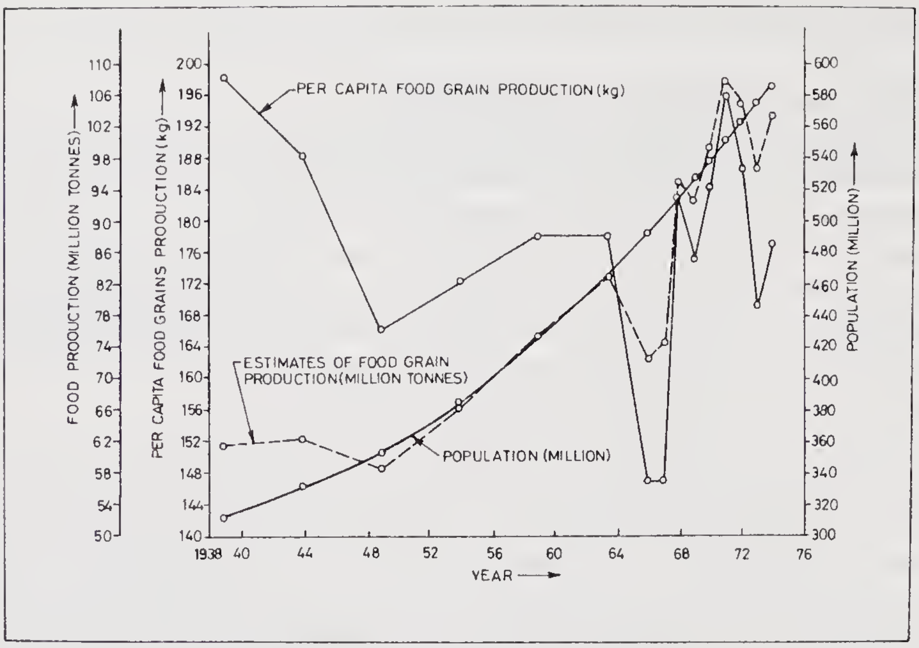

Figure 1. Population and food dilemma of India (based on data in National Agricultural Commission Report 1976)

to note that the per capita food availability continued to drop sharply till Independence, as brought out in figure 1.

2.2 *Post-Independence phase*

After Independence, although the highest priority has been laid on irrigation development and impressive developments have indeed taken place *e.g.* attainment of 58 MHA of irrigated area and large projects, it has continued on a technologically-oriented *ad hoc* project-by-project basis without any integrated policy analysis. In fact the colonial policy of extensive irrigation has continued to be followed uncritically. Developments have also been concentrated in those areas where developments had taken place earlier without much concern for regional equity. Study of several projects, shows that even when such technologies as storage dams and groundwater development are available, the old approach of inadequate and unreliable water supplies has continued and little attention has been given to the package of associated developmental activities at the field level. A high technology bias is also distinctly evident. Ever higher dams and larger canals have been the sole preoccupation of all concerned. Projects continue to be taken up on an *ad hoc* basis without detailed coordinated regional planning. Completion periods of projects get extended on various grounds and irrigation adaptation follows a leisurely pace. Conceptual awareness that integrated river basin planning and conjunctive surface and groundwater development should be undertaken are often stated in Government announcements or Commission Reports, but neither are these planned nor implemented.

Of late, increasing attention has been laid on field-level developments, incorporating them with integrated rural development through command area development (CAD) and water management. The CAD proposes a systematic programme of land consolidation, scientific land-shaping, construction of water courses and field channels to carry water to individual fields, field drains development, and a system of roads which will enable farmers to carry the produce to the market. Besides the above measures, adequate and timely supply of inputs is proposed to be ensured and marketing and other infrastructural facilities created so that the farmers are able to derive optimum benefits from available land and water. By the end of March 1980, 76 CAD projects had been undertaken which covered an ultimate irrigation potential of 15·3 MHA in 16 states and Union Territories. The area covered under the field channels and land levelling to the end of March 1980 was 30,82,570 HA and 9,36,970 HA respectively. But achievements are poor and the machinery is neither adequately motivated nor appropriately educated.

Similarly soil and water conservation programmes were initiated during the First Plan period and they have progressively intensified over the successive Plan periods. Till 1979–80, an area of 23·40 MHA was treated by various soil conservation measures. Considering the magnitude of the problem of land degradation, its regional and interstate ramifications and the high national priority accorded to tackle it, the Sixth Plan aims at an additional target of 7·1 MHA on the base of 23·4 MHA. However, the same comment as for CAD applies here.

Mention may also be made of the proposed modernisation programme. It has been realised that there are a number of old irrigation projects and even those constructed recently which are not able to meet the irrigation requirements. These are planned to be modernised but details and targets have yet to be developed.

A policy analysis was attempted only by the Second Irrigation Commission in 1972. However, as a perusal of the Irrigation Commission Report (1972) or National Commission on Agriculture (1976) will indicate, it is generally an assemblage of facts or an *ad hoc* enunciation of some policy issues without consistency and the critical analysis needed for the scientific formulation of a water resources developmental policy. Similarly other documents of Government or senior Government policy makers give no idea of the scientific policy (Rao 1976; Murthy 1975; U N Country Paper 1977).

There is mention of a strategy consisting of (a) expeditious completion of ongoing projects, (b) action on a few selected projects to set the tempo of future development, (c) modernisation of irrigation, (d) optimisation of benefits through better operation of existing systems and conjunctive use of surface and groundwaters and adoption of *warabandi* and (e) efficient water management in the Sixth Plan.

The need for detailed project formulation has been noted. It is further noted that "project consultancy and design engineering organisations would need considerable strengthening in such disciplines and types of projects where such consultancy organisations do not exist . . .. The requisite expertise where it is not available in the country could be drawn from amongst highly experienced and motivated Indians abroad". It is even stipulated that all project reports shall be completed in a phased manner by 1989–90.

It has been stated that "Stress is laid on dealing with interrelated problems through a system approach rather than in separate compartments, on greater management efficiency and intensive monitoring in all sections and active involvement of the people in formulating specific schemes of development at the local level and in securing their speedy and effective implementation".

Further, "The maximisation of production and income from every available litre of water will be one of the important objectives of the Plan. This will call for detailed attention to on-farm management of water jointly by the farmers in the command area of an irrigation project and the project authorities. Command area management in unirrigated areas and catchment area management in the catchment areas of major river systems will all have to be designed in such a manner that the people concerned and the administration can work together as partners in elevating and stabilising yields without damage to the ecosystem".

The targets, pronouncements, and strategies sound very impressive. Much has also been achieved. But when one reviews the efficiency of achievement, one is disappointed, as the Sixth Plan itself notes. The reason is not far to seek. If one examines the details of the plans and projects one finds a lack of scientific policy, detailed planning and design. Construction and management is also not efficient. There are also serious institutional and personnel deficiencies. In short, modernisation has not taken place as yet.

3. Developmental targets and implications

Between 1950–51 and 1978–79 the underlying trend rate of growth of national income was 3·5 %, of agricultural production 2·7 % and of industrial production 6·1 %. In per capita terms, income has grown at a trend rate of 1·3 %, which after allowing for the rising share of investment in national income, has meant a modest 1·1 % per annum rise in per capita consumption. The actual growth rates have generally been much lower than the targeted growth rate (Sixth Five Year Plan 1981).

In the Sixth Plan a growth rate of 5·2 and 5·5 % in the subsequent ten year periods has been envisaged. An annual growth rate of 5·20 in the value of output during the plan and 3·75 in the subsequent decade in agriculture has been postulated.

This is planned to be achieved by a rapid and long-term growth rate of irrigation of 4·2 % so that the ultimate gross irrigation potential of 113 MHA is achieved by 2000 AD against the 1978–79 figure of 58 MHA. It may be noted that the ultimate potential of 113 MHA was proposed to be achieved by 2025 AD by the National Agriculture Commission and the rate of achievement over the same period in the past has only been about 28 MHA in contrast to postulated additional 55 MHA. It is not spelled out as to how this dramatic doubling of the rate of achievement will take place particularly when it is noted that the past achievements have been extremely disappointing.

The aforesaid plans are based on utilizing the currently estimated utilizable potential of 105 MHM out of which 77 MHM shall be for irrigation. The components of development are given in figure 2 on the basis of the National Agricultural Commission (1976).

In addition, a national perspective for water resources development has also been developed for storage and interbasin transfer. It envisages the construction of 18·49 MHAM of storage capacity to enable additional utilisation of 20·96 MHAM of water for irrigating an additional 35 MHA and generation of 40 million kW of hydropower capacity. The particulars are given later on the basis of the Government of India document, but these are extremely flimsy (National Perspectives 1980). The development is proposed to be completed by the turn of the century.

Several contradictions are easily noted in these targets. First, the proposed development is *ad hoc* and conjectural. It is not based on any scientific policy or integrated regional development techno-economic plan. There is no evidence that the inefficiently developed irrigation plan will not continue. Second, the environmental issues have not been examined. The current policy of development envisages almost total low-flow diversion. This will be totally unacceptable from environmental

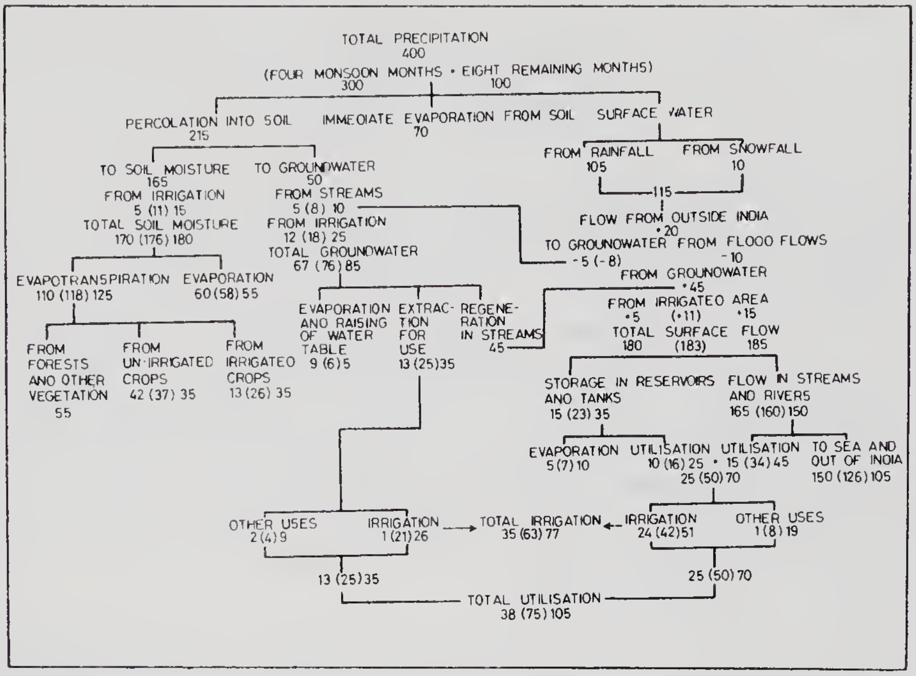

Figure 2. Approximate distribution of average annual water resources of India as in 1974 (2000 AD) and 2025 AD (MHM). Source: Natl. Agric. Comm. Rep. Vol. 5, 1976

considerations and demands for other uses (Lahiri 1975; Chaturvedi 1976). Third, the rapid rate of development contemplated is not shown in institutional modernisation, development of personnel to do the job and advance planning required to achieve these targets. The past achievement also does not inspire confidence about future targets being achieved. Fourth, although field-level developments have been mentioned, adequate emphasis has not been laid and uptill now neither plans nor institutional arrangements have been developed to achieve these targets. Fifth, groundwater development is likely to face energy constraints in view of the increasing difficulty of procuring oil and the perpetual constraints of electric energy, to mitigate which adequate emphasis on rapid hydroelectric development has not been placed.

4. Scientific developmental policy

The central point to be emphasized is that instead of vague concepts, an *ad hoc* approach and project-by-project contingency development, appropriate concepts, scientific policy, integrated regional development plans based on a systems approach and detailed projects should be developed well ahead of time. Some of these points are discussed below.

4.1 *Conceptual issues*

The first point to be noted is that technological development has to be an instrument of developmental objectives. According to the Sixth Plan (1980–85) these are visualised to be (i) a significant step-up in the rate of growth of the economy, the promotion of efficiency in the use of resources and improved productivity, (ii) strengthening the impulses of modernization for the achievement of economic and technological selfreliance, (iii) a progressive reduction in the incidence of poverty and unemployment, (iv) a speedy development of indigenous sources of energy with proper emphasis on conservation and efficiency in energy use, (v) improving the quality of life in general with special reference to the economically and socially handicapped population, through a minimum needs programme whose coverage is so designed as to ensure that all parts of the country attain nationally accepted standards within a prescribed period, (vi) strengthening the redistributive bias of public policies and services in favour of the poor, contributing to a reduction in inequalities of income and wealth, (vii) a progressive reduction in regional inequalities in the pace of development and in the diffusion of technological benefits, (viii) promoting policies for controlling the growth of population through voluntary acceptance of small family norms, (ix) bringing about harmony between the short and long-term goals of development by promoting the protection and improvement of the ecological and environmental assets, and (x) promoting the active involvement of all sections of the people in the process of development through appropriate education, communication and institutional strategies (Sixth Five Year Plan 1981).

Water resources have to be developed in the context of these objectives. For this purpose, first, certain basic concepts of modern water resources and environmental systems planning should be followed in future, in contrast to the *ad hoc* approach of the past. It must be emphasised that technology in the present context of development of water resources has to be an instrument to attain these objectives, embedded in the socio-economic development and not an elitist activity visualised merely in terms of certain grand projects. Tremendous possibilities for economic development and employment generation through development of water resources exist. For instance it is well-known that the yields in Indian agriculture are extremely poor. The basic reason for this is the nonavailability of adequate and reliable water, because of which other inputs of modern agriculture cannot be used. Yield and other relevant statistics given in tables 2 and 3 bring out the immense potential for increasing production and employment if water and corresponding inputs could be made available (World Bank Operations 1972).

Table 2. Comparative yields of some important crops (1969)

	Yield (kg per hectare)		
Country	Paddy	Wheat	Cotton
Japan	5,550	—	—
UAR	5,110	—	790
USSR	—	—	770
France	—	3,580	—
USA	4,790	2,060	490
Taiwan	3,510	—	—
Thailand	1,840	—	—
Pakistan	1,820	1,070	310
India	1,610	1,170	120

Source: Chaturvedi (1976)

Table 3. Developmental potential in agriculture

Country	Agricultural output per farm worker (dollars)	Arable land per agricultural worker (hectares)	No. of agricultural workers per hectare of arable land	Fertilizer used per hectare of arable land (kg)	Agricultural output per hectare of arable land (dollars)	Gross domestic product per capital (dollars)
Group I						
Israel	1,825	333	0·31	80·5	557	905
Argentina	1,080	13·1	0·07	n.a.	78	465
Japan	402	0·4	2·39	303·7	961	337
Greece	391	1·9	0·52	38·0	205	297
Mexico	369	4·1	0·30	9·4	110	321
Group II						
Egypt	365	0·6	1·76	87·0	643	155
Turkey	326	2·6	0·39	1·5	127	254
Yugoslavia	250	1·8	0·57	28·0	141	179
Brazil	229	1·4	0·45	13·0	104	145
Taiwan	228	0·6	2·10	203·8	477	97
Pakistan	182	1·5	0·73	3·2	133	64
Philippines	181	1·2	0·77	12·5	139	113
India	114	1·2	0·80	2·3	91	70
Thailand	94	0·9	1·13	2·3	106	84
Average	229	1·3	0·97	39·3	218	129

Source: Changes in agriculture in 26 Developing Nations, 1948–1968 (U.S. Department of Agriculture, Foreign Agricultural Economic Report No. 29, 1965), as quoted in World Operations, Johns Hopkins Press, 1972.

The second point to be emphasized is that water is a crucial vector of the geophysical-biological environment and an important resource of the environmental-ecological system. Its development has thus to be in the context of socio-economic development consistent with environmental enhancement. A long-term view of the environmental state and dynamics has also to be maintained. Thus, for instance, it is necessary that certain minimum flows and water quality of surface flows is maintained, groundwater quality is constantly watched, and soil erosion is reduced.

The third point to be emphasised is the need for a creative approach. One can develop a number of technological options and one must choose critically instead of being conditioned by certain techno-economic myths. For instance there is need for conjunctive surface-groundwater and energy planning but this is more than what is meant in the Government document. Again there is need for integrating traditional technological solutions of surface diversions and conventional groundwater development with watershed development to alter land-water dynamics itself. These points are elaborated later.

In this context it may be emphasised that technology includes, besides constructed structural products, development of appropriate organisation and incentive systems. One must, therefore, think of total technological systems development. For instance when we think of dams and canals, or public or private tubewells, each has an appropriate organisation and the totality of the technological system has to be developed. One set may be better than another from the point of view of appropriateness of organisation rather than technological structure.

The fourth point to be emphasised is that water is an environmental-resource vector which has a dynamics explained through the hydrological cycle in terms of state and processes. The technological activity seeks to modify this cycle in terms of varied demands. There is thus a spatial and dynamic interlinkage of the various projects from hydrologic, economic and environmental considerations. Thus regional dynamic long-term planning is mandatory even though activity has to be initiated through individual projects.

Thus water resources development has to be undertaken in terms of individual projects developed creatively and with sensitivity in accordance with a long-term dynamic developmental policy in the context of socio-economic environmental multiobjective policies to satisfy the multipurposes. Although development has to be undertaken in terms of projects, to identify the optimum portfolio of projects long-term policy and systems planning is mandatory. Some of the policy issues with focus on various multipurposes are discussed below but it must be emphasised that the developmental policy has to consider all the purposes integrally and should be region-specific.

4.2 *Policy issues with focus on habitat requirements*

Water supply for human settlements for drinking and other domestic purposes may be considered to be the most important demand. These requirements are a small portion of the total demand. It is considered that adequate resources and technology are available in all parts of the country to meet this demand and this could be adequately met if there is the political will.

In this context, we have also to have a policy for habitat. As tubewells and canals are developed for irrigation these can be easily used for supplying habitat demands not only of sustenance but also of environmental enhancement and recreation.

4.3 *Policy issues with focus on irrigation*

Agricultural needs account for about 90% of resource development and are crucial for socio-economic development. Water is also important for electrical energy and navigation. Water resources development for agriculture should be integrated with energy system planning and transportation system planning for several reasons as discussed later. For developing the policy, we however concentrate on water resources development for irrigation in the first instance, but also integrate the policy with electrical energy development and flood mitigation.

The possible important technological options for multipurpose water resources development are given in figure 3. Additional programme and policies for modifying the susceptibility to flood damage and modifying the loss burden are given in figure 4.

All these options are interlinked and not necessarily exclusive *i.e.* they are open-interactive sets. A portfolio has to be chosen so that, consistent with conservation of resources and environmental improvement, the planning objectives generation of employment generation, economic efficiency and equity are optimally obtained temporally and spatially, taking into account the regional, hydrologic, agro-climatic and demographic potential and the developmental scenario over a period of time. The alternative configurations, scale, operating policies and timing can be identified through systems planning as discussed later. Further, as stated earlier, technological planning does not mean only optimum capacity and timing of the projects, but also

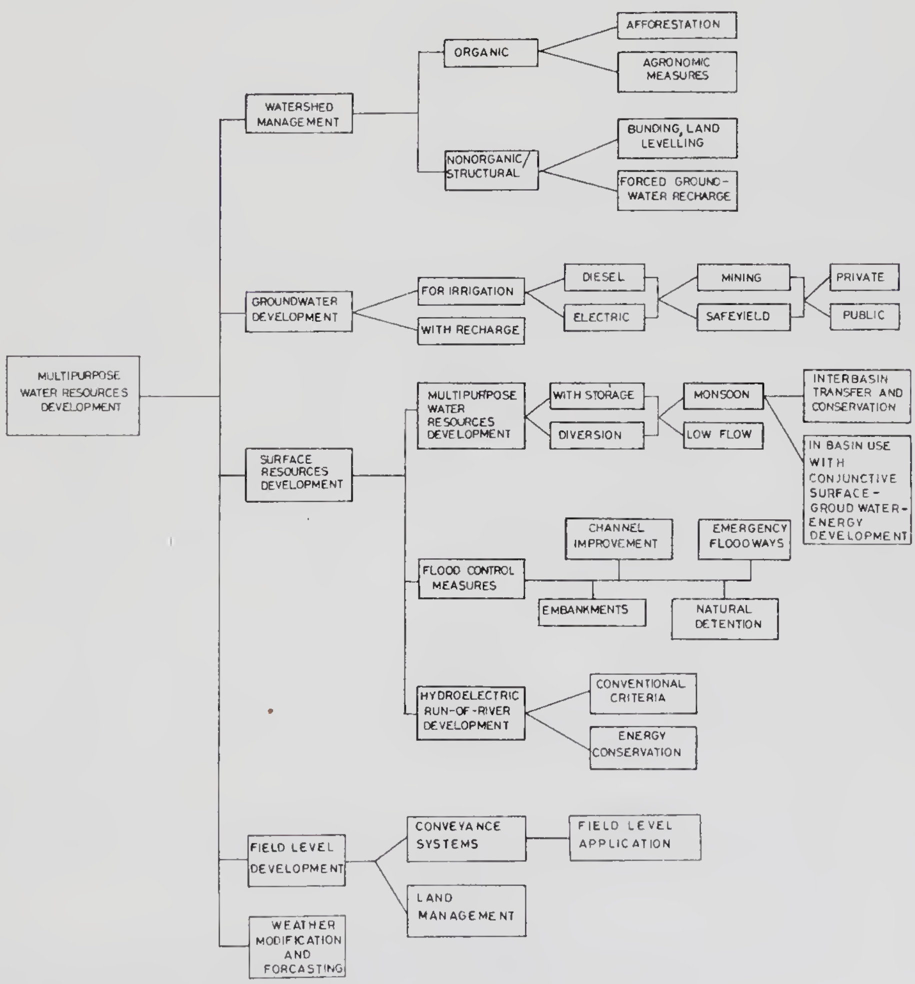

Figure 3. Technological options for water resources development

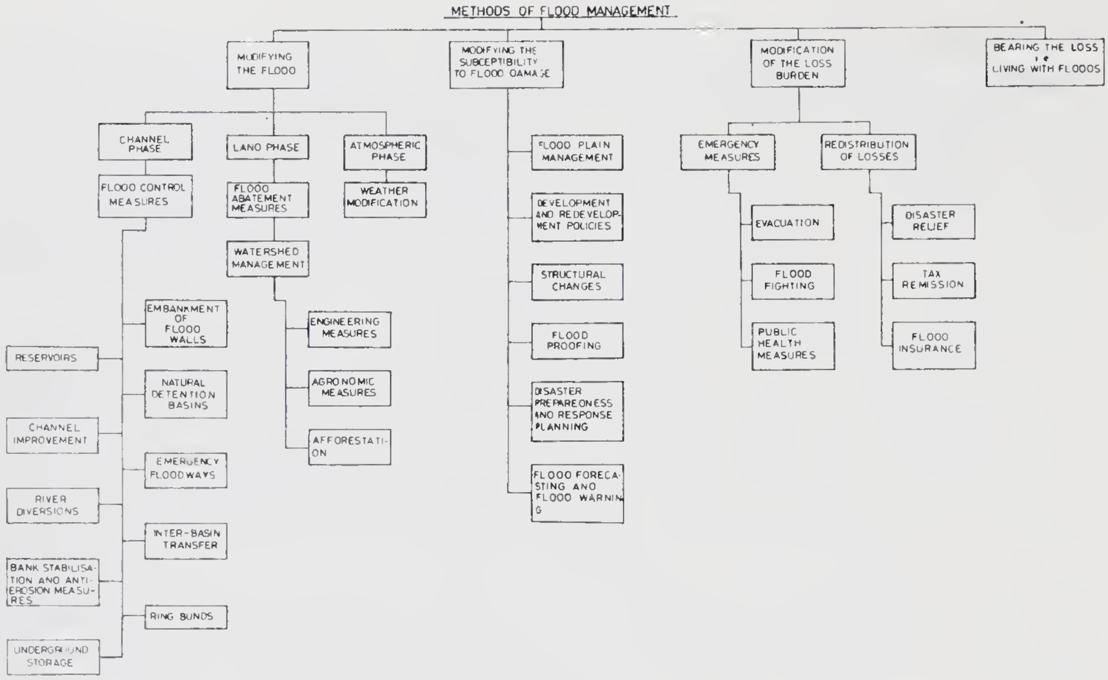

Figure 4. Programmes and policies for modifying the susceptibility to flow damage and modification of the loss burden. Source: Natl. Comm. on Floods (1980)

development of an appropriate organisation and incentive system. For instance, better economies in ground-water technological options may be obtained if cooperatives are developed at the field level. This is a difficult task requiring social management and, therefore, while it may be attempted in the long run, less efficient technology of individually-developed small-scale tubewells may be encouraged, if necessary.

Let us examine each set starting with watershed management. Traditionally, water resources developmental activities have centred around spatial and temporal transformation through structural techniques of diversion works, dams and tubewells after certain land-water interactions have taken place. It may be worth considering altering land-water dynamics through organic and non organic/structural techniques as shown in figures 3 and 4 for flood mitigation, erosion control and water resources development through additional groundwater recharge. Certain areas like the alluvial plains of the Ganga basin offer attractive opportunities (Indo-U.S. Scientists Workshop 1981). The scheme of watershed management is particularly important in conjunction with groundwater recharge as discussed later and for development of runoff from the entire land area. The issue is that the hydro-geological interaction, particularly from the resource point of view is as shown in figure 5. By technological intervention, the natural state can be altered at any level of interaction.

Groundwater development, particularly in the alluvial Indo-Gangetic plains and Eastern coastal regions is of particular importance and priority as it can be developed fast. There are several policy issues such as what should be the scale—small or large; what should be the organisation—private or public; whether it should be diesel or electric and whether there should be mining or whether development should be confined to safe yield. Each can be considered a different technology and tested through systems models. Some aspects may be noted.

Groundwater development through private low capacity pumps has the advantage of mobilising local initiative, generating fast development, employment through simple

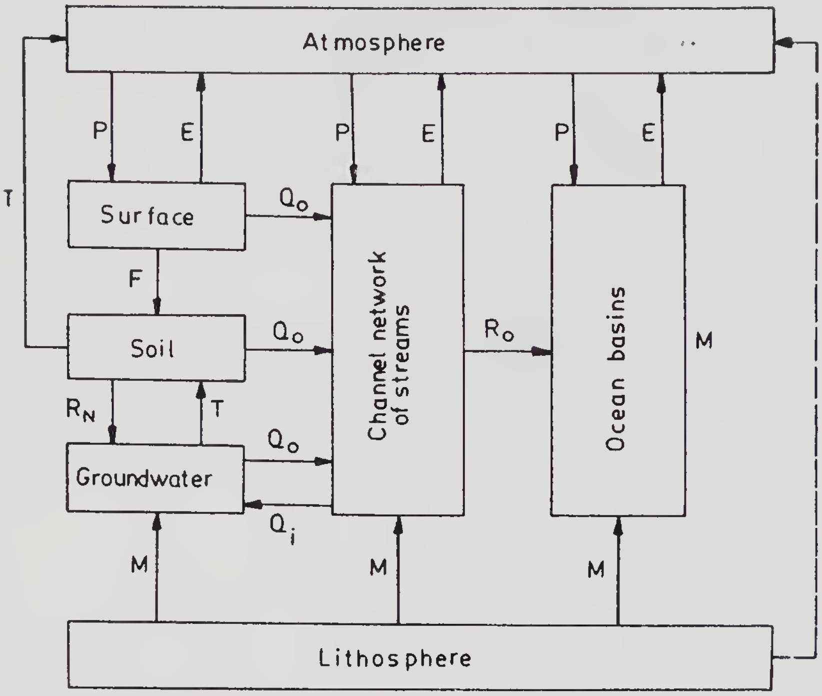

Figure 5. Hydrogeological interaction. *P*: precipitation, *E*: evaporation, *T*: transpiration, Q_0: surface runoff, *F*: infiltration, Q_i: groundwater seepage, *M*: water of volcanic origin, R_N: percolation

construction techniques and assurance of more dependable supplies. Public tubewells provide economies of scale. It is debatable which contributes more to social justice. It can be argued that private development be through low-capacity diesel tubewells and public development be through high-capacity ones. Studies in one river basin indicate that large-scale tubewells give only 5% additional benefits while posing management problems (Chaturvedi & Khepar 1981). These results are based only on one study and more studies are required. An optimum development has to be worked out for each planning unit (village, block, district) through a systems study.

In certain situations it may be possible to develop groundwater in conjunction with surface water by storing the latter through groundwater recharge. Three technological options have been suggested. One is storage of monsoon flows through induced groundwater recharge by heavy pumping prior to monsoons along perennial and non-perennial rivers. The scheme has been termed Ganga Water Machine (Revelle & Herman 1972; Chaturvedi *et al* 1975; Revelle & Lakshminarayan 1975; Chaturvedi 1981a). The second option is by heavy irrigation during monsoons through leaky canals with conjunctive prior groundwater development and its lowering (Chaturvedi & Srivastava 1978). This has been termed as Kharif Channel Conjunctive Development and has been shown to be more economical than the first one. However, one or both can be used as found suitable.

The third alternative could be to pump down the excess rainfall at the field level itself and thereby have additional resources and reduce floods. The conventional tubewells could be used for this purpose through suitable provision of ordinary valves. Alternatively, a low-capacity low-head reversible pump would be required for this purpose. Preliminary studies have indicated its techno-economic feasibility (Sohoni 1976). It may be noted that for pumping down the water, no additional energy would be required, except may be at the start of the operations or for achieving high rates of recharge. The scheme is termed micro water machine. It may be noted that at this time considerable secondary energy would be available.

Certain constricting myths have arbitrarily been imposed by technologists and these have lead to *a priori* rejection of some of the basic options. For instance, groundwater development is often restricted to the so-called safe yield, equivalent to annual recharge. There is no reason why secular reserves could not be developed, of course, subject to a policy that in the long run a steady optimum level of groundwater and recharge is obtained from considerations of economic growth taking into account possible recharge from surface water resources or interbasin transfer. For instance, after surface water resources have been developed groundwater availability will be enhanced and therefore mining may be done in the first instance. There may be the problem, however, that in this process the performance of the shallow well may be affected but an appropriate policy can be developed.

Surface resources have been developed for a long time but here too several issues have been neglected. For surface development, the two basic options are diversions with and without storage. Storage projects are very attractive and mandatory from an electricity generation point of view and even more so when planned from considerations of conjunctive surface, groundwater and energy development point of view. Figure 6 clearly shows the substantial advantages in additional water and power supplies. The issue of induced groundwater has also to be added, and the problem has to be considered in the context of spatial availability of the resources and demands (Chaturvedi 1979). It may be emphasized that current storage developments do not generally consider this integrated development and, therefore, do not represent optimal development.

It is also mandatory that catchment area development such as watershed management and upstream construction work is completed before the storage works are undertaken so that sedimentation does not jeopardise their economic life.

Surface diversions being economical and quick to construct have been the first priority in water resources development so far. The benefit/cost ratio is particularly attractive if capacity is limited to low flows. From environmental considerations, unlimited low-flow diversions are, however, unacceptable. Perhaps limited low-flow diversions may be tolerated, but the needless mass-scale diversions have created an extremely precarious position. In the long run, minimum flows will have to be restored by substituting with other technological options and the issue of navigation has to be considered.

Surface diversions of monsoon flows, that are known as kharif channels, on the other hand, are extremely attractive, particularly if developed conjunctively with groundwater development, as discussed earlier. The groundwater table may be developed such that groundwater recharge during monsoons from kharif channels plus groundwater development from long-term policy considerations plus permissible low-flow diversions or release if there are storage works to meet the non-monsoon requirements are adequate to meet winter (rabi) and summer requirements. Correspondingly, the capacity of kharif channels can be finalised.

Monsoon flows can also be used, and have been used, through local lift schemes. This is attractive when the diversion canal may interfere with drainage and floods, as in the lower parts of the Ganga basin and Bangladesh. Lift schemes are, however, important for interbasin transfer and conservation, as discussed later.

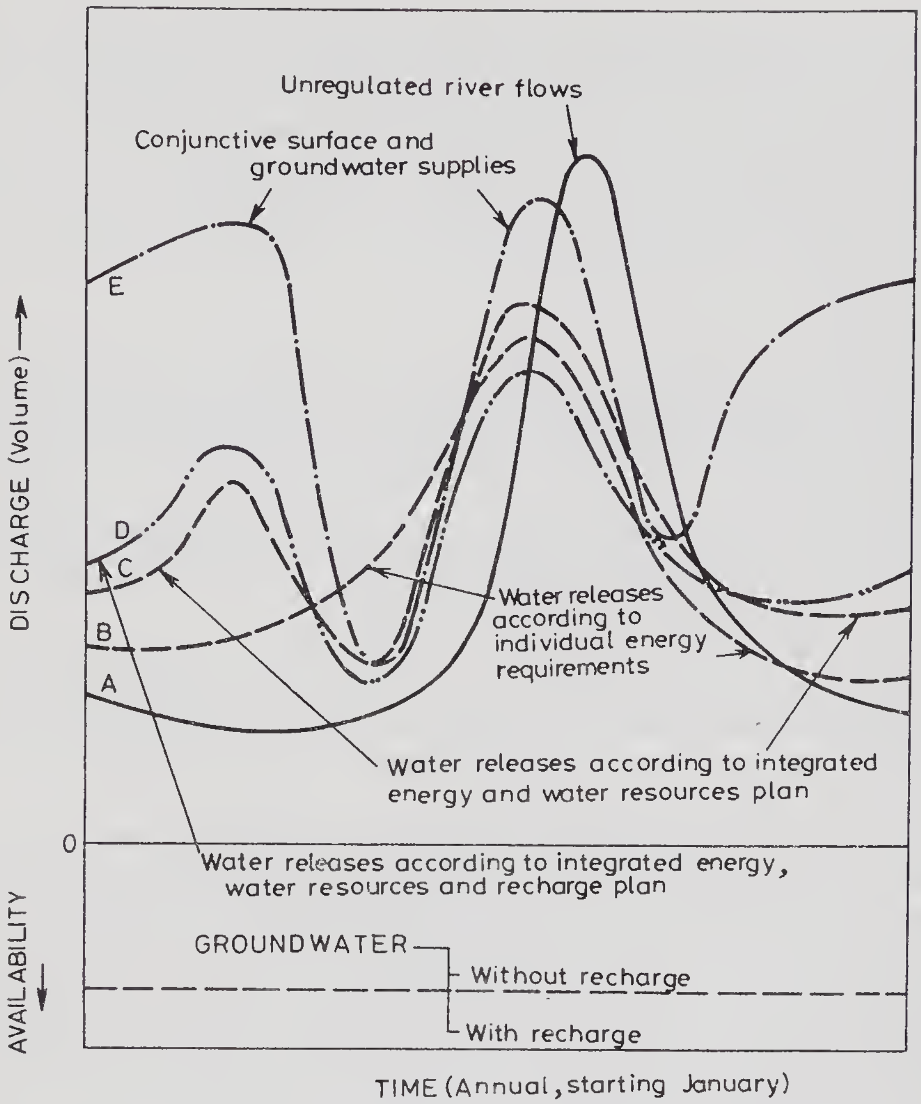

Figure 6. Conjunctive surface and groundwater development and integrated water and energy plan

The focus of attention so far has understandably been on major schemes, as they yield better benefit/cost ratio and even more important, are technologically more glamorous. It is important that total water resources development is considered integrally. It is considered that the resource availability and developmental attractiveness of the small or even non perennial schemes can be considerably improved by storing monsoon waters through appropriate technology and their development should be part of an integrated development with a portfolio of projects of appropriate capacity and with identified timing.

Besides the direct approaches of water resources development the supplies can be increased by more efficient conveyance and utilisation of water. This can be divided into two parts, the main distribution system, consisting of main canals, branches, distributaries and minors. Secondly, increased efficiency at the field level which includes increasing the efficiency of the conveyance from the main distribution system to fields and application at the field. The division has been made because the first was in the Government Sector and had received some attention but the second had, with the organisation of command area development activities, been left completely to the farmers till recently. Even in the first, many works are old and there is considerable scope for improvement and modernisation. The second has been termed field-level development. It is considered that it may be the most economical, easy to undertake and has large employment-generation potential. There is a choice of several alternatives, and sophisticated analysis is required to decide optimal strategies (Chaturvedi & Khepar 1981). In view of its importance we shall refer to it again later.

4.4 *Hydroelectric development*

The hydropower potential of India is quite rich and is still largely untapped. The country's economically exploitable hydropower resources have been estimated at 75,400 MW of which only about 10% of the potential is utilised at present (Sixth Five Year Plan 1981).

In addition, the potential of Nepal is 85,000 MW, of which almost none has been exploited. It is further considered that these estimates are on the low side and the potential is almost the double of these estimates.

At present hydroelectric development is being undertaken on an *ad hoc* project-by-project basis with capacity fixed on the basis of 90% availability of water resources annually with water availability estimated on a 10-day period on the basis of 90% availability. This is a gross under-utilisation of these resources for the following reasons.

First, we have to consider 90% reliability of the system and not of the individual project. Through complementarity of the different modal choices *viz* (i) thermal (coal and nuclear), (ii) run-of-river hydro and (iii) storage hydro, individual project capacities would be much larger through a systems approach.

Second, besides systems planning of production, integrated systems planning of supply and demand has to be considered which will lead to further optimal development of the potential. Reference has already been made to conjunctive surface groundwater and energy planning. The approach has been applied in a real-life study (Chaturvedi 1979).

With the increasing crunch on liquid energy fuel, the groundwater development tempo, which is crucial to agricultural development and consequently to national development, is in a serious state of jeopardy. Alternative sources of energy have to be developed fast and hydro-electric development has also to be accelerated.

In irrigation and hydro-projects, capacity and operation are planned on the assumption that irrigation supplies have to be met first. A nominal allocation is made, as a power cushion on an *ad hoc* basis. This is wrong. Alternatively optimal capacities and operation schedule have to be carefully worked out through multiobjective analysis with integrated surface-groundwater and energy planning. Often planning from energy considerations will be dominant (Chaturvedi & Rogers 1985).

4.5 *Policy issues with focus on flood mitigation*

A unique characteristic of water resources in India is extreme temporal variation. A drought can very soon be followed by serious flood followed by a long period of water scarcity. Flood and drought are not only extreme stress characteristics for the water component of the physical environment, but for human and other biosystems as well.

A study of the flood problem has been carried out by the National Commission on

Floods (NCF 1980) recently. It has been estimated that about 40 MHA of area may be considered as 'flood-prone' of which 10 MHA have already been provided with reasonable protection. It is considered that 80% of the flood-prone area could be provided with reasonable protection, and that at the present level of prices, these activities will cost Rs. 51,000 crores.

Technological options for flood mitigation and programmes and policies for modifying the susceptibility to flood damage and modification of the loss burden are given in figure 4. Prevention of floods through organic activity such as afforestation and agronomic practices, appear to be important. Precipitation conservation at field level by bunding and forced groundwater recharge, storage, kharif channels and embankments, planned integrally appear to be feasible leading to flood mitigation and water resources development (Chaturvedi 1981a). The matter is not discussed further as it has to be developed in concrete terms for each river basin. We would only like to emphasize that the problem of flood management has so far been neglected in planning water resources development in India. Flood mitigation is also necessary for modernised agriculture and employment generation.

4.6 *Policy issues with focus on navigation*

Somehow navigation has been completely omitted from water resources development in India. Several reasons appear to be responsible for this omission. One, in the colonial policy, navigation was not found to be economical. Second, flow diversions for irrigation conflict with navigation requirements and apparently the latter have been summarily overlooked. Third, Indian rivers have large inter-seasonal variability and this may have posed some problems for navigation.

It appears, however, that overriding all these factors is the fact that integrated planning has not been carried out and navigation has been dropped on an *ad hoc* basis as water resources development is carried out on the basis of the functional orientation of planning agencies. It is not often realised that 2–3 m depth and 30–40 m width is enough for large-size navigation requirements. These dimensions would be provided even by many canals and rivers if environmental considerations were developed.

4.7 *Policy issues with focus on environment*

The natural land-water state is one level of the environment-resources vector. With development, it gets changed to another state. Any perturbation has ecological-biological-physical besides socio-economic implications which are extremely complex. It is difficult to say what are the minimum surface flows and groundwater development from environmental considerations but it would be logical to argue that there must be a limit to physical development and any large-scale perturbation must be carried out only after careful study of the environmental implications.

4.8 *Drought policy*

Drought is difficult to define as it relates to water availability as well as techno-economic capability of development under a given environment. Israel is a semi desert with an annual rainfall of 500 mm with wide spatial and temporal variation. Yet it has the most highly modernized irrigation and agriculture development. In India according to the Irrigation Commission, 16% of the total geographical area accounting for over

11% of the population has been classified as drought-prone. The strategy of development would be to emphasize efficient use of local water resources supplemented by imports. Priority has to be given first to drinking and other domestic uses of water, then for industry and then for appropriate agriculture, including animal husbandry. The matter is one of detailed analysis and does not alter basic policy options.

It will follow from the above that an integrated water resources development taking into consideration all demands and resources availability on a long-term basis on a regional and interregional basis has to be carried out. The above discussion is only a background for detailed system studies as discussed later.

5. Field level water management

Much of the foregoing discussion was in terms of technological schemes for water resources development in the context of agricultural demands with some environmental constraints. Demand is not constant, but is a function of techno-economic capability of the users. For instance, in India, while on the one hand, water availability is inadequate, on the other hand, application is most inefficient and wasteful. It has been estimated that only 40% of water released at the canal head is made available to crops. Thus, if more efficient water management were practised, much larger areas could be irrigated or more water could be made available to the same farmers.

The technological solutions are lining of distribution systems, land levelling and adoption of appropriate water management at the field level. An integrated field-level water management can be worked out to identify optimal investment in each of these three components and to determine the shadow prices so that the relative advantage of field-level and macro-level development can be established (Chaturvedi & Khepar 1981). We do not visualize a complete change to sprinkler system or trickle irrigation. The gravity flow system will remain the predominant technology but unit water requirements should be reduced over the course of time. In long-term planning of water resources, the urgency of the gradual improvement in efficiency has to be emphasized. Field-level development has been neglected in the past in view of certain political-organisational reasons. From economic, employment generation, and environmental considerations, field-level management has the highest priority.

Water management at the watershed level, which we have emphasized is, however, not a mere technological issue, but is a problem of adult education, formation of cooperatives, etc., or in short, a problem of social change as a component of integrated rural development.

6. Interbasin transfer

Temporal and spatial variability are usual features of water resources but the condition in India is acute. Figure 7 brings out these characteristics, suggesting the need for large-scale interbasin transfer. The possibility of interbasin transfer has implications for the planning of all regional developmental projects in ensuring that important possible benefits are not pre-empted and the possibility of providing flexibility in the projects without undue extra commitment of investments is explored at the outset.

Two schemes have been proposed in this context and are worthy of examination. One is the National Water Grid proposed by Rao (1976). The other is the National

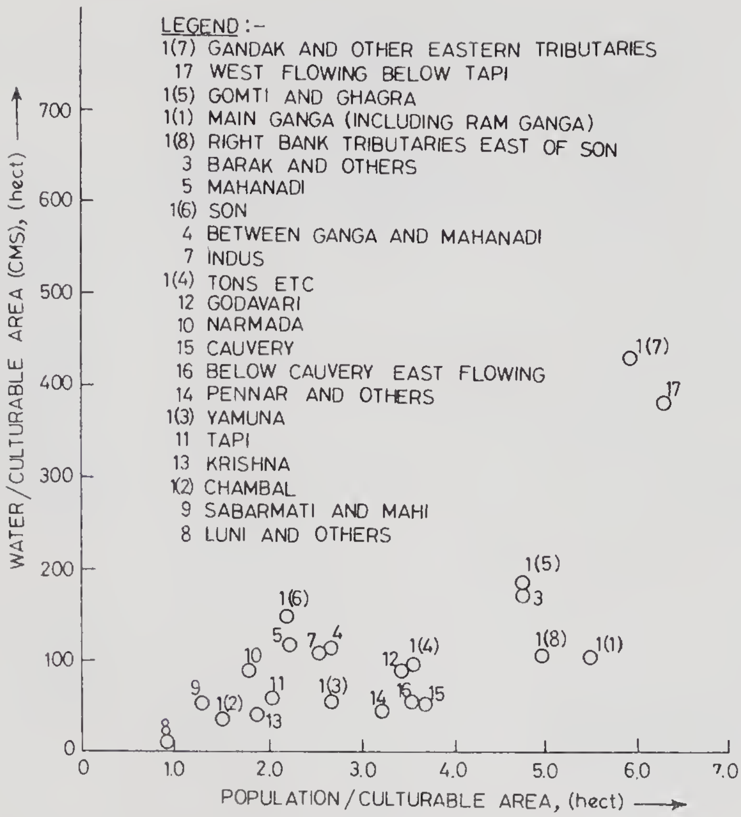

Figure 7. Basic resource relationships

Perspective for Water Resources Development developed by the Ministry of Irrigation (1980). Both are described briefly as follows.

6.1 *National water grid*

For considering interbasin transfer, Rao has considered four zones, as shown in table 4. In view of the hydrologic-physiographic conditions of the country, 17,000 cumecs of monsoon flows have been proposed to be pumped up the river Son to the river Narbada involving a lift of about 550 m. Part of it is proposed to be used for scarcity areas in the south Ganges basin and the rest is proposed to be transferred through the Narbada to the river basins of the west flowing rivers, Sabarmati, Mahi, Narbada and Tapti, which are very deficient as shown in table 4. The east-flowing rivers of Zone 3 are proposed to be interconnected to transfer the surplus water of the North to the South. The water of the west-flowing rivers in Kerala, Zone 4 are proposed to be transferred to the scarcity areas of the east. The scheme is shown in figure 8.

6.2 *National perspective*

The National Perspective for water resources development envisaged by the Ministry of Irrigation, Government of India emphasizes development of water resources for the entire nation overriding narrow regional considerations. Essentially it seeks to increase the utilisation potential by storing the surface flows presently considered non-utilizable. The plan is based on optimum development of available storage sites, big and small, wherever feasible and interlinking of the major rivers. It is considered that

Table 4. Zonal distribution of land-water resources

Zone No.	Total water (annual discharge ($\times 10^9$ m^3)	Percentage of land cultivated	Water potential (% of total)	Proposed interbasin links
1. Indus, Brahmaputra and Ganga (North Zone)	1045	44	77	Brahmaputra-Ganga, Ganga-Narbada
2. Sabarmati, Mahi, Narmada and Tapti (West-flowing)	70	19	5	Ganga to Narbada and to others
3. Subarnarekha, Brahmani, Baitarni, Mahanadi, Godavari, and Cauveri (East-flowing)	195	35	14	From northern rivers of the region to southern rivers
4. West-flowing rivers in kerala	40	2	3	To be transferred to the East
Total	1350	100	99	

Source: Rao 1978

besides the currently estimated utilizable potential of 105 MHM, an additional 20·96 MHM of water, an additional 35 MHA of irrigation and 40,000 MW hydroelectric energy, perennial inland navigation and extensive flood mitigation shall be provided.

The perspective comprises two main components *viz.*, (i) The Himalayan rivers development; and (ii) peninsular rivers development. These are briefly outlined below.

6.2a *Himalayan rivers development* The Himalayan rivers development scheme envisages construction of storage reservoirs on the main Ganga and the Brahmaputra and their principal tributaries in India and Nepal along with inter-linking canal systems to transfer surplus flows of the eastern tributaries of the Ganga to the West apart from the linking of the main Brahmaputra with the Ganga. Apart from providing irrigation to an additional area of about 22 MHA and the generation of about 30 million kW of hydropower, it will provide substantial flood control in the Ganga-Brahmaputra basin. It would provide 1332 cumecs (40,000 cusecs) to Calcutta Port and would provide navigation facilities across the country. The scheme will benefit not only the States in the Ganga-Brahmaputra Basin, but also our neighbours—Nepal and Bangladesh—as well as the northern and western states in our country. Implementation of this scheme will however largely depend on the cooperation of neighbouring countries.

6.2b *Peninsular rivers development* Amongst the peninsular rivers, the Mahanadi and the Godavari are likely to have sizeable surpluses. It is, therefore, possible to divert the surplus of the Mahanadi and the Godavari to the water-short rivers *viz.*, the Krishna, the Pennar and the Cauvery. The Mahanadi will also be linked on the north with Bura-Balang, and 7·4 MHM of Mahanadi waters will be utilised for irrigating the coastal areas in Orissa and interlinking the rivers to even out the hydrological variations.

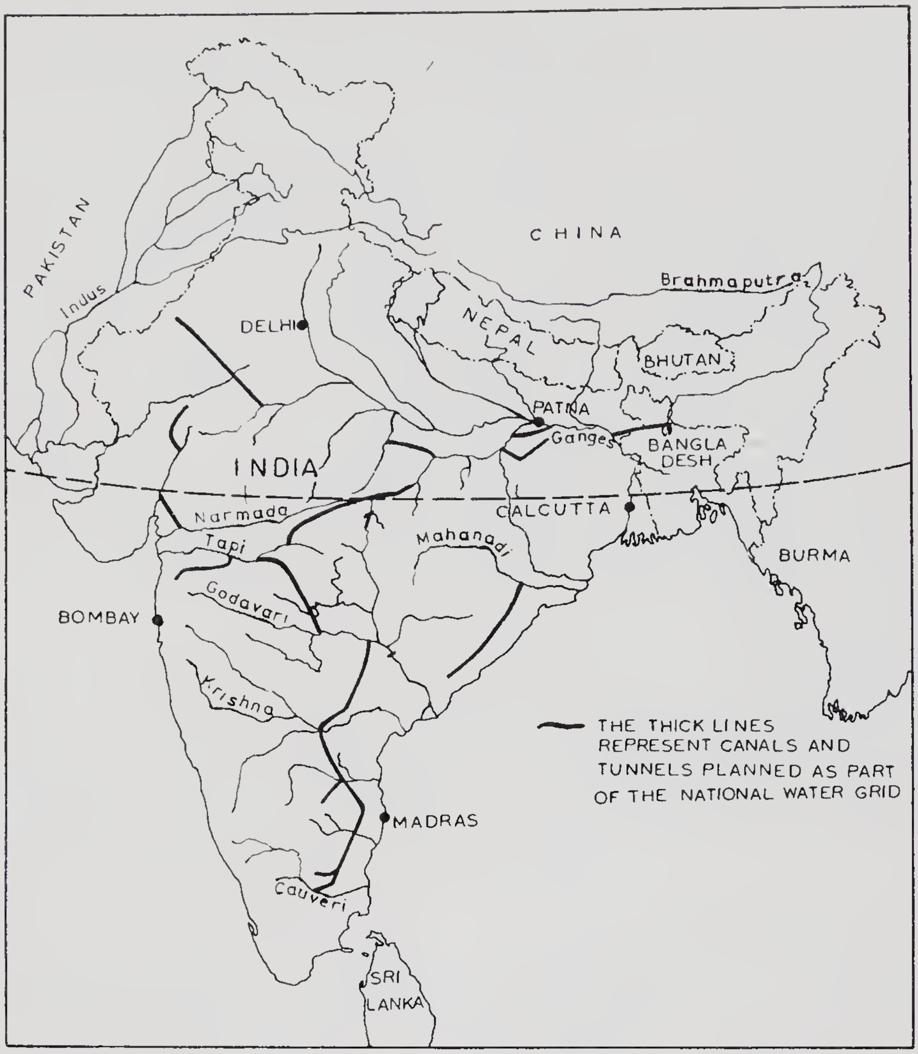

Figure 8. The drainage network in India and Bangladesh and national water grid (from Rao 1976)

Essentially this proposal contemplates diversion of 1·85 MHM of Mahanadi flow to the Godavari and a transfer of 3·70 MHM from the Godavari and its tributaries to the Krishna Basin. This would mean a net diversion of only 1·85 MHM from the Godavari to the Krishna.

The link from the Mahanadi to the Godavari will be along the East Coast and would not involve any lift. The links between the Godavari and the Krishna will be from Polavaram to Vijayawada, Inchampalli to Pulichintala, Inchampalli to Nagarjunasagar and Wainganga to Srisailam. The last two links would involve lifts of the order of 109 m and 122 m respectively.

6.2c *Interlinking Ken with Chambal* The Ken, Dhasan, Betwa, Sindh and Chambal rivers are southern tributaries of the Yamuna. There is a proposal to construct dams on these and store waters optimally by interbasin interlinkages.

6.2d *Division of west-flowing rivers* Similarly, there is a proposal to construct a contour channel on the western ghats and provide storage, wherever possible.

It is important to note that both the above proposals are conceptual and much study is required before the concepts can be finalised and the feasibility of these projects determined. There are many other possibilities and optimal schemes have to be worked out. Furthermore, these are not necessarily contradictory and an optimal scheme may have elements of both or several others.

Some improvements are as follows. Rao's scheme is complemented and improved by visualising both mass and energy conservation and transfer as proposed by Chaturvedi (1973). Consider the interlinkage of Zones I and II, which is crucial. The surplus water flowing down the Himalayas which is proposed to be transferred is also capable of producing energy in the Himalayas which at present is not planned to be utilised beyond 90–95 % assured supplies round the year. Thus, much of the monsoon flows and possible secondary energy is wasted. Since the marginal cost of extra energy generation in the Himalayan run-of-river scheme is small, the installed capacity of these developments should be planned from a consideration of the production of this secondary energy also. This can be stored and transferred by pumping the Ganga water and storing it in the Narbada, which has tremendous and economical storage potential. This can be later released as firm energy which is almost three times more valuable than the secondary energy and particularly as peak energy which is further almost three times more valuable.

The National Water Perspective has also to be related to detailed basin planning and preceded by it. The results of a study of integrated agricultural development in the light of the current and ultimate potential without taking into account interbasin water transfer but taking into account the variable cost of surface and groundwater development in river basins is given in table 5. The variation in shadow price of water in

Table 5. Costs of surface water and ground water in various basins (1976–77) (Rupees/hectare meter)

	Surface water			Ground water		
River basins	Development cost	Operation and maintenance cost	Total	Development cost	Operation and maintenance cost	Total
Basin 1	183	121	304	189	435	624
Basin 2	318	180	498	429	645	1074
Basin 3	289	235	524	333	668	1001
Basin 4	136	85	221	316	835	1151
Basin 5	117	50	167	186	379	565
Basin 6	177	126	303	250	467	717
Basin 7	353	185	538	320	115	1435
Basin 8	154	99	253	424	785	1209
Basin 9	563	264	827	387	671	1058
Basin 10	156	96	252	241	690	931
Basin 11	1166	517	1683	397	2015	2412
Basin 12	220	91	311	361	893	1254
Basin 13	134	66	200	404	700	1104
Basin 14	166	77	243	199	1164	1363
Basin 15	370	160	530	269	1224	1493
Basin 16	269	119	388	339	892	1231
Basin 17	744	313	1057	364	1229	1593
Basin 18	814	322	1136	421	1065	1486
Basin 19	1374	503	1877	416	896	1312
Basin 20	396	170	566	238	1670	1908

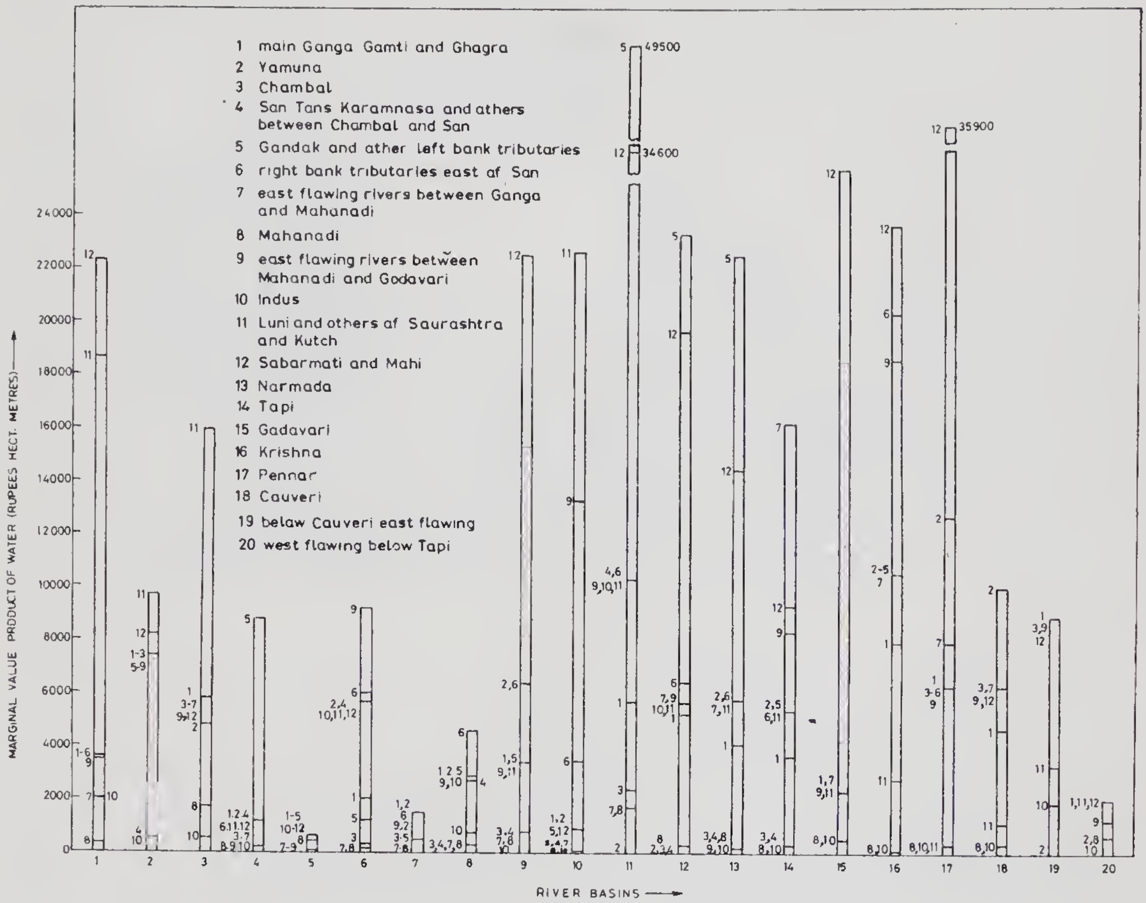

Figure 9. Marginal value product of water in different sub-basins of India in various months. Note: (1) Policy option is individual basin optimal plan at developed level of water resources with unrestricted command area and crop group area constraint. (2) Numbers refer to months starting from January. Source: Singh (1980)

different months in different basins at the stage of full utilization is shown in figure 9 (Singh 1980). Several alternative agricultural policies were studied. The water utilization and shadow prices were considerably different. The total utilization of water and fertilizer and net return are also shown in figure 10. The central point is that interbasin transfer in terms of appropriate technological configuration, capacities and timing can only be developed through a systems approach taking into account techno-economic interlinkages with detailed regional and national planning.

7. International issues

Before discussing the systems planning approach the international issues involved in India's water development may be briefly reviewed. On the west, the Indus basin waters have already been agreed to be divided with Pakistan. Of the total of 21·3 million hectare-meters, India has obtained approximately 20% of the flows.

On the east a dispute exists about the minimum flows of Ganga at the India-Bangladesh boundary—the Farakka Barrage. The Ganga and its numerous tributaries also flow through Nepal. In order to arrive at an appropriate policy, the scientific approach would be the development of a policy in totality and in isolation for each country and then through scientific analysis we can arrive at a bargained optimal policy.

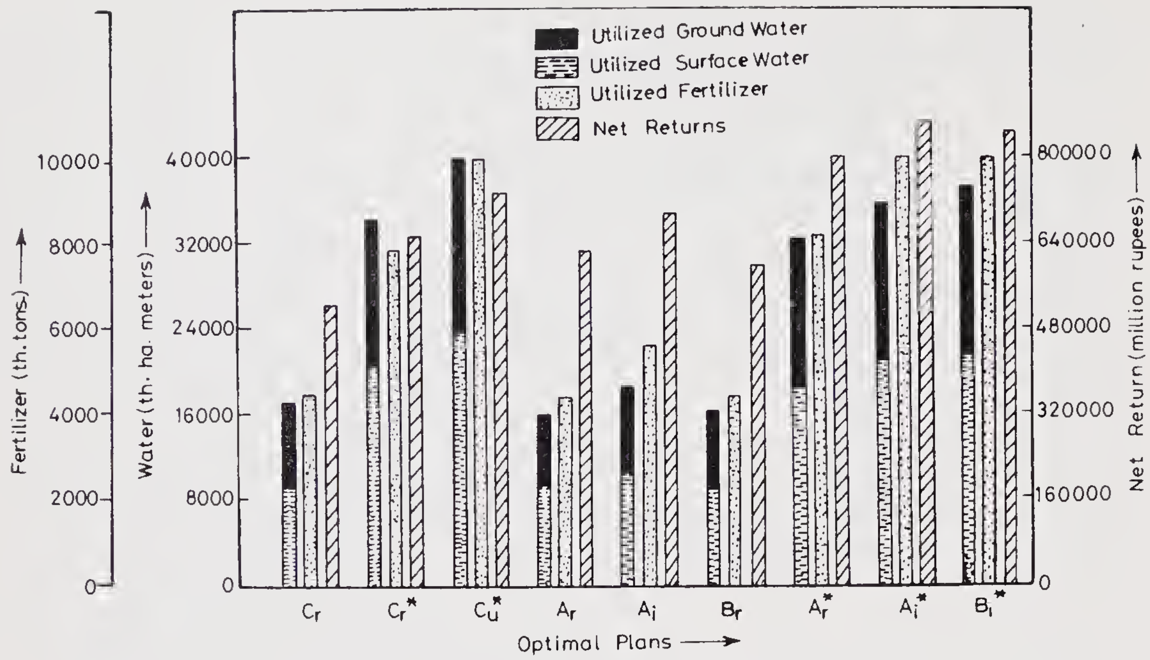

Figure 10. Utilisation of water and fertilizer and net returns under various optimal plans for the country as a whole (Source: Singh 1980)

Bangladesh and part of West Bengal constitute the largest delta of the world. Out of the total area of 204,000 sq. km of Bangladesh, 85,000 is in the delta. The average annual discharge from the Ganga, Brahmaputra and Meghana of 18·69, 19·82 and 5·10 thousand cumecs with a total of 43·61 thousand cumecs is second only to the Amazon (Leeden 1975). These carry the world's highest sediment load, with 1451×10^6 and 726×10^6 metric tons in the Ganga and the Brahmaputra respectively. To give a quantitative idea, the estimated 2177×10^6 metric tonnes of average annual suspended load in the Ganga and the Brahmaputra is larger than that in the dreaded Yellow river, almost four times greater than the next highest sediment laden river Yangtze and twenty times the silt load of Nile (Leeden 1975). The flows are extremely variable over time. The Ganga draining an area of 1,098,600 sq. km above Goalundo has an average annual flow of 11468·3 cumecs (405,000 cfs) with a maximum and a minimum of 70933·6 and 1161 cumecs (2,505,000 and 41,000 cfs). The Brahmaputra draining an area of 580,000 sq. km above Goalundo (including catchment areas outside India and Bangladesh) has an average annual flow of 19340·4 cumecs (680,000 cfs) with a maximum and minimum of 71330 and 3115 cumecs (2,519,000 and 110,000 cfs). The Brahmaputra flows are much more uniform and the high flows start in May while in the Ganga they start in July.

The Ganga and the Brahmaputra unite at Aricha, the combined flow being known as the Padma river. The drainage area of the Padma between Goalundo and its confluence with Meghana is 12960 sq. km most of which is flooded during the high-flow season. The maximum observed flow of the Padma at Goalundo is 91180 cumecs.

The Meghana river, with a catchment of 80200 sq. km constitutes one of the highest rainfall areas of the world. It joins the Padma at Chandpur dumping another 5,100 cumecs into this tremendous water mass. The numerous channels in the delta have developed the configuration in the context of the geophysical-hydraulic characteristics of the land water mass.

The control of these three major rivers from the Bangladesh point of view, draining an area of 1,733,200 sq. km only 7·5 % of which lies inside Bangladesh, poses a unique hydraulic problem which can be considered in terms of four closely interacting components; (i) high-flow (flooding) problem, (ii) river instability problem, (iii) low flow problem and (iv) the problem of the sea: tides, cyclones and salinity intrusion. In this context, water resources have to be carried for the multipurposes in view of the multiobjectives.

In developing a solution for this region, geophysical-environmental considerations have an overriding consideration in the choice of technology. Efforts should be aimed at improving the drainage and also, not to interfere with the surface drainage by construction of storage works and canals. Plentiful groundwater availability indicates that priority be given to drainage and groundwater development. Flood mitigation is an important consideration and watershed management with forced groundwater recharge as well as induced groundwater recharge appears to be indicated. It is unfortunate that while the solution may be somewhat on the lines of the Rhine Delta, practices from the arid areas of the Punjab and Western Uttar Pradesh in India are being adopted.

As the configuration is, the Brahmaputra waters are available from the hydraulic, silt and salinity intrusion point of view only for the eastern portion of Bangladesh. Therefore, in view of the geophysical and hydraulic characteristics and to control the land-water system, the Brahmaputra waters should be made more manouverable. It would thus be reasonable that the Brahmaputra is diverted to meet the Ganga upstream of the present confluence, with as high a discharge as economically possible. Since the Brahmaputra has little irrigation potential and the Ganga will have to be developed to meet the irrigation requirements of its long catchment upstream in India, the Brahmaputra link with as high a discharge as economically possible is definitely indicated from the total as well as Bangladesh's point of view. The location should be upstream so that a proper hydraulic geomorphological configuration is developed. There is no doubt the problem of fouling with drainage of the northern rivers and land use in densely populated regions but these are matters for detailed techno-economic studies.

The water management strategy will also require that first the aforesaid hydraulic management is obtained after which structured solutions may be defined. In conjunction with these structured solutions, the watershed management in the upstream area which is the major source of floods and sediment has to be taken up principally through afforestation in Nepal. The various schemes of groundwater recharge of monsoon flows in India would confer direct benefits to Bangladesh.

Regarding irrigation development, as stated earlier, the policy of groundwater pumpage through the micro water machine rather than low-flow diversion appears to be the preferred strategy particularly in view of abundant groundwater supplies, environmental considerations, and drainage/flood management. As far as the policy for India is concerned it appears that the minimum flows at Farakka should be diverted from the considerations of the land-water system in the west.

The matter requires detailed engineering-economic-systems analysis, but as a policy of development it appears that this is a unique case where optimal integrated development from environmental-economic considerations is much superior as compared to the optimal independent development. But it should not hold up any upstream developments as the case is more of excess of water than shortage of water in Bangladesh.

Unfortunately, in the dispute with Bangladesh the issue of the development of the water resources of Nepal has been neglected. Nepal has very rich water resources development potential and for India, development in Nepal is of utmost importance. These should be taken up integrally with the development in India and with the highest priority. It is interesting and important to note that from hydroelectric considerations there is a remarkable analogy between the potential development of Sweden and Nepal. Unfortunately while almost 60 % of the potential of 25 MkW has been developed in the former, not even 1 % of the potential of 85 MkW has been developed in the latter.

8. Technological policy

We have discussed some issues of developmental policy and technological strategies for water resources development in the foregoing. A package of technologies with some indication of the pros and cons subject to detailed determination of production function was indicated. Their selection, capacity, location and scheduling has to be determined from detailed systems planning for which an approach is indicated in terms of local, regional and national planning subject to detailed analysis. Likely technological activities are indicated in table 6. While regional planning has to be in terms of the river basins, we have developed a coarse spatial-temporal matrix for developing a technological matrix as a first step for systems analysis. The country is divided into five regions. The time is divided into three units, short run, medium run and long run. Each technology is envisaged to be started at the optimal time so that each phase is optimally completed.

According to the Sixth Plan complete utilization is scheduled in over 20 years. In our judgement, technological, organisational and institutional capabilities do not warrant such a schedule, but with the utmost efforts for modernization on these fronts, a schedule of 30 years is feasible. However, if the present approach continues water resources cannot be developed even over a much longer period and then too the development will be suboptimal.

The policy on which the recommendation of table 6 is based is that (i) a tempo for completing development over this period is built up and (ii) schemes are taken up on priority which have comparatively higher attractive marginal productivity. It hardly need be stated that table 6 is a tentative policy approach and an integrated regional and temporal trajectory of development has to be worked out as shown in figure 11 with regional focus in the Ganga Basin for illustration.

9. Planning approach

It is not as yet adequately appreciated in the engineering profession that water resources development is not a mere technological problem, but is integrally related to total socio-economic-technological developmental planning. Accordingly in the systems planning approach, for convenience, the issues may be grouped under three interacting heads (i) analysis of the physical phenomenon, (ii) socio-economic evaluation criteria, and (iii) systems planning. A typical set of issues and models required to develop water resources at a regional level is shown in table 7. Planning studies and

Table 6. Developmental technological policy

River basins	**A** Short run (5 years)	**B** Medium run (10 years)	**C** Long run (15 years and above)
1. Indus basin	1A1 Modernise the system through systems planning. 1A2 Start rural level water management modernisation and environmental development. 1A3 Develop field level recharge at village level.	1B1 Complete 100% net irrigation, 250% cropping intensity world standard yields with environmental development at local level with particular emphasis on groundwater quality. complete continuing major projects	1C1 Continue improving efficiency and environmental state with integrated development in national context completed. All major water resources and hydroelectric works completed
2. Ganga basin	2A1 Develop groundwater through private and public enterprise (diesel and electric) irrespective of mining. 2A2 Same as 1A1, 1A2 & 1A3. 2A3 Start on a number of multipurpose projects with emphasis on development in Nepal and Bhutan also.	2B1 Kharif channels, storage works in India and Nepal, conjunctive surface and groundwater development on annual yield basis at optimal level completed and continued. Integrated policy of optimal development. 2B2, 2A2 and 2A3 continues.	2C1 Integrated development in national context continues. 2C2 Low flows restored. 2C3 State 1B1 obtained all over the region and continued to be increased as in 1C1. 2C4 2A3 continues.
3. Narbada and Western rivers	3A1 Start total water resources development leading to 3C1. 3A2 Develop groundwater as in 2A1. 3A3 Same as 1A2	3B1 3A1 continued leading to 3C1	3C1 Complete water resources development in integrated national context aiming 1B1
4. East flowing	4A1 Start river basin water resources projects development leading to 4C1	4B1 4A1 continued leading to 4C1	4C1 Regional grid leading to 1B1 completed
5. West flowing rivers south of Tapti	5A1 same as 4A1	5B1 same as 4B1	5C1 same as 4C1

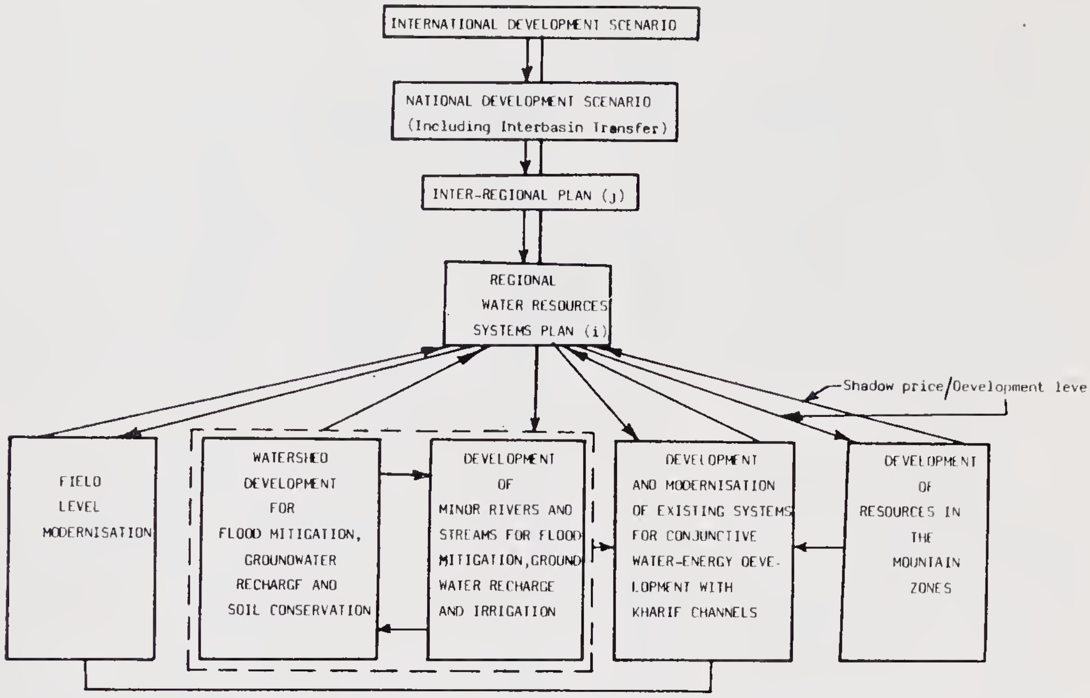

Figure 11. Technological set of options and hierarchy of planning (with focus on the Ganga basin)

Table 7. Relevant issues and models

Socio-economic studies		Water and applied resources studies
General and related sector planning studies	System studies	Analysis of physical phenomena
1. Development strategies 2. Social evaluation of key resources 3. Resources availabilities 4. Evaluation of loss function and risk criteria 5. Project selection criteria	1. Regional optimal allocation of water resources 2. Optimal development constrained by economic and physical resources 3. Project evaluation and selection	1. Description of physical phenomena 2. Analysis and simulation of physical phenomena
	Issues Models	
1. Intersectoral resource allocation model 2. Population studies 3. Food demand models 4. Agricultural sectoral model 5. Technology-efficiency-equity models	1. Preliminary system formulation model 2. System analysis-deterministic model 3. System analysis-stochastic model 4. System simulation models 5. Simulation of crop activities 6. Power sector models 7. Space structuring models 8. System environmental models	1. Hydrologic models 2. Hydrogeological exploration models 3. Surface-ground water simulation model 4. Ground water recharge model 5. Crop-water fertilizer response models 6. Water quality models

their progression are shown in figure 12. We start with (i) regional water availability, (ii) water demand, and develop (iii) technological solutions. Each of these three is progressively refined. Reference may be made to the set of case studies to appreciate the details of the aforesaid component studies (Chaturvedi & Rogers 1985) and to standard texts for the approaches to carry out the study. Systems planning of the water resources of Uttar Pradesh is currently being carried out on these lines and the set of component studies shown in figure 13, gives an idea of the approach (Chaturvedi 1981b).

Regional planning is interrelated to national policy planning at one end and project planning at the other as shown in figure 14. We shall briefly discuss the planning at two levels, as related to integrated rural development and in the context of national planning.

As we have emphasized water resources development or any technological activity should be subordinated to socio-economic environmental development. The starting issue is what the rural needs are and how the set of technological activities can be planned so as to generate employment through agriculture and allied activities. For example, as discussed earlier, diesel-operated tubewells were considered to be the first choice in the Ganga basin with other sets of technologies on a bigger scale supplementing it. Activity can be developed at village, block, and district level for the related technological activities. Thus, teams can be developed for manufacturing screens (ferrous or plastic) at block or district level. Industries can be developed for manufacture of pumps and motors at suitable levels from demand and corresponding

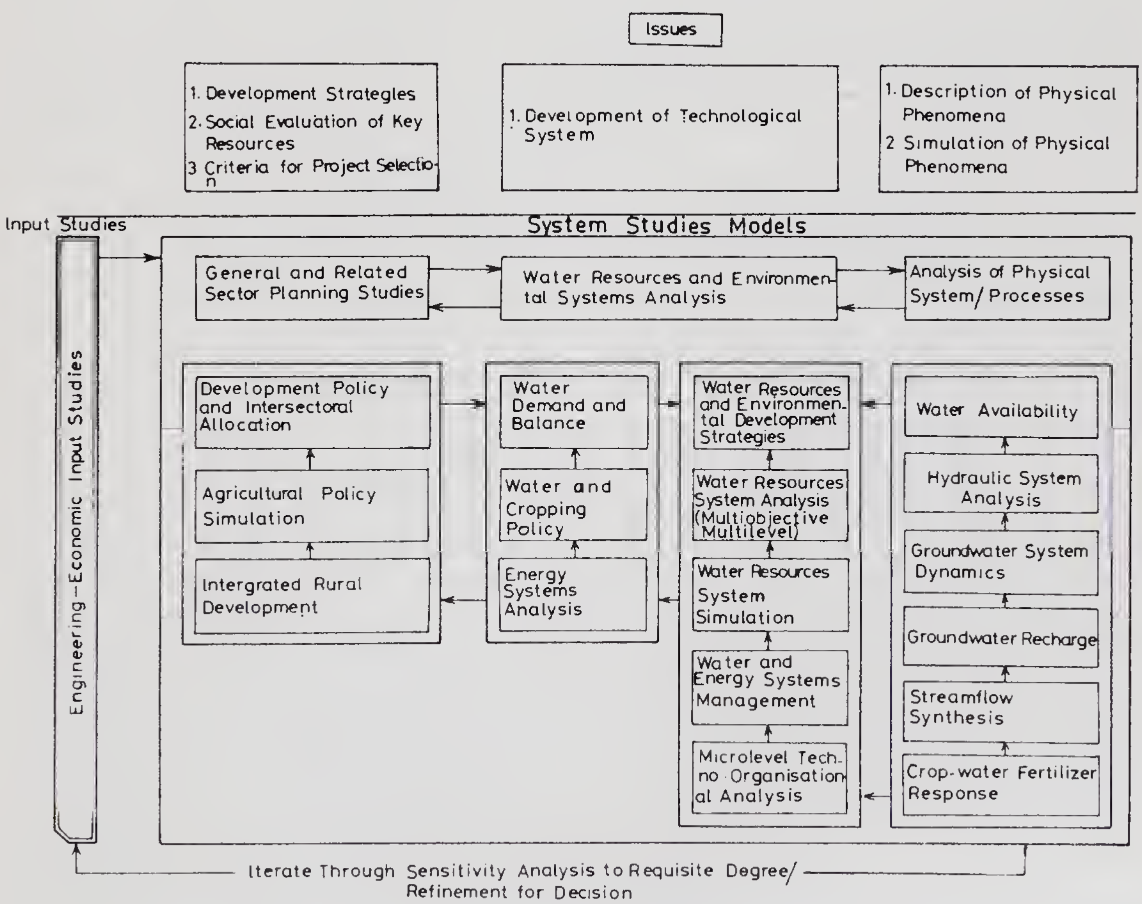

Figure 12. Issues and systems analysis modelling morphology

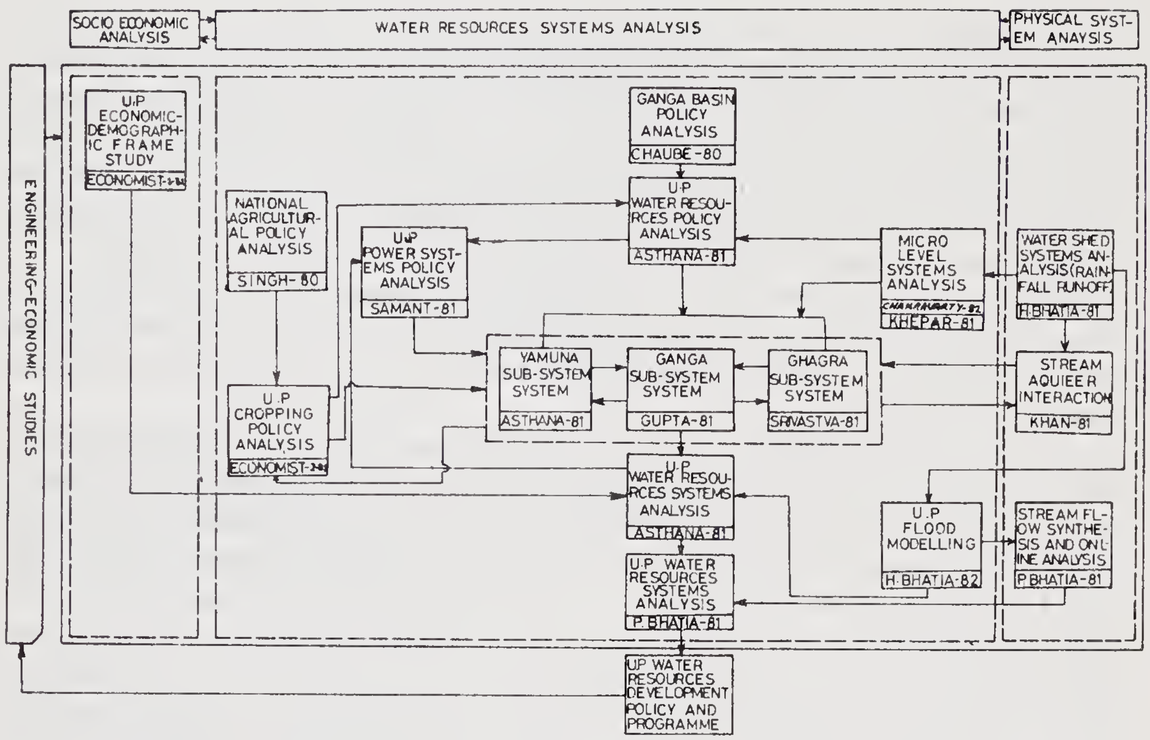

Figure 13. Water resources systems development planning scheme

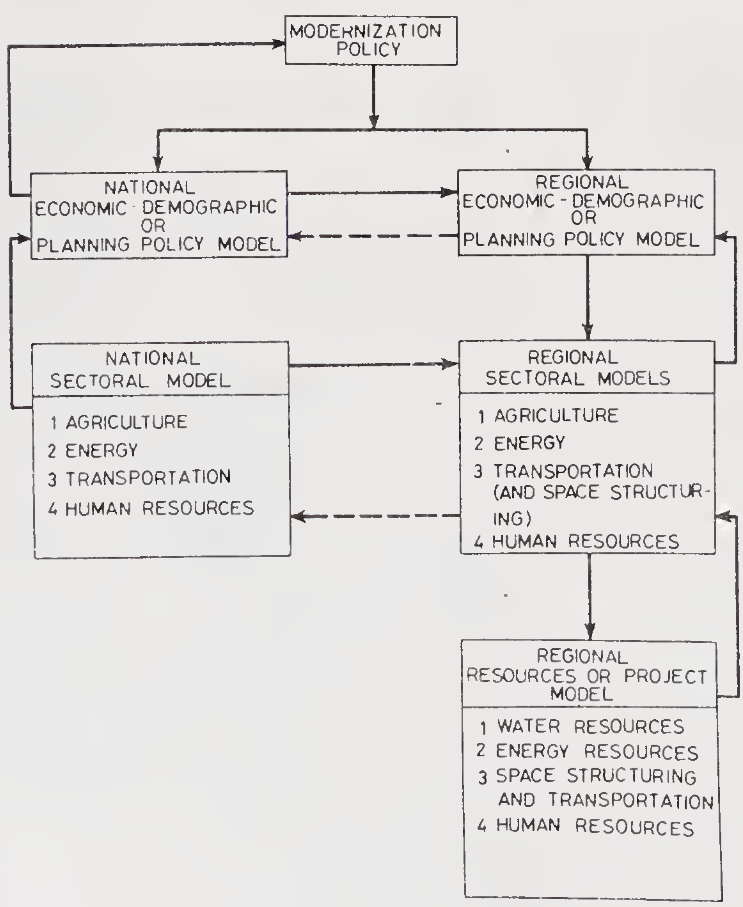

Figure 14. Regional systems analysis modelling morphology

economies of scale of supply. The central issue is to develop employment, technological culture and resources for appropriate development in which the local people are committed and take the lead in active development.

Development of water resources on such a large scale has national and international interlinkage. With the development at the proposed scale, partial equilibrium analysis is no longer valid and general equilibrium analysis is called for. The detailed approach developed for market economies may not be applicable, and therefore, a more heuristic multilevel analysis to study the interaction at national, regional and farm level has to be developed. At the national level, the policy objective may be said to be to develop irrigation in different regions consistent with balanced regional growth and self-sufficiency (in view of non-market economy and transportation problems), the multi-objective of optimal productions of the major crops, optimal employment generation and optimal nutrient production is obtained at minimum costs and with optimal environmental enhancement. Taking into account regional agro-climatic and techno-hydrological environmental attributes and budgetary allocations, the trajectory of water resources developmental policy can be worked out. The trade-off between the three objectives or more as may be visualised can be studied. At the regional level, the objective is that, given the cropping pattern and targets, what the options and scheduling policy of the projects should be. At the farmers' level, the objective is that given the projects and corresponding potential of pattern and quantities of water, what the optimum cropping pattern from considerations of financial returns is. An iterative solution satisfying the three-level decision follows (Chaturvedi & Duggal 1978). As another example of the implication of national interlinkage in view of the changing cropping pattern as development of water resources in different parts of the country takes place, reference may be made to the work of Singh (1980). Optimal water development was studied for nine policy options for the country, divided into 20 river basins.

For the above it may be concluded that there are three factors which lead to the necessity of a long-term national policy planning for water development. One is the circular causatory interlinkage of demand and supply through the technological activity. Second is the possibility of interbasin water transfer and correspondingly optimal interrelated development at the regional and national level. And, the third is the interlinkage due to the development taking place over a period of time. National policy analysis is important not only to determine balanced growth, but even to determine optimum individual project timing, capacity and technological design in view of varying project characteristics and possibility of integrated water transfer viewed as resource and energy. It is considered that most of the projects currently planned or under execution and the management of existing projects is inefficient, and the proposed systems studies at national, regional and village levels should be carried out immediately so that currently proposed developments do not irreversibly and inefficiently commit the valuable natural resources. It could be possible that the technological options are provided with sufficient flexibility for possibility of increasing the capacity, optimally, over a period of time. For instance, the capacity of the series of storage dams due to be constructed over the Narbada or run-of-river hydroelectric development in the Himalayas must be decided from the consideration of the feasibility of the National Water Programme at the appropriate time.

It is important to emphasize that in water resources development, as in all activities, it is not only the end product or the decision that is important, but more so the process of decision making that is to be emphasised. Technology is a creative art and science and not merely a routine activity as it often becomes.

10. Institutional and technological modernization

Models are an important part of systems analysis. They are valuable as they enable us to perform so to say, "thought experiments". But they do not replace judgement and creativity as real-life issues are much too complicated. They complement judgement by allowing analysis and creativity over a much wider range. It would be clear from the above that water resources development for the new India can no longer be on the currently adopted *ad hoc* project-by-project basis on outdated colonial policy concepts and technological perceptions, but will have to be on a scientific and long-term basis with concern for the people and the environment. The first pre-requisite for the new approach is Institutional and Educational modernization of the profession. Governmental agencies have to get rid of the bureaucratic-colonial heritage and have to reorient themselves as agents of modernization. The engineers have to be educated to develop proper concepts, attitudes and skills. They have to become specialists and engineers rather than officers. This modernization is required in all phases of technological activity-planning, design, construction, management and research.

We do not elaborate on the institutional change and technological modernization for the new task except to underline that it is most urgent and it involves a complete conceptual and organizational modernization. An integral issue is a colossal programme of long-term continuing education. It is a sad fact that least capability in terms of higher education and research has taken place in water resources sector. The educational programmes must be developed in collaboration with the major educational institutions of the country for this task. These should be specifically designed in collaboration with professional bodies for continuous updating at all levels. Furthermore, institutional change and education at the users' level are also important components of the modernization task. Village cooperatives have to be developed and provided with extension services. In short a complete individual and organizational revolution is called for. It is interesting to note that the Sixth Plan has identified these issues as part of the objectives for achieving development.

One issue may be specifically mentioned. The first step in this revolution is intellectual freedom. Even after 30 years of political independence, mental slavery and a sense of inferiority to the West continues in India. Foreign experts are often invited for instant development recipes. Some Indian techno-bureaucrats hanker after foreign trips or instant education courses without ever realising that development must in the last analysis be indigenous. Collaboration is no doubt valuable, but it must be on equal terms and indigenous development is the first pre-requisite for meaningful collaboration. Unless there is intellectual freedom and commitment to the development of the poor, appropriate technological development is a distant goal.

11. Conclusion

As stated at the outset, our effort has been to demonstrate that a revolution in concepts and approach, and institutional and technological modernization is needed to meet the tremendous challenge of water resources development in India. The first step is a break from the colonial hangover, and attainment of intellectual freedom.

A scientific approach to planning leads to (a) scientific policy and programme at the national level and (b) scientific policy and activities at project level.

A scientific planning approach is indicated. It is necessary to implement it immediately, otherwise the individual projects will be inefficient and wasteful of developmental potential and development would not be attained in due time.

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The Ganga-Brahmaputra-Barak Basin

M C CHATURVEDI

Applied Mechanics Department, Indian Institute of Technology, New Delhi 110016, India

Abstract. The physiographic-hydrologic-agroclimatic characteristics of the Greater Ganga Basin, one of the biggest river basins of the world and supporting the largest human population are described. A brief historical background of the development of the basin and the reasons for the desperately poor conditions are also discussed. The various issues involved in the planning of the water resources of this basin are outlined and a scenario of technological choices for the development at macro and micro levels has been developed. It has been brought out that interlinked competing issues, multipurpose and multiobjective considerations, spatial and temporal variations in the availability, and the large number of possible technological choices have made the application of a systems approach mandatory for integrated planning for future economic development of the basin.

Keywords. Ganga Basin; systems approach

1. Introduction

The river Ganga and its tributaries, and the flat and fertile plain through which they flow, are one of the earth's great natural resources. For thousands of years, abundant water and generous land have provided the foundation for a highly developed civilization based on agriculture and for one of the world's largest concentrations of human populations. But the farming is mainly traditional and at a subsistence level, with little surplus, and as a result the population has remained overwhelmingly rural and desperately poor. Although irrigation from canals and wells has been practised for millennia, chiefly to protect against uncertainties of the monsoon rains, the water resources are largely untapped; the small fraction of water used for irrigation is poorly managed, its productivity is low, and the people continue to be exposed to the vagaries of nature—droughts and floods.

Deeply-embedded cultural, social and economic practices inhibit modernization of agriculture and fuller utilization of water resources. Capital investment and technological changes on a large scale are also required. As experience elsewhere shows, the introduction of technological changes on the required scale might break the chains of tradition that now bind the people in misery and poverty.

The development of such a large and complex system is a tremendous technological challenge. It is a typical systems problem as the various elements are interlinked in a variety of ways. Several studies have been undertaken by Chaturvedi & Rogers (1985) to explore essentially, an approach to analysis. As a prelude to systems studies, the salient characteristics of the system, a brief historical background of the development and the possible future approaches to it are given. The data is based on published material and papers from various sources, particularly background material presented at a Workshop on Integrated Development of the Ganga-Brahmaputra-Barak Basin (1978) held at the Gandhi Peace Foundation, New Delhi. This data, however, must be considered tentative, and the studies demonstrate only the applicability of a systems approach.

2. System characteristics

The system comprises the drainage basins of three international rivers, the Ganga, the Brahmaputra, and the Barak or Meghna. This is also called the Greater Ganga Basin and is shown in figure 1, with a schematic developmental sketch in figure 2 showing the projects and the schemes. It covers parts of four countries: India, Nepal, Tibet and Bangladesh, although primarily the system is focussed on India. In area as well as in population and development opportunities the Ganga again has the central focus. The Ganga basin itself is usually divided into eight or nine sub-basins (i) the Main Ganga (including Ramganga), (ii) the Yamuna, (iii) the Chambal, (iv) the Tons, Karmnasa and others between the Chambal and the Son; (v) the Son; (vi) the right-bank tributaries east of the Son; (vi) the Gomti, the Ghagra and others between them; (vii) the Gandak and other left-bank tributaries. Sometimes the Ramganga is treated separately.

The Greater Ganga system, next to the Amazon in South America, is the second largest international river basin in the world so far as runoff is concerned. It drains an area of 1.38 million sq km. With 326 million (1971), nearly a twelfth of the world's total population, the basin is the most populous in the world. The system carries a peak flow of over 1,41,000 cumec at its estuary and empties annually about 127.61 m ha m of water into the Bay of Bengal of which 80% is in the monsoon.

The physiographic characteristics of the system are the steep and geologically young Himalayas in the north and east and the Vindhyas in the south. On the west a low unnoticeable watershed separates this basin from the Indus basin. The Brahmaputra and the Barak/Meghna meet the Ganga at its tail end. The extensive alluvial plains of the Ganga and its tributaries and the Brahmaputra valley as they meet the Bay of Bengal form a vast delta comprising most of Bangladesh and West Bengal in India. More than half of the territory of Bangladesh is less than 7 m above sea level.

The system has a monsoon climate. The annual precipitation in the region is shown in figure 3. The problems of land and water development in the Greater Ganga Basin arise from the highly seasonal flow of the river and its tributaries. This can be observed in figure 4. These figures represent the average seasonal flows in the river Ganga alone. Further, there is considerable yearly variation leading to the most severe floods and droughts. The flows of three of the major rivers are shown in figure 5.

2.1 *The Ganga*

The great river of the north Indian plains is officially as well as popularly known as the Ganga, although internationally it is known by its anglicized name, Ganges. From time immemorial it has been the holy river of the Hindus. For most of its course it is a wide and sluggish stream, flowing through one of the most fertile and densely populated tracts of territory in the world. Despite its importance, its length of 2506 km makes it the 15th longest river in Asia and the 39th longest river in the world (Encyclopaedia Britannica 1978).

Rising in the Himalayas and emptying into the Bay of Bengal it drains a quarter of the territory of India, while its basin supports a concentration of about 300 millions, a population larger than any state or even continent, except China and India.

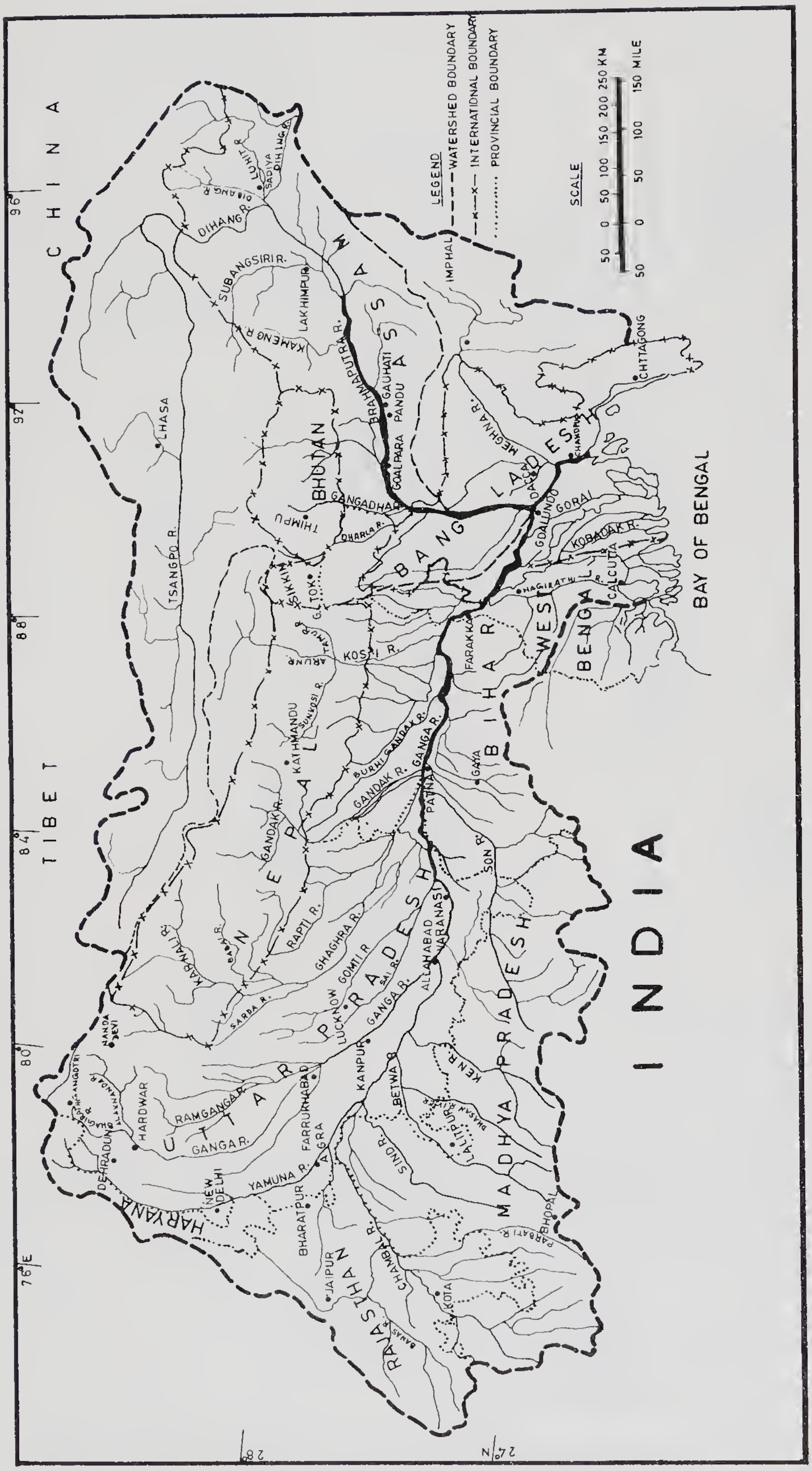

Figure 1. The Ganga-Brahmaputra-Meghna river system

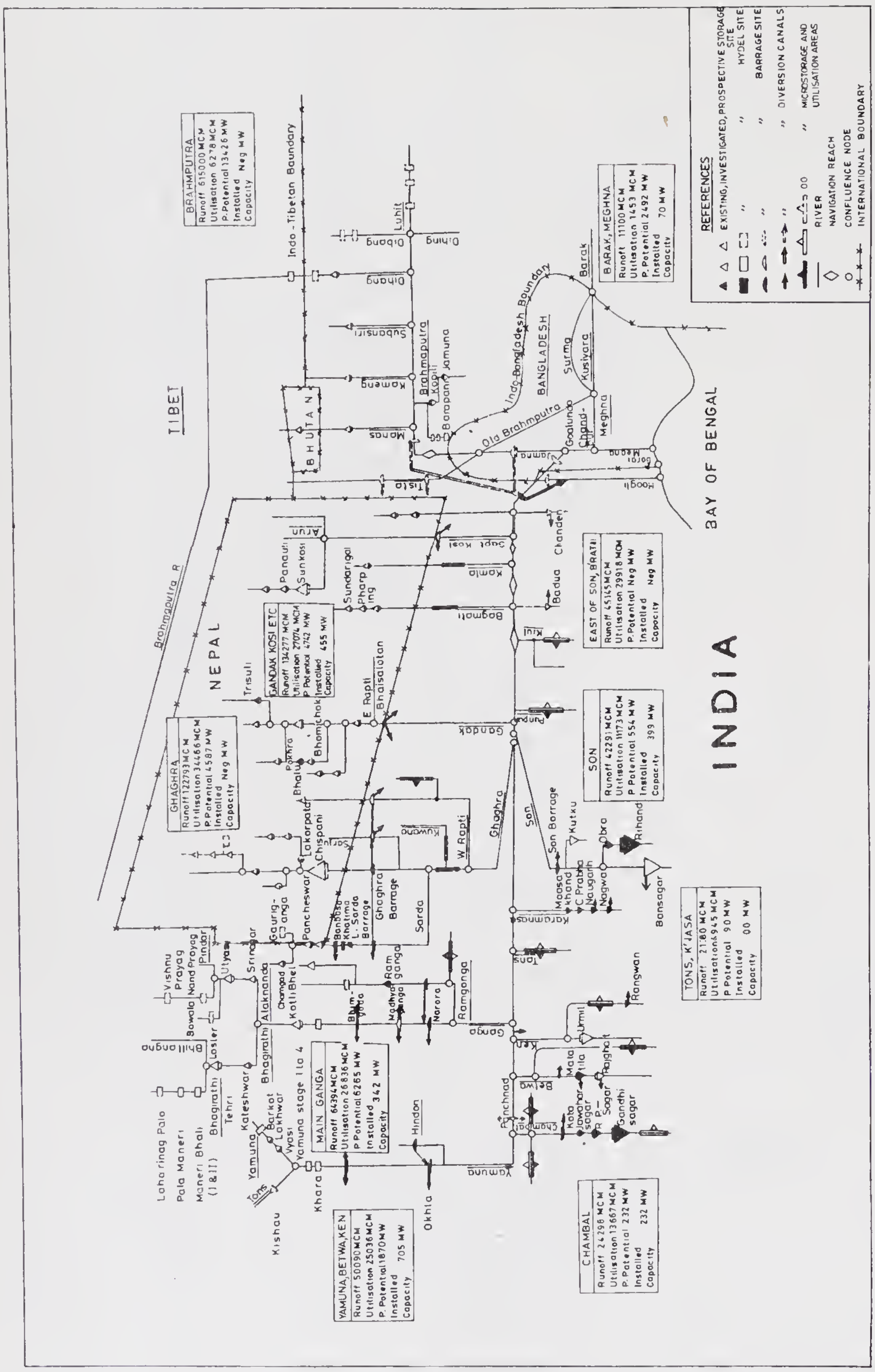

Figure 2. Macro and micro level projects for irrigation and hydel energy development in Ganga-Brahmaputa-Meghna river system (schematic)

Figure 3. Annual isohyetes (cm)

The Ganga rises in the southern Himalayas on the Indian side of the Tibet border. Its five head streams—the Bhagirathi, the Alakhnanda, the Mandakini, the Dhauli Ganga and the Pindar—all rise in the Uttarakhand division of the state of Uttar Pradesh (UP). Of these, the two main head streams are the Alakhnanda (the longer of the two) and the Bhagirathi. The Bhagirathi, which is traditionally known as the source of the Ganga, rises in India from the Gangotri glacier in the Himalayas at an elevation of about 7,010 m above mean sea level. After its confluence with the Alakhnanda at Dev Prayag, the river assumes the name Ganga. After draining the middle ranges of the Himalayas the river debouches into the plains at Hardwar. From Hardwar down to Allahabad where the Yamuna joins it on the right bank, a distance of about 720 km, it generally flows in a south/south-easterly direction. Lower down, the river flows eastwards and past Varanasi, in UP the Ganga is joined by a number of tributaries on both banks. Of

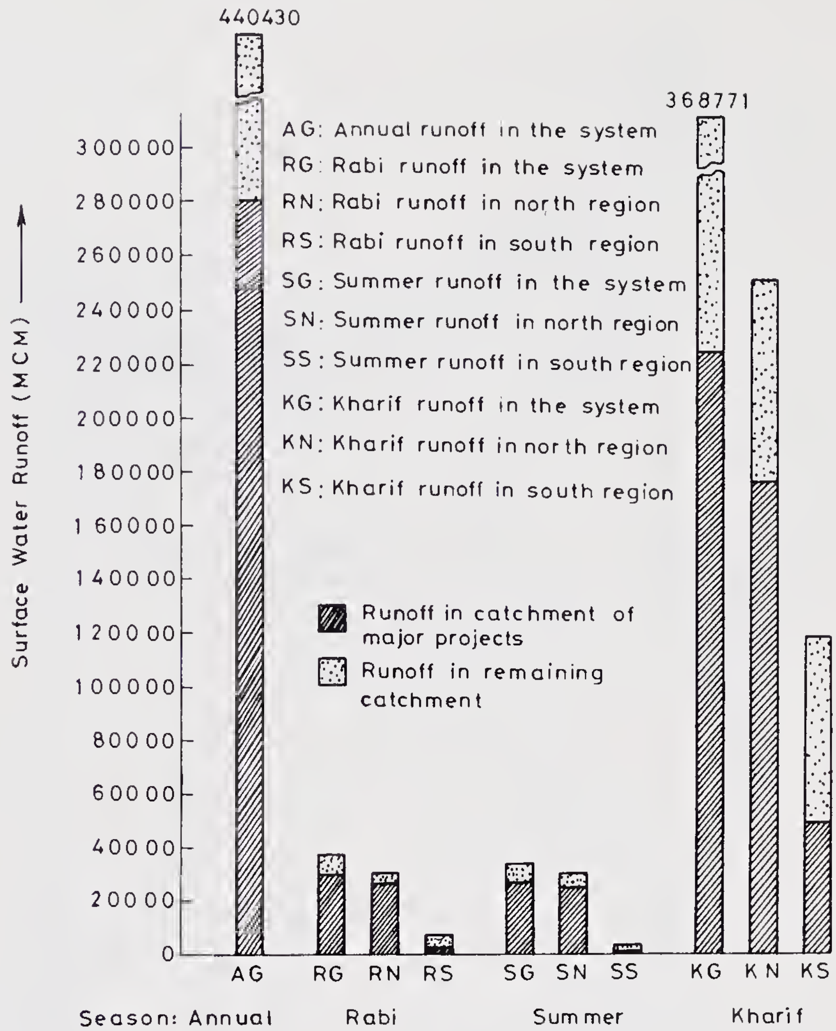

Figure 4. Surface water resources in the system

the left-bank tributaries in the upstream reaches, prior to Varanasi, the Ramganga and the Gomti are the most important. The Yamuna has a number of important tributaries like the Chambal, the Sind, the Betwa and the Ken joining it from the South. The Tons and the Karamnasa are other right-bank tributaries in UP.

After leaving UP the Ganga forms the boundary between UP and Bihar for a length of about 110 km and in this reach the Ghagra which flows down from Nepal joins it near Chapra. The river then enters Bihar below Ballia and flows more or less through the middle of the State. During its course of nearly 445 km in Bihar the river flowing eastwards is joined by a number of major tributaries on both banks. The Great Gandak, the Bagmati and the Kosi and the Burhi Gandak join it on the left bank. The first three flow down from Nepal into North Bihar. The Son, the Pun Pun, the Kiul, the Chandan, the Gerua and others join the Ganga on the right bank.

Before entering West Bengal, the river swings and flows almost due south. The delta of the Ganga can be said to start from Farakka. The river divides into two arms about 40 km below Farakka. The left arm, known as the Padma, flows eastwards into Bangladesh while the right arm, known as the Bhagirathi, continues to flow in a

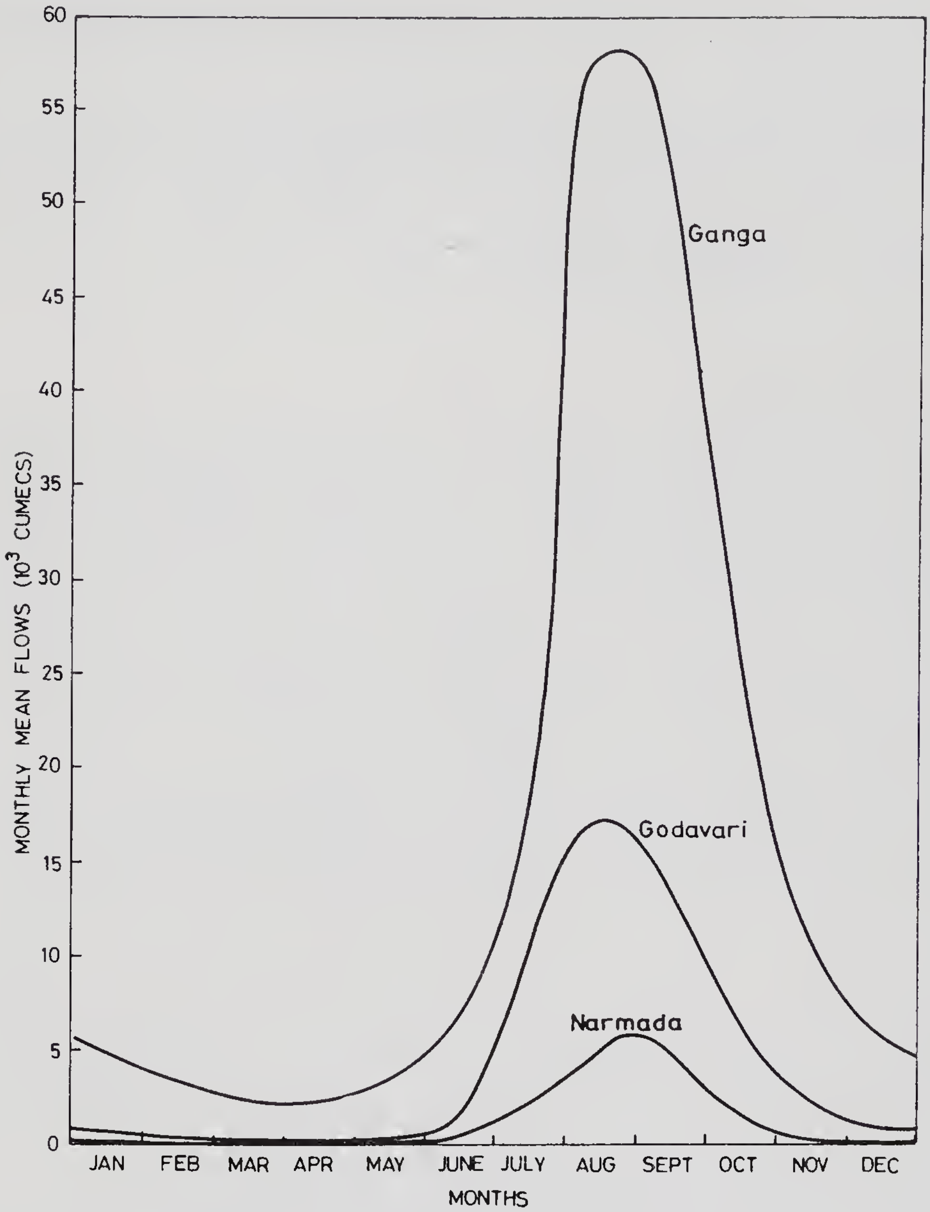

Figure 5. Monthly mean flows of some major rivers at their tail ends

southerly direction in West Bengal. Till some three hundred years ago, the Bhagirathi-Hooghly constituted the main arm of the Ganga carrying the bulk of the flow. Thereafter the Padma arm opened up more and more leaving Bhagirathi a mere spill channel of the Ganga flowing mostly during high stages of flow. The river ultimately flows into the Bay of Bengal about 145 km downstream of Calcutta. The length of the river (measured along the Bhagirathi and the Hooghly) during its course in West Bengal is about 520 km. Several tributaries join the Bhagirathi-Hooghly in West Bengal. The Ganges in Bangladesh flows past Kushtia and Pabna till the Brahmaputra (locally called Jamuna) joins it at Goalundo.

The united stream of the Brahmaputra and the Ganga beyond Goalunda continues to flow south-east under the name Padma. At Chandpur, 105 km below Goalunda, the Padma is again joined on the left bank by the Meghna, whose source is in the high mountains, which are subjected to intense rainfall. From this confluence downwards, the river, known as the lower Meghna becomes a very broad estuary making its exit into the Bay of Bengal.

The precipitation over the Ganga basin is brought about by the south-west monsoon as well as by cyclones originating over the Bay of Bengal. The average annual rainfall in India varies from 35 cm on the western end of the basin to about 200 cm near the delta. The river drains an area of 106.96 mha (excluding Tibet) and the average annual flow of the Ganga at Farakka is about 55.01 mham.

2.21 *The Brahmaputra*

The Brahmaputra rises in the great glacier in the northern-most chain of the Himalayas in the Kailash range just south of a lake called Konggyu Tsho. The river under its Tibetan name of Tsangpo flows eastwards through southern Tibet for about 1700 km keeping a course roughly parallel to the main range of the Himalayas. In this long journey it meets a number of tributaries. After turning south or southeast it enters Arunachal Pradesh in India as the Dihang river. At the town of Sadiya, India, the Dihang turns to the southwest and is joined by the two mountain streams of Luhit and Dihang. After the confluence, about 1500 km from the Bay of Bengal, the river is known as the Brahmaputra (the son of Brahma,.the creator).

The river then rolls down the Assam valley from east to west for about 720 km with its channels meandering from side to side forming many islands. In Assam the river is mighty even in the dry season and during the rains its banks are more than 10 km apart. The largest island Majuli covers an area of 1250 sq km. As the river follows its braided 700 km course through the valley, it receives several rapid Himalyan streams, including the Subansiri, the Kaneng, the Dhansiri, the Manas, the Champamati, the Saralbhanga and the Sankosh. On the south bank, the main tributaries are the Noa Dihing, the Buri Dihing, the Disang, the Dikhu and the Kopili. The Brahmaputra also has some important tributaries flowing through North Bengal. They are the Tista, the Jaldhaka, the Torsa, the Kaljani and the Raidok. Emerging swiftly from narrow gorges with steep slopes, these rivers widen out considerably in the plains.

Swinging round the western spurs of the Garo Hills, near Goalpara, the river enters the alluvial plains of Bangladesh, through which it flows southwards for another 270 km until it joins the Ganga at Goalundo. Below the confluence of the Tista, the old channel of Brahmaputra branches off the left bank. From here to Goalunda the river is called the Jamuna.

In Tibet the precipitation is in the form of snow which begins to melt in March following the intrusion of warm air. Coming down the central basin in India, the annual rainfall, brought by the southwest monsoon, is about 250 cm. Further down in Bangladesh the rainfall over the basin averages about 240 cm. The river drains a total catchment area of 23·41 m ha (excluding Tibet and Bhutan) at Bahadurabad (Bangladesh) and the average annual runoff at this site is 61·5 m ha m.

2.3 *The Barak/Meghna*

The Barak river, the head stream of the Meghna rises in the hills in Manipur (India) at an elevation of about 2900 m. It flows south-westerly winding its way along hill ranges for about 250 km. Thereafter it takes a sharp reflex bend and flows north. It changes direction to west when emerging from the hills and follows a meandering course till it enters Bangladesh. Many tributaries join the Barak. Near the border, the Barak bifurcates into two rivers, the Surma and the Krishiyara which again join and flow in a southerly direction under the name of Kalii. It takes the name Meghna before it meets the Padma, which carries the combined flow of the Ganga and the Brahmaputra, at Chandpur.

Below Chandpur the combined river, also known as the Lower Meghna, becomes a very wide and deep estuary. It enters the Bay of Bengal through four principal channels. The distance between Chandpur and the sea is about 130 km. The Meghna is thus about 950 km long, of which 550 km including the estuary from Chandpur to the sea lies in Bangladsh.

The river has a steep slope while flowing in the hills in India. After entering Bangladesh it travels through the low-lying alluvial basin. When the Meghna flood meets that of the Padma at Chandpur, its floods are backed and its basin acts as a gigantic detention reservoir, without which the area between Goalundo and Chandpur would be under much deeper water. At flood stages, the slope of the Meghna downstream of Bhairab Bazar, where it meets the old Brahmaputra, is only about 1:88,000 which reflects the influence of back-water from the Ganga-Padma.

There is copious rainfall in the watershed of the Meghna and the Barak rivers. Around the foothills in Assam, the rainfall reaches 500 cm on the windward side. At and near Cherrapunji, where rainfall is amongst the highest in the world, the average annual precipitation is about 1100 cm. In the plains of Bangladesh the rainfall varies from 200 to 300 cm. The drainage area of the Meghna at Bhairab Bazar is about 8·02 m ha and average annual runoff is 11·1 m ha m.

2.4 *Some systems characteristics*

Despite the wide physiographic-geographical diversities some characteristics of the system may be mentioned.

The Ganges-Jamuna area was once densely forested; historical writings indicate that in the 16th and 17th centuries, wild elephants, buffaloes, bison, rhinoceroses, lions and tigers were hunted there. Most of the original natural vegetation has disappeared from the Gangetic basin as a whole and the land is intensely cultivated to meet the needs of an ever-growing population. Hence, irrigation is increasingly depleting the low flows.

In ancient times the Ganga and some of its tributaries in the east were navigable. The Ganga was navigable upto Agra. It has almost disappeared now and is practical only in West Bengal and Bangladesh.

The Ganga as well as its tributaries and distributaries, are constantly vulnerable to changes in their course in the delta region. Such changes have occurred in comparatively recent times, specially since 1750; the most spectacular of these changes was the eastward diversion of the Tista river and the ensuing development of the new channel of the Jamuna, which occurred in 1787 with an exceptionally high flood in the Tista.

The delta of the Greater Ganga system is one of the biggest in the world covering an area of 56,700 km^2.

The salient statistics of the region are shown in table 1. Some important characteristics of the region are summarised in table 2. The salient pieces of information about the entire Ganga basin and relevant statistics for India are given in table 3. The details for the Ganga Basin in terms of eight sub-basins are given in table 4.

Table 1. Salient characteristics of the Greater Ganga basin

No	Item	Unit	Ganga India	Ganga Nepal	Ganga Bangladesh	Total or average figure for basin	Brahmaputra India	Brahmaputra Bangladesh
1	2	3	4	5	6	7	8	9
	A. Land							
1.	Geographical area	Mha	86·14	14·08	6·74	106·96*	18·71	4·7
2.	Cultivable area at present cultivation	Mha	60·30	3·98	3·64	67·92	12·15	3·0
	B. Population							
1.	1971 Census	Million	221·19	11·29	27·03	259·51	17·65	24·83
2.	Population density	per sq km	257·00	80·00	401·00	243	94	528
3.	Agr. population	Million	149·74	10·34	19·06	179·14	11·93	17·5
4.	Agr. population	%	67·6	91·6	70·5	69·03	67·6	70·5
	C. Water							
1.	Mean annual rainfall	cm/yr	60–200	100–250	150–212	120	212	200
2.	Total annual runoff	mhm	55·01***	—	Neg	55·01	51·25	10·25
3.	Irrigation potential (present)	Mha	17·81	1·202	2·95	21·96	2·3	1·46
	D. Energy							
1.	Hydropower potential	Mkw	13·274	85·00	Neg	98·27	13·43	Neg
2.	Hydropower installed	Mkw	1·83	0·41	Neg	2·24	00·18	Neg
3.	Hydropower installed	%	13·79	0·49	Neg	2·33	1·34	0·0
	E. Unit figures							
1.	Land per capita	Ha	0·39	1·25	0·25	0·4	1·06	0·189
2.	Utilizable water/unit cultivable land	m^3	116·00	—	—	—	171·0	—
3.	Cropping intensity	%	125	—	—	—	118·0	—
4.	Irrigation intensity	%	23	—	—	—	21·3	—
5.	Utilizable and utilized water resource							
a.	Surface	mhm	18·5/70·4	—	—	—	0·61/70	—
b.	Ground	mhm	10·64/39·4	—	—	—	0·02/1·1	—
c.	Total	mhm	29.14/59.4	—	—	—	2·68/23·5	—

Note:
A. (i) *** Inclusive of runoff of Nepal; (ii) ** 29·3 Mha in Tibet and 5·29 Mha in Bhutan not included in this figure; (iii) * 2·9 Mha in Tibet not included in this figure; (iv) Neg = Negligible; Agr. = Agricultural; (v) These figures are derived from Irrigation Commission Report.
B. The figures have been taken from various published sources and are only indicative.

3. Developmental issues

Although technological activities for water resources development have been undertaken in the past, the region still provides unique opportunities for the development of the huge unutilised potential. The best way would be to have an integrated approach, treating the entire river basin as one. This may not be possible from political considerations, but at least developmental planning may be carried out in totality, as well as from each country's point of view and then a bargained developmental plan for each country may be developed.

The development in the Ganga basin in the pre- and post-Independence period has been *ad hoc* and of the project-oriented technological type. The policy in the pre-Independence period was one to support sustenance agriculture. It is now necessary to develop an appropriate integrated future developmental policy. The approach has

Total or average figure for basin	Barak/Meghna India	Barak/Meghna Bangladesh	Total or average figure for basin	Total for greater Ganga basin	Total in each country India	Total in each country Nepal	Total in each country Bangladesh
10	11	12	13	14	15	16	17
23·41**	4·4	3·62	8·02	138·39	109·25	109·25	15·06
15·15	1·11	2·87	3·98	87·05	73·56	3·98	9·51
42·48	5·33	19·10	24·43	326·42	244·17	11·29	70·96
181	121	528	305	236	223	80	471
29·43	3·60	13·46	17·06	222·03	165·27	10·34	50·02
69·28	67·6	70·5	69·83	68·02	67·69	91·58	70·5
212	450	240	350	—	—	—	—
61·5	6·0	5·1	11·1	127·61	112·26	—	—
3·76	0·115	0·47	0·585	26·305	20·225	1·202	4·88
13·43	2·5	Neg	2·5	114·2	29·2	85	Neg
0·18	0·08	Neg	0·08	2·5	2·09	0·41	Neg
1·34	3·2	Neg	3·2	2·23	7·16	0·49	Neg
0·55	0·82	0·189	0·33	0·42	0·45	1·25	0·18
—	379·0	—	—	—	—	—	—
—	124·0	—	—	—	—	—	—
—	13·0	—	—	—	—	—	—
—	0·20/27	—	—	—	19·21	—	—
—	0·75/11·3	—	—	—	10·735	—	—
—	1·03/9·7	—	—	—	32·85	—	—

been briefly reviewed in the context of an overall policy for India (Chaturvedi 1985), but it is reviewed in greater detail for the Greater Ganga Basin.

3.1 *Technological choice*

The physiography, hydrologic input, vector specification of precipitation and demand characteristics and the socio-economic milieu largely determine the technological choice. The salient characteristics are as follows.

The basin is like an elongated bowl with very high and steep mountains on the north and comparatively low mountains on the south and east and a very flat alluvial plain in between. The precipitation takes place during 3 or 4 months of the monsoon and thus there is tremendous variation in the water availability over the year, as shown in figure 4. Even during the monsoons, precipitation is neither uniform nor dependable. The physiographic condition of steep mountains followed by flat plains and the hydrologic characteristic of monsoon-concentrated precipitation lead to heavy floods.

Table 2. Summary of salient features of the Greater Ganga Basin

Item	Total for Greater Ganga basin	Share for India
Land		
Geographical area (10^6 ha)	138·39	109·25
Cultivable area (10^6 ha)	87·05	73·56
Population		
1971 Census (million)	326·42	244·17
Population density (per km^2)	80—645 with an average of 240	223·0
Agricultural population (million)	222·03	165·27
Agricultural population (% of total)	68·02	67·69
Water		
Mean annual rainfall (cm/yr)	60–450 with an average of 350	—
Total annual runoff (m ha m)	127·61	112·26
Irrigation potential (m ha)	26·3	20·2
Energy		
Hydropower potential (MW)	114·2	29·2
Hydropower installed	2·5	2·09
Unit figures		
Land per capita	0·42	0·45
Utilizable water/unit culturable land (m^3)	116–379	—
Cropping intensity	—	118–125
Irrigation intensity	—	13–23
Utilizable water (m ha m)		
(a) surface	—	19·21
(b) groundwater	—	10·735

The Himalayas, which form a considerable portion of the catchment area of the Greater Ganga Basin, are very young, erodible and have very steep slopes leading to high flows and very heavy sediment loads—the highest in the world during the monsoons (Leeden 1975). While the storage potential is large, it is a very small proportion of the total water resources of the region—only about 8% (Rao 1976).

Most of the storage and hydroelectric potential of the Himalayan region is in Nepal. Increasing population in Nepal is going to exacerbate the erosion, sedimentation and flood problem due to cutting of forests for agriculture and energy demands. Thus, it is both in India's and Nepal's interest to collaborate in the rapid development of the watershed, social forestry, storage and hydroelectric energy, in the Himalayan region for utilising the valuable water resources and hydroelectric potential and reducing the hazards of erosion and floods. Water for this region is like oil for the middle east countries with the further advantage of non-depletability. It can be said that gravity is the biggest asset of this region. The economy of this region can be built around the development of water, light industry and tourism rather than food crop-oriented agriculture as necessity demanded in the past. Of course, these transitions will take

Table 3. Salient statistics of the Ganga basin

Item	Ganga Basin	Total India	Ganga (% of total)
Land			
Geographical area (10^6 ha)	86·14	328·06	26·3
Cultivable area (10^6 ha)	60·30	199·92	30·1
Population			
1971 Census (million)	221·19	546·9	40·4
Population density No/sq. miles	286–1180	470	—
Rural population (%)	80–93	—	—
Cultivators and agricultural labour (%)	55 + 22	of total labour force	
Water			
Mean annual precipitation (cm/year)	60–200	118	—
Potential evapotranspiration (cm/year)	155–175	228	93
Total annual runoff (m ha m)	55·01	188·12	29·3
Groundwater (percent of total)	26·6	—	—
Utilizable water resources			
(a) surface	18·50	66·60	27·8
(b) surface as percent of total	34	—	—
(c) groundwater	10·64	26·10	41·0
(d) total	29·14	92·70	31·4
Unit figures			
Land/Capita (hectares)	0·27	0·37	
Utilizable water/unit culturable land (m^3)	116·0	115·00	100%
Cropping intensity	125	—	—
Irrigation intensity	23·0	20·6	—
Hydropower potential (MW)	13,285	—	—
Hydropower installed (MW)	1,830	—	—

place integrally and over the course of time. Agriculture has to be developed taking into account the agro-climatic-environmental implications. Transportation will have to be developed and roads built as development takes place. These should be undertaken on priority in accordance with an appropriate modernization policy because if these activities are undertaken after the construction of dams, erosion will seriously reduce the storage potential of the region. The highest priority has also to be laid on watershed management and afforestation. Sectoral activity in the area of water-energy resources has to be planned in the context of a long-term modernization policy and a techno-economic developmental programme. Of course consistency of resource-allocation in different sectors will have to be borne in mind.

The Vindhya region is also mountainous. Similar considerations of watershed management and afforestation apply but the problem is not so acute. Secondly, the region provides excellent storage facilities for dams but the water availability is correspondingly limited. The implication of this aspect will be discussed later.

In the plains the physiographic-agroclimatic-resources and base conditions are quite different. Agriculture has a tremendous potential for employment generation and economic development. Of the several inputs required for this transformation

Table 4. Salient water land and population statistics of Ganga basin

Sl. No.	Sub basin	Land: Catchment area (inside India)	Culturable area (% of 1)	Net sown area (% of 2)	Cropping intensity	Precipitation	Evaporation	Water: Annual runoff	Surface runoff	Annual ground water recharge
		m. ha	%	%	%	cm	cm	m hm	m hm	m hm
		1	2	3	4	5	6	7	7a.	8
1	Main Ganga (including Ram Ganga)	13·98	64·1	86·9	132	128	175	6·12	1·33	3·0
2	Chambal	13·95	72·6	64·4	110	79	275	2·43	1·80	1·24
3	Yamuna	22·68	73·8	77·8	125	87	260	6·56	1·43	3·05
4	Tons, Karamnasa & others between Yamuna & Son	2·86	66·3	77·9	131	106	225	1·41	1·04	0·47
5	Gomati, Ghagra & others between them	10·11	76·0	84·7	131	108	225	12·28	2·66	1·89
6	Son	7·13	50·5	60·4	121	139	180	4·23	3·13	1·09
7	Gandak and other left bank tributries	5·73	76·4	87·7	137	154	180	17·47	3·77	1·36
	Right bank tributaries east of Son	9·71	69·3	69·2	117	130	175	4·51	3·34	2·52
	Total	86·15	68·6	76·0	125·5	116·39	211·8	55·01	18·50	14·62

dependable and adequate water supplies are most important. The possible technologic options are described by Chaturvedi (1985). The choice of technology should be based on detailed analysis but the following may guide the analysis.

Provision of water through river diversion is most economical for irrigation and has, therefore, been given priority in the past, but there is a certain limit over which the low flows cannot be reduced. Secondly, river-diversion based surface flows cannot give assured supplies. The region is rich in groundwater which can be readily exploited by the people, individually and collectively. Conjunctive surface and groundwater is more advantageous technologically and economically, and should be given the highest emphasis. Possibly, both development and distribution are done through cooperatives. Detailed systems analysis is required to identify the specification of appropriate capacities of surface and groundwater timing and trajectory, cropping pattern, organisation and operation of the system.

Emphasis in the past has been on flow diversions limited to low flows. Recently, canals with capacities to cater for kharif irrigation have been developed. This is attractive, because it provides for irrigation from groundwater recharge. Appropriate design will again require detailed analysis and groundwater dynamics modelling.

Utilizable		Utilized % of utilizable			People			Unit figures			
Surface runoff (% of 7)	Ground water (% of 7)	Surface (% of 9)	Ground water (% of 10)	Total utilized % of utilizable	Population	% of total population	Density/km²	Culturable area/capita	Water/capita	Water/culturable land	% gross sown area irrigated
%	%	%	%	%	m	%	No/km²	ha	m³	%	
9	10	11	12	13	14	15	16	17	18	19	20
21·7	35·1	80·0	37·2	74·0	49·69	9·25	353	0·18	1830	101·80	18·3
74·2	35·8	46·1	64·0	52·0	15·35	2·91	110	0·66	2400	36·15	13·3
21·8	33·7	109.2	43·0	70·0	45·66	8·60	201	0·37	2100	57·25	23·6
73·8	26·5	36·5	29·5	35·10	6·83	1·37	239	0·28	2750	99·0	25·0
21·9	12·0	80·0	89·5	80·9	36·29	6·35	259	0·21	3910	184·3	26·1
74·0	18·9	32·85	10·0	29·5	7·88	1·57	111	0·45	6750	148·0	15·7
21·5	5·9	69·04	11·0	56·6	26·22	4·85	457	0·17	7200	431·0	9·0
74·3	38·7	85·0	9·2	60·0	33·27	6·30	342	0·20	2100	104·60	37·1
33·6	19·3	71·0	39·4	59·1	221·29	41·20	259	0·32	3630	145·26	21·0

We have emphasized conjunctive surface and groundwater development, but since surface water resources have already been considerably developed the focus will be on groundwater development along with modernization of the existing systems. Groundwater development represents the so-called 'divisible technology' and is very attractive for the development and diffusion of the culture of technology. It could provide employment in construction as well as through intensive irrigation, leading to the most productive agriculture and the highest possible cropping intensity.

There is a serious problem of energy scarcity as electrical energy supplies have not been developed adequately and diesel is going to be in increasingly short supply. There is thus a case for urgently resolving the energy problem through a scientific energy policy. On an *ad hoc* basis we may plan on development through diesel tubewells.

Groundwater is a major user of energy and surface water is a rich source of energy through hydroelectric generation. There is thus a strong case for conjunctive surface-groundwater and energy development.

In surface water resources development, the focus has been entirely on diversion of the low flows of the major rivers. Mostly, the diversion site has been the mountain foothills and the diverted flows basically represent the low flows of the Himalayan

Table 5. Developmental programme

Phase	Alluvial plains	Himalayan region	Vindhyan region
A. 1st five years	1. Intensive groundwater development through energised/diesel pump sets for 100% irrigation intensity 2. Development and modernisation of existing systems for conjunctive water energy development with kharif channels 3. Development and modernization of water distribution and field management such as efficient water use, land levelling and environmental development. 4. Watershed development for flood mitigation, groundwater recharge and soil conservation with development of minor rivers and streams.	1. Complete road network 2. Intensive water-shed development 3. Start storage projects, hopefully in Nepal as well	1. Start development of storage projects with provision for additional storage from annual pumped storage schemes and develop surface and groundwater irrigation 2. Start modernization as in 2 of plains 3. Environmental management
B. 2nd five years	1. Increasingly energise A.1 2. Complete A. 2 3. Continue A. 3 4. Continue A. 4	1. Continue A. 2 2. Continue A. 3	1. Continue A. 1 2. Continue A. 2 3. Continue A. 3
C. 3rd five years	1. Complete B. 1 and continue B. 3 and B. 4	1. Complete A. 2 2. Continue A. 3	1. Complete A. 2 and A. 3 2. Continue A. 1 3. Start transfer part of annual pump storage projects
D. Next 15 years	1. Continue increasing efficiency of water use and environmental management *ie* B. 3 and B. 4	1. Complete all development and continue increasing environmental efficiency	1. Complete C. 3 and continue increasing environmental and resources efficiency

catchment region. The flows of the vast catchment of the plains are carried down in the numerous minor streams. Some, which may even be quite large according to international standards, like the Gomti, have been neglected. The runoff from the plain area, which is a major component of the total runoff, thus causes floods and is wasted.

The focus should be on land-water dynamics, attempting to develop the land by organic as well as structured means, so that floods and soil erosion are mitigated and water resources are developed through groundwater recharge and storage. Possible technologies are bunding, appropriate watershed management through cropping practices and afforestation, storage through check dams to prevent submergence, and to increase water detention, additional groundwater recharge by heavy pumping before monsoons. The approach is so far conceptual, but its feasibility warrants detailed study. In this connection the concept of the Ganges-Water Machine along perennial and non-perennial rivers and forced groundwater recharge may also be mentioned (Chaturvedi 1981a). For convenience, we may consider the above issue under two heads (a) development of minor rivers and streams for flood mitigation, groundwater recharge and irrigation and (b) watershed development for flood mitigation, groundwater recharge and soil conservation.

In groundwater development the question arises about the annual quantum to be developed. Under the natural land-water dynamics a certain utilizable potential known as safe yield is estimated. With the increasing perturbation of land water, a long-term groundwater developmental policy has to be developed, which may lead to mining in the short run. Mining may have repercussions on the yield of shallow wells and surface discharge and, therefore, land-water dynamics has to be modelled to identify an appropriate dynamics policy of groundwater development.

The foregoing discussion relates to macrolevel development and distribution. An equally important aspect is field-level distribution and use. In the past, due to certain colonial-bureaucratic reasons, use of water and development of land was left almost entirely to the farmers. It is well known that our water use is most wasteful, and integral lining of water courses, land levelling and associated technological activities at the field level have to be carried out. Technology is, however, more than development of projects. It is a process of social change and has to embrace adequate institutional and motivational mechanisms. Field-level development has to be integrated with rural development and can be a major source of employment generation and promotion of modernization. Workshops can be developed in mofussil towns for the construction of pumpsets and strainers. Drilling of tubewells and canal lining can be developed through rural entrepreneurship. Command area development and water management activities have been started but they have to be considerably extended and strengthened.

Our concern is primarily the development of water resources for irrigation. To a certain extent, this will contribute to flow reduction although specific conventional and non-conventional technological alternatives will have to be developed as flood damage is a serious matter in this region. Besides loss of life and property, agricultural development is seriously affected by floods in these regions.

We have developed five conceptual interacting technological sets: (i) development of resources in the mountain zones, (ii) modernization of existing systems for conjunctive water-energy development with kharif channels, (iii) development of minor rivers and streams for flood mitigation, groundwater recharge and irrigation, (iv) watershed development for flood mitigation, groundwater recharge and soil conservation and (v) field level modernisation. A long-term regional water resources system plan has to be developed to identify the optimal portfolio of projects so that land-water development is obtained over optimal time. This exercise has to be carried out for each planning region to arrive at the optimal plan for the Ganges basin. Water resources availability continuously increases from west to east, but it is almost equally unreliable all over. There should thus be increasing emphasis on groundwater development as we move eastward. In fact, the problem increasingly becomes one of managing excess monsoon water through groundwater recharge and drainage without disrupting the local terrain. To this extent, the problem in Bangladesh is essentially hydraulic rather than hydrologic, as discussed later.

The north-east, the Barak and the deltaic regions have certain specific physiographic-hydrologic characteristics although as discussed earlier their development is integrally linked with the rest of the region. The problems of the north-east region are similar to the Himalayan region, but increasing attention has to be paid to integrated flood management along with hydroelectric generation. The problem of the Barak region is essentially a problem of flood management. The problem of the deltaic region is essentially a hydraulic problem as mentioned earlier.

One of the important aspects of water resources development is the generation of electricity. Although this is generally accepted, several policy issues and outstanding potential technological options have been completely missed in the development activities so far, as discussed below.

The storage-hydroelectric potential in the Himalayas is large and very economical. There is also a very large run-of-river hydroelectric potential in the Himalayan region. The Vindhya region also provides considerable potential, which is also exceedingly economical for two reasons—the storage/height ratio is one of the highest in the world and the foundation conditions are faultless.

The point to be emphasized is that first, the storage and run-of-river plants have to be developed jointly so that, through suitable operating policies, optimal capacities in each plant and in the system are obtained. Implicit is integrated planning of the total power sector (Chaturvedi 1981b, 1985). Even then, if there is surplus potential of secondary energy, it can be converted into primary energy, by using the secondary energy to pump the large monsoon surface flows for storage in the Vindhya region, either in the Ganga basin or in the adjoining Narmada basin. In principle, this is a novel annual pumped-storage scheme for both hydro-energy and resource conservation.

Implicit in these suggestions is integrated water sector and power sector planning. Besides the interlinkage of water and energy sector for supply, there is an important supply-demand interlinkage. Groundwater development may account for a major portion of electric energy demand (as much as 20 to 60% at different stages of development) while water supplies may be met either from surface or groundwater sources. An integrated surface-groundwater-energy planning as discussed under systems planning can contribute to significant economics.

Further issues relate to environment and navigation. From both considerations, minimum flows have to be maintained. It is again a matter of economic analysis, but it can definitely be said that the largescale low-flow diversions of the past may be unacceptable both economically and environmentally. It is interesting to note that when the first major canal of the region, the Ganga Canal, was contemplated it was considered mandatory to ensure that navigation did not suffer and therefore the canal was joined again with the Ganga at Kanpur (Cautley 1860). The importance of navigation diminished not only because more attractive technological options like the railways or the roads developed, but also because economic development did not take place. River transport would be the most attractive means of transportation for the increasing agricultural and other bulky commodities that constitute about 80–90 % of the goods traffic. It is often not realized that only about 4 meters of draft is needed for river transport and even 2 m would be enough. River transport should be complementary to other modal choices instead of being competitive, and integrated water, energy and transportation systems planning can lead to significant economies.

To consider the complex, interlinked as well as competing issues, involving large variations in technological choices and capacities—spatially and temporally, for multipurpose use, integrated systems planning is mandatory. Before identifying a programme of development, it is necessary to consider the international issues involved in the development of the Greater Ganga Basin. These have been discussed elsewhere (Chaturvedi 1985).

In the dispute with Bangladesh, the simple fact that the development of Nepal is crucial for the development of the Ganga basin and is in the interest of both countries has been lost sight of. Highest priority has to be given to the integrated development of water resources in the region irrespective of whether the sites are located in Nepal or India.

3.3 *Development programme*

The developmental policy for the water resources of the basin may now be summarised and a tentative schedule may be postulated, as shown in table 5. In the schedule, our concern has been mainly development of water supply for irrigation. We have concentrated on the three main physiographic regions. Similar policy schedules can be drawn up for energy and navigation and then integrated-hierarchial systems planning can be carried out as discussed later. It will be seen that the schedule depends primarily on management potential, the internal and international political and financial policy of giving credit for development rather than on technological considerations. We have postulated a time schedule from our experience of developing the water resources of this region over the last 30 years, considering only management and technological factors and not considering the financial or political factors as a constraint. If the latter are uncongenial, it can only slow down the development and make it slightly less economical. We believe that if earnest efforts are made, in 5 years almost complete and dependable irrigation can be provided in almost the entire region. It can be made more and more economical with full development in 30 years of irrigation, flood control, hydroelectric energy and the environment. This may be contrasted with the contemplated attainment of about an additional 5 % irrigation at a crawling rate. Of course the proposed schedule, will require a revolution in technological management and institutions, and a high order of political and social commitment.

The conceptual policy issues developed so far have to be quantified through systems studies.

4. Conclusion

As stated at the outset, the Greater Ganga basin is one of the world's great natural resources with an outstanding potential for hydroelectric energy and agricultural production. Neglect over the last few centuries has led to serious environmental degradation and human depravation, leading to one of the most intense concentrations of population. The natural resources and environmental development offers an outstanding opportunity for economic development and employment generation. It is a very complex problem, making a systems approach mandatory.

For the successful application of technology, institutional modernization is a precondition. Concepts and approaches developed in colonial days still reign supreme; these have to be jettisoned first and foremost.

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The coordinating model of the Ganga Basin

M C CHATURVEDI, PETER ROGERS* and SHYANG-LAI KUNG**

Applied Mechanics Department and Centre for Systems Engineering and Policy Studies, Indian Institute of Technology, New Delhi 110016, India

* Department of Environmental Engineering, Harvard University, Pierce Hall, 121 Cambridge, Massachusetts 02138, USA

** Argonne National Laboratory, 9700, S Case Avenue, Argonne, Illinois 60439, USA

Abstract. A scheme of model studies required to analyse a complex large scale system through decomposition approach is outlined. First, the total system is proposed to be modelled to identify interlinkages of the subsystems. Then the subsystems are analysed in detail to develop response functions. Finally the optimal system functioning is obtained by modelling the entire system in terms of response functions of the components.

A linear programming model is developed for modelling the total system to identify the interlinkages. Its application is demonstrated in the Greater Ganga Basin using published data. Trade-off is developed between power generation and irrigated area in various seasons.

Keywords. Large scale systems; multilevel hierarchical approach; co-ordinating screening model; linear programming model

1. Introduction

Systems analysis of large systems is an integrated-hierarchial multilevel and multistage activity because of the complexity, scale and dynamic nature of the problem. Multilevel hierarchial analysis may be carried out in several ways (Lasdon 1970; Haimes 1977; Chaturvedi 1974). In the first instance, the total system may be modelled to identify the order of interlinkage of the sub-systems. In the second study, the sub-systems may be examined in detail and their response expressed as a function of the interlinkage over the likely range as anticipated from the first study. Finally, the optimal system functioning may be obtained by modelling the entire system in terms of the response functions of each of the sub-systems as obtained from the second study.

The type of model depends upon the characteristics, scale and complexity of the system, as well as on the objectives of the analysis. The first study carried out through a model called the coordinating-screening model is for coarse screening and deterministic modelling dividing the year into two or three time periods. A linear-programming approach may be used. Further, by adapting the inflows over a range to cover the likely variability of inflows, the implications of the stochastic nature of inputs may be studied (Jacoby & Loucks 1972; Chaturvedi & Srivastava 1981). For the second series of models for sub-systems analysis, any appropriate systems analysis approach using deterministic and stochastic models may be used (Hall & Dracup 1970; Biswas 1976; Chaturvedi 1984). And finally for the third-stage analysis, mathematical programming models and simulation models, singly or hierarchially, may be used. For studying the Ganga basin, the hierarchial modelling scheme shown in figure 1 was

A list of symbols is given at the end of the paper.

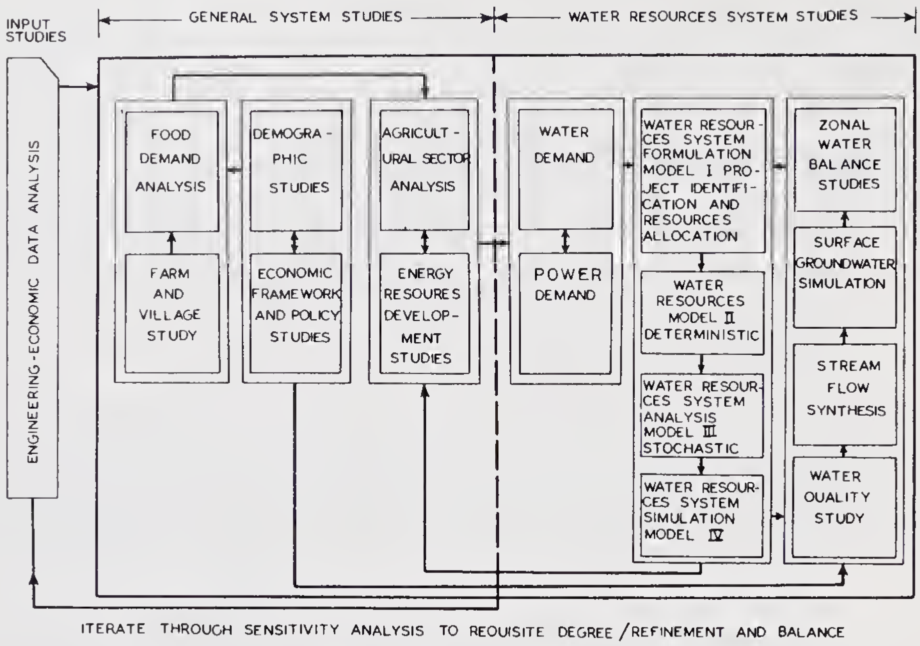

Figure 1 Water resources systems analysis modelling morphology

developed. The scheme with slight modifications has been applied to study the Punjab water resources (Chaturvedi 1979).

It must be emphasised at the outset that the study brings out only an approach to analysis and the quantitative figures given are meant only to illustrate the approach for the decomposition of the system and have no real life implication.

2. The model

The first stage preliminary screening of the Ganga basin is discussed in this section.

For the first coordinating-screening model, a simple linear model was constructed to coordinate all the demands placed upon the system (Chaturvedi 1974; Chaturvedi and Rogers 1975). This model is then used as a tool to explore the various goals to be attained and the constraints on development. Once the system has been fully explored by this inexpensive model, it can be broken up into smaller, more manageable pieces for more detailed analysis. However, the overall model can still be used to coordinate the results of the detailed studies as they become available, or the second coordination can be in terms of the response functions of each of the sub-systems.

Figure 2 shows the schematic layout of the Ganga basin used in the coordinating model. There are 49 river-schematic nodes of interest at which junctions, diversions, groundwater pumping and return flows occur. The model considers 5 storage reservoirs, 6 hydropower plants, and 25 major irrigation works as already developed and looks for the optimal allocation of the water resources for agriculture and power subject to meeting downstream flows for navigation, water supply and salinity control in the delta.

Table 1 summarises the system sketch and the water continuity relationships. The number in each row shows the connection and the flow direction for each of the parameters or division variables—X, river flow; Y, diversion; Z, diversion for irrigation; P, flow for hydroelectric generation; V, storage locations; A, area for irrigation; T,

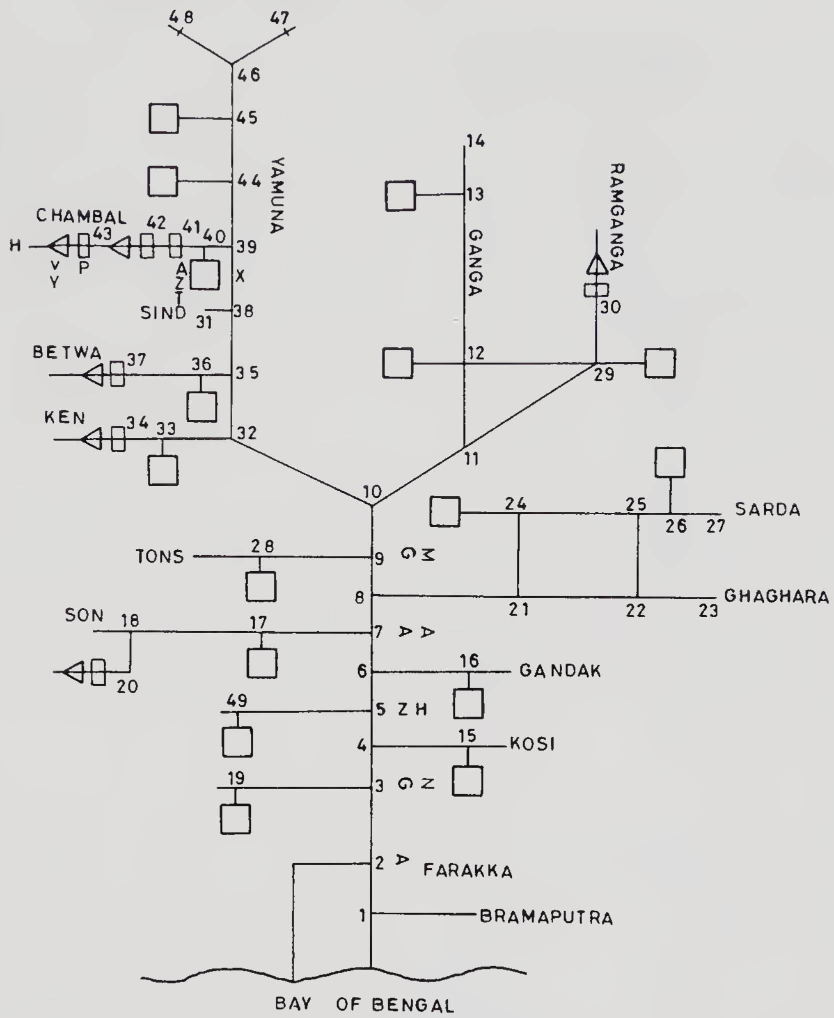

Figure 2. Schematic diagram of the Ganga basin

groundwater development; D, groundwater return flow; H, the hydrological input. For example, a negative number $(-k)$ from a row of node i indicates that water flows from node k towards node i. On the other hand, a positive number (k) implies that water flows away from node i towards node k.

2.1 *Objective function*

The major uses for water in the basin are to produce energy and for agriculture; therefore, the coordinating-screening model is formulated on the basis of these two uses. Other uses of water (such as water quality control, navigation, urban water supply, flood control, etc.) are not fully studied and are constrained by minimum or maximum river flows.

An objective function is thus constructed to include the major water uses for energy production and irrigation. This objective function will enable the model to select the best mix of these uses of water. The objective is to maximise agriculture and energy in the following form.

$$\max Z = f_a \cdot \sum_i \sum_j (A_{ij}) + f_p \cdot \sum_j \sum_i (P_{ij} \cdot K_i), \tag{1}$$

Table 1. System identification table.

Node no.	X	Y	Z	P	V	A	T	D	H
1	1-2							-2	1
2	2-3	2	2			2	2	-3	
3	3-4-19		3			3	3	-4-19	
4	4-5-15		4			4	4	-5-15	
5	5-6-19		5			5	5	-6-19	5
6	6-7-16		6			6	6	-7-16	
7	7-8-17		7			7	7	-17	7
8	8-9-21								8
9	9-10-28							-28	9
10	10-11-32							-32	
11	11-12-29							-12-29	11
12	12-13	-29	12			12	12	-13	
13	13-14		13			13	13		
14	14								14
15	15		15			15	15		15
16	16		16			16	16		16
17	17-18		17			17	17		
18	18-20								18
19	19		19			19	19		19
20	20	20		20	20				20
21	21-22-24							-24	
22	22-23	22							
23	23								23
24	24-25		24			24	24		
25	25-26	-22						-26	
26	26-27		26			26	26		
27	27								27
28	28		28			28	28		28
29	29-30	29	29			29	29		
30	30	30		30	30				30
31	31								31
32	32-33-35		32			32	32	-33-35	
33	33-34		33			33	33		
34	34	34							34
35	35-36-38		35			35	35	-36-38	35
36	36-37		36			36	36		
37	37	37		37	37				37
38	38-31-39		38			38	38		38
39	39-40-44							-40-44	39
40	40-41		40			40	40		
41	41-42	41		41					
42	42-43	42		42	42				
43	43	43		43	43				43
44	44-45		44			44	44	-45	44
45	45-46		45			45	45		45
46	46-47-48								
47	47								47
48	48								48
49	49		49			49	49		49

where f_a is the net benefit of agriculture due to irrigation and f_p is the net benefit of energy production.

2.2 *The constraints*

The constraints of the coordinating model are formulated according to system identification in table 1 and the schematic layout in figure 2. There are six major types of constraints, (i) hydrological constraints, (ii) agricultural constraints, (iii) capacity constraints, (iv) municipal water supply, (v) economic constraints, (vi) environmental constraints, and others. A complete description of the constraint set for each node is given in appendix A.

2.2a *Hydrological constraints* (i) Continuity constraints—a typical constraint of this kind will be

$$X_{ij} + Z_{ij} = H_{ij} + X_{i+1,j} + D_{i+1,j}. \tag{2}$$

The amount of water that flows away from node i (river flow X_{ij}, irrigation diversion Z_{ij}) equals the amount of water that flows towards node i (river flow $X_{i+1,j}$, groundwater return $D_{i+1,j}$ and hydrological input H_{ij}).

(ii) Groundwater returns—a certain fraction (ξ_j) of the unpumped groundwater is returned to the river at a downstream node,

$$D_{ij} = \xi_j \left[\theta_i AG_i - \sum_j T_{ij} \right]. \tag{3}$$

For example, at node i, the groundwater pumped in a year is $\Sigma_j T_{ij}$ and the amount of groundwater left is $\theta_i AG_i - \Sigma_j T_{ij}$, of which ξ_j portion is returned to the river at a downstream node during the jth period.

2.2b *Agricultural constraints* (i) Field irrigation requirements for each crop are provided by surface water and groundwater irrigation,

$$T_{ij} + Z_{ij} = \alpha_{ij} A_{ij}. \tag{4}$$

It is assumed for simplicity that the irrigation water is lost to the river system. This water is either evapotranspirated or percolated into the aquifer.

(ii) Culturable land and current irrigation level: irrigation cannot exceed the culturable land at each district and it should reach at least the current irrigation level,

$$AL_i \leqslant A_{ij} \leqslant AH_i. \tag{5}$$

(iii) An artificial constraint is imposed in the model to make the summer season a land preparation season for the following kharif season (*i.e.*, irrigated acreage at any district during the summer season equals that of the kharif season):

$$A_{i2} = A_{i3}, \tag{6}$$

where A_{i1}, A_{i2}, A_{i3} are areas irrigated in rabi, summer and kharif seasons respectively.

2.2c *Capacity constraints* (i) Irrigation channel: new capacity for irrigation channels at each agricultural district is provided in order to divert more surface water for irrigation. The increased channel capacity at node i becomes $ZH_i + Z\text{NEW}_i$,

$$Z_{ij} \leqslant m_j \cdot (ZH_i + Z\text{NEW}_i), \tag{7}$$

where m_j is the number of months during the jth period.

(ii) Groundwater storage: annual groundwater irrigation at any agricultural district cannot exceed the available groundwater storage at that district,

$$\sum_j T_{ij} \leqslant \theta_i AG_i. \tag{8}$$

(iii) Diversion channel: the amount of water diverted cannot exceed the capacity of the channel,

$$Y_{ij} \leqslant m_j \cdot YH_i. \tag{9}$$

(iv) Reservoir live storage: The reservoir cannot store more water than its live storage capacity during any period of time,

$$V_{ij} \leqslant VH_i. \tag{10}$$

(v) Hydropower plant capacity: The water that drives the turbine cannot exceed the generating capacity. New turbines can be installed for necessary expansion of the power plant,

$$P_{ij} \leqslant m_j(PH_i + \mathrm{PNEW}_i). \tag{11}$$

2.2d *Municipal water supply* Water is diverted from the Ganga to meet the municipal water demand at Calcutta,

$$Y_{ij} \geqslant m_j \cdot YL_i. \tag{12}$$

2.2e *Economic constraint* Power demand distribution: the energy generated during each period must satisfy the distributional demand (η_j),

$$\sum_i (P_{ij} \cdot K_i) \geqslant \eta_j \sum_j \sum_i (P_{ij} \cdot K_i). \tag{13}$$

2.2f *Environmental and other constraints* In order to maintain river flows for navigation, water quality control, irrigation requirements downstream and other purposes, several minimum flows are provided,

$$X_{ij} \geqslant m_j \cdot XL_i. \tag{14}$$

3. Data used

Input data of the coordinating-screening model contains hydrological inputs (H_{ij}), field irrigation requirement given in appendix B (α_{ij}), culturable land (AH_i), low flow requirement (XL_i), groundwater availability ($\theta_i AG_i$), fractions of groundwater return (ξ_j), reservoir live storage (VH_i), hydropower plant capacity (PH_i), power conversion factor (K_i), and power demand distribution η_j).

3.1 *Hydrological input*

Since the model is deterministic, the hydrology of a typical single year is required. For flood protection and other purposes, a hydrology of extreme events which would have a chance of realization of one year out of every 50 or 100 years may be more appropriate. The hydrological inputs (H_{ij}) at various nodes are given in table 2. This table is constructed according to the estimated average monthly flows in the sub-basins of the Ganga by Briscoe (1974).

Table 2. Hydrological inputs (m cu m/season)

Node no	Rabi	Summer	Kharif
1	80561	43891	346812
5		680	12925
7		773	14694
8		1814	34474
9		421	7995
11		636	12092
35		188	3580
38		188	3580
39		188	3580
44		471	8949
45		471	8949
14	3823	3330	22806
15	6501	8030	37461
16	1052	350	14838
18	8338	7229	53410
19	259	57	931
20	688	229	9697
23	5551	4785	32928
27	5551	4785	32928
28	370	123	5217
30	764	654	4489
31	575	194	8236
34	575	194	8236
37	575	194	8236
43	2506	777	32984
47	936	809	5569
48	936	809	5569
49	259	57	931

Total:

(1) Include Brahmaputra (node)

Rabi	Summer	Kharif
119620	182327	742096

1044043 m cu m/year.

(2) Exclude Brahamaputra (node)

Rabi	Summer	Kharif
39059	38436	395284

472779 m cu m/year.

3.2 *Field irrigation requirements*

Monthly field irrigation requirements (α_{ij}) are estimated as per crop, rainfall, temperature, wind, humidity, sunshine, solar radiation and other factors at each agricultural district. These monthly requirements are then aggregated into three seasons for the simplified three-season model: (a) rabi season (November, December, January, February and March); (b) summer season (April, May and June); and (c) kharif season (July, August, September and October). Field irrigation requirements for different seasons at various agricultural districts are presented in table 3.

Table 3. Field irrigation requirements at various districts (Seasonal)–(meter/unit area)

Node no	A_{max}	A_{min}	Rabi	Summer	Kharif
2	6600	660	0·5860	0·0510	0·3300
3	6600	660	0·6200	0·1310	0·3800
4	1900	190	0·6200	0·1310	0·3800
5	1900	190	0·6200	0·1310	0·3800
6	2600	260	0·6200	0·1310	0·3800
7	3000	300	0·6200	0·1310	0·3800
12	24000	2400	0·5490	0·2730	0·5720
13	20000	2000	0·5210	0·2150	0·5340
15	19000	1900	0·6200	0·1310	0·3800
16	19000	1900	0·6200	0·1310	0·3800
17	33000	3300	0·6340	0·1430	0·3700
19	26100	2610	0·6610	0·1390	0·3950
24	40000	4000	0·6140	0·1990	0·5020
26	36800	3680	0·6140	0·1990	0·5020
28	19000	1900	0·6490	0·1400	0·3750
29	20800	2080	0·4920	0·2250	0·4820
32	20000	2000	0·6220	0·1960	0·5140
33	3100	310	0·6450	0·1610	0·4560
35	20000	2000	0·6220	0·1960	0·5140
36	4700	470	0·6450	0·1610	0·4560
38	20000	2000	0·6220	0·1960	0·5140
40	100000	5000	0·6360	0·2280	0·7240
44	50000	2000	0·5320	0·2690	1·039
45	50000	2000	0·5100	0·2440	0·7800
49	26100	2610	0·6610	0·1390	0·3950

Total A_{max} = 57·42 m ha
A_{min} = 4·64 m ha

3.3 *Culturable land and current irrigation level*

Information about culturable land at each agriculture district is reported by the Irrigation Commission (1972). Table 3 also gives the culturable land districtwise. The current irrigation level has been assumed at 10 % of the culturable land in most districts.

3.4 *Current irrigation capacity*

Table 4 lists some capacities of irrigation channels as recorded in the Irrigation Commission (1972). New capacity ($Z\text{NEW}_i$) is constructed in the coordinating model to allow more surface water diversion for irrigation.

3.5 *Groundwater storage*

Groundwater storage at an agriculture district is the product of annual groundwater availability (θ_i) and area (AG_i) over which groundwater is available. Aquifer is assumed to be fully recharged annually. These groundwater storages are given in table 5

3.6 *Reservoir live storage, hydro-power plant capacity, and power conversion factor*

Figures of reservoir live storages, current power plant capacities, and power conversion factors are presented in table 6. Although preliminary study indicates that there is a

Table 4. Current channel capacities

Node no	m cu m/mon	Node no	m cu m/mon
2–7	—	29	5·7
12	155·7	32	—
13	297·5	33	56·6
15	283·2	35	—
16	311·5	36	85·0
17	283·2	38	—
19	28·3	40	260·5
24	283·2	44	90·6
26	396·4	45	424·8
28	28·3	49	28·3

Table 5. Groundwater availability

Node no	m cu m	Node no	m cu m	Node no	m cu m
2, 3	2255	15	6462	32, 35, 38	2987
4, 5	677	16	4454	33	579
6	902	17	11659	36	877
7	621	19	11277	40	23816
12	7467	24	8960	44, 45	2987
13	2987	26	4480	49	10600
		28	2838		
		29	3734		

Total groundwater capacity: 122512 m cu m.

Table 6. Power conversion factors, power plant capacities and reservoir live storages.

Node no.	$K = \dfrac{\text{MW}}{\text{m cu m/month}}$	PH (MW)	VH (m cum)
20	0·1816	195	10608
30	0·2270	130	2220
37	0·0454	13	780
41	0·0272	64	
42	0·0908	111	1567
43	0·1090	75	6920

reservoir and a power plant at node 34 (KEN), they are removed from the model because they are not reported in the Irrigation Commission (1972). Appropriate new power plant capacity ($P\text{NEW}_i$) may be installed in order to attain higher energy production. Power production factor (K_i) is calculated by using a head of one half dam height.

3.7 *Power demand distribution*

Distributional constraints may be imposed on the energy production so that the energy output meets the monthly or seasonal demand (η_j). Initial values of the demand distribution are taken at 0.0955, 0.0797, 0.0762, 0.0515, 0.0630, 0.0784, 0.0797, 0.0797, 0.0938, 0.1233, 0.1039, and 0.0753 for the respective twelve months. These distributions should be reevaluated according to the power requirements for groundwater pumping and other irrigation facilities.

3.8 *Other water demands*

Water uses such as water quality control, navigation, and other purposes are not well developed. These water uses are considered in the model as minimum river flows and are presented in table 7.

4. Matrix Generation

The coordinating-screening model described above is a form of linear program and can be solved by IBM/MPSX. The matrix preparation for this IBM/MPSX used in Italy on the Tiber River Basin by Rogers & Chi (1973) is employed to generate the matrix of the Ganga Basin in the MPSX input format. The Ganga Basin linear program for a simplified three-season model consists of 490 constraint rows of which most are continuity equations, about 1050 decision variables and 3500 non-zero matrix elements.

5. Solutions

In this simplified three-season model solutions using various assumptions have been obtained. In each solution the summer season (June irrigation) is assumed to be land preparation and the model is constrained so that the area under irrigation during the summer season at each district must also be irrigated in the kharif season. In most solutions energy is maximized subject to different constraint sets.

5.1 *Solution* 1

Maximizing energy under current power plant capacity,

$$\max Z = f_P \cdot \sum_j \sum_i (P_{ij} \cdot K_i). \tag{15}$$

In this solution, energy production is unrestricted by the distributional constraints. The maximum energy under the current generating capacity is 55,863 GWh

Table 7. Low flow requirements.

Node no.	XL (m cu m/month)
2	100
5	50
7	240
9	285
10	255
44	38
45	180

(19,876 GWh in rabi season, 15,427 GWh in summer season, and 20,560 GWh for kharif season; which are 35 %, 28 % and 37 % respectively). Compared with the installed capacity (95,093 GWh/year),* hydropower facilities are about 60 % (55·863/95·093) utilized.

The energy output of the system is limited by water availability at power plant nodes 20 and 30 (Ramganga). On the other hand, the installed turbine capacities and reservoir storage capacities have restricted the energy production at power plant nodes 37 (Betwa), 41, 42 and 42 (Chambal) where large quantity of water is bypassed from reservoirs through diversion channels.

5.2 *Solution* 2

Maximizing energy with new power plant capacities,

$$\max Z = f_P \cdot \sum_j \sum_i (P_{ij} \cdot K_i). \tag{16}$$

If new turbines are installed when necessary, the energy production reaches 103, 932 GWh ignoring the distributional constraints**. All hydrological inflow upstream of power plants are utilized for energy.

New capacity is not needed at nodes 20 (Rihand) and 30 (Ramganga) since they are restricted by the availability of hydrological inputs. The system requires new turbines at nodes 37 (Betwa), 41, 42 and 43 (Chambal). These additional capacities*** are 72 MW at node 37, 103 MW at node 41, 445 MW at node 42 and 635 MW at node 43. When new turbines are installed, the energy production will only be limited by the hydrological inputs. However, excessive new capacities are required at these power plants (nodes 37, 41, 42 and 43) due to the extremely high kharif season inflows, which the reservoirs cannot regulate.

The annual irrigated acreage under this scheme reaches 56·8 m ha (17.2 m ha in rabi season and 39.6 m ha in the kharif season). This irrigation level is also the maximum area that can be fully irrigated under the current constraints.

5.3 *Solution* 3

Maximizing energy subject to various levels of irrigation, while energy output also meets the distributional constraints,

$$\max Z = f_p \cdot \sum_j \sum_i (P_{ij} \cdot K_i). \tag{17}$$

Since energy and irrigation are the major water uses in the model, it is useful to understand how these two interact with each other. For this purpose, energy is maximized according to demand distribution subject to different levels of irrigation usage.

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* This is the installed hydropower capacity at 65 % load factor.

** If energy production must satisfy demand distribution, then the energy output will only reach 74,172 GWh even when new turbines are installed.

*** The new installed turbines have capacities at 110, 158, 685 and 977 MW for power plants at nodes 37, 41, 42 and 43 respectively at a 65 % load factor.

To facilitate the solution, the power distributional constraints are formulated in the following form:

$$\sum_i (P_{ij} K_i) \geq \eta_j \cdot \sum_j \sum_i (P_{ij} K_i), \tag{18}$$

where distribution values of η_j are subject to adjustment to simulate real demands.

With an irrigation level lower than 55 m ha (15.9 m ha in the rabi season, 39·1 m ha in the kharif season) the energy output reaches a maximum level at 54,254 GWh (23,362 GWh in rabi, 10,465 GWh in summer and 20,427 GWh in kharif.) On the other hand, when energy production is less than 36,461 GWh (15,700 GWh in rabi, 7,033 GWh in summer and 13,728 GWh in kharif), the irrigation level is maximized at 56.8 m ha (17.2 m ha in rabi and 39.6 m ha in kharif). It is not possible to generate energy higher than 54,254 GWh by sacrificing irrigation and it is not feasible to insist on an irrigation level higher than 56.8 m ha by giving up energy production. For any level of irrigation between these two extremes (55 and 56.8 m ha), there is a corresponding energy production (between 36,461 and 54,254 GWh). No further parametric study on energy and irrigation in these ranges is made since the difference between the two irrigation levels is relatively small. Solutions of these two extremes are shown in figure 3.

Any point inside the boundary *ABCD* is feasible but not efficient. Furthermore, points between *A* and *B* are not efficient because the irrigation level can be increased from zero to 55 m ha without any loss of energy. Similarly, points between *C* and *D* are not efficient. Points that fall on the line *BC* denote the production frontier. Point *C* represents operating the system for agricultural maximization and treating energy as a residual. The marginal rate of transformation of energy for agriculture at any point on the line *BC* is the gradient of the line segment *BC*. This rate is estimated at

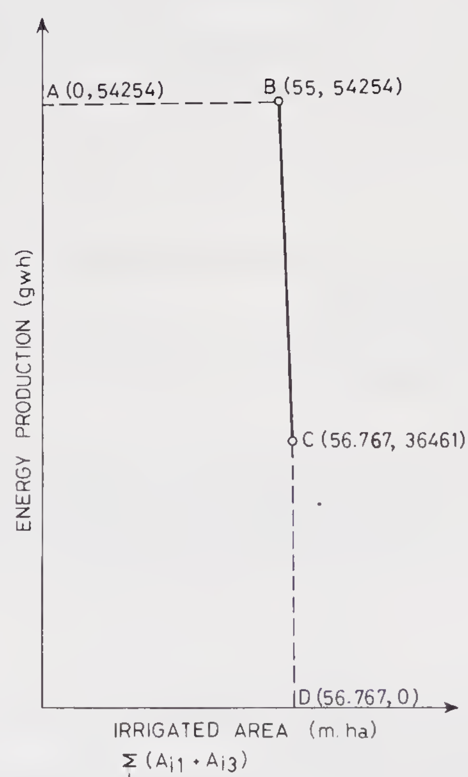

Figure 3. Trade-off between energy and total irrigation

$-10{,}070$ GWh/m ha (*i.e.*, to gain 1 m ha of irrigation between points *B* and *C* 10,070 GWh energy is sacrificed).

The range of irrigated acreage is only 1.8 m ha (56.8 − 55) while energy production has a relatively wide range (from 36,461 to 54,254 GWh) of variation. No substantial irrigation can be gained by giving up energy production (at a rate of 10,070 GWh for only 1 m ha).

Irrigated acreage is at capacity level at most downstream districts where water is available through accumulation of inflows. Reservoirs are full in the kharif season to regulate the excessive monsoon water for irrigation in the following rabi season.

5.4 *Solution* 4

Trade-off between rabi irrigation and kharif irrigation,

$$\max Z = \sum_i A_{i3}, \text{ subject to various levels of } \sum_i A_{i1}. \tag{19}$$

Since the reservoirs and groundwater storage can regulate the water for irrigation from one season to the next, there is a definite trade-off between rabi irrigation and kharif irrigation. Solutions (points *B*, *C*, *D*, *E*, *F*, *G* and *H*) shown in figure 4 illustrate the

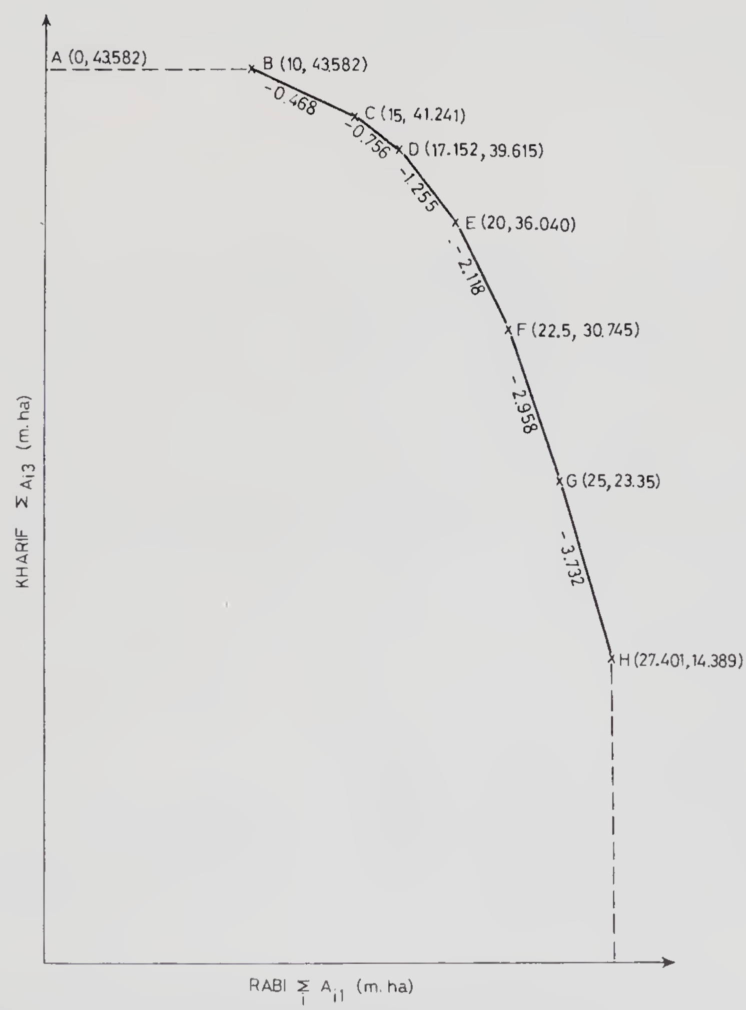

Figure 4. Trade-off between kharif and rabi irrigations

corresponding irrigation level in the kharif season for each irrigation level in the rabi season. It is not feasible to irrigate in the rabi season at a level higher than 27.4 m ha. The maximum level of irrigation in kharif can be achieved at a higher level (43.6 m ha). Point D (at which rabi irrigation is 17.2 m ha and kharif irrigation is 39.6 m ha) represents operating the system for maximum annual total irrigation. Steeper gradients (-2.96, -3.73) at points E, G in figure 4 indicate that 2.96 and 3.73 units of irrigation acreage in kharif season would be given up for every unit increment of irrigation in the rabi season. This is because the June irrigation (summer season) binds the irrigation level of the kharif season ($A_{i2} = A_{i3}$); therefore, a large quantity of river flow in the kharif season is wasted.

5.5 *Solution* 5

Maximizing energy subject to different levels of rabi and kharif irrigations,

$$\max Z = f_P \cdot \sum_j \sum_i (P_{ij} K_i), \tag{20}$$

this solution is obtained assuming that no new power capacity is provided and energy production must satisfy the demand distributional constraints. For every rabi irrigation level (according to §5.4) the energy is maximized while increasing kharif irrigation level until infeasibility. To obtain solutions among rabi irrigation, kharif irrigation and the corresponding energy production, the parametric procedure of linear programming is adopted.

6. Results

Solutions (rabi irrigation, kharif irrigation and energy production) are presented in table 8 and figure 5. The convex plane $DGHIJKLN'E$ represents the operating production frontier. Any point that falls on or inside the feasible region but not on this plane ($DGHIJKLN'E$)* is not efficient and is dominated by that plane. Point I in figure 5 represents operating the system for agricultural maximization and treating energy production as a residual. Points that fall on the line DE represent operating the system for energy maximization. The rates of marginal transformation are calculated between energy and kharif irrigation for each given rabi irrigation as shown in figure 6.

The range of variation for energy production as defined in figure 6 is 17,793 GWh (54,254 − 36,461 GWh) and irrigation acreage has a variation of 15.3 m ha (56.8 − 41.5 GWh). The range of these variations is relatively narrow and no substantial amount of energy will be sacrificed for further agricultural development and vice versa. Basrur (1975) discussed the difficulties of identifying a trade-off between energy and irrigation under the system described in this paper.

At some agricultural districts, June irrigation has bound the following kharif irrigation because less water is available during the summer season.

Reservoirs are used to store the excessive monsoon water to their storage capacities for the irrigation of the following rabi season.

* Point N' in figure 5 is a linear extrapolation point on the line EN to prevent the production frontier from going to points M and N where the rates of marginal transformation are negligible.

Table 8. Solutions of maximizing energy subject to different levels of A_1 and A_3.

Point in figure 5	A_1 m ha	A_3 m ha	$A_1 + A_3$ m ha	Energy GWh
	7·5	18·12	25·62	54254
		40·0	47·5	54254
		43·58	51·08	45443
	10	15·61	25·61	54254
		40·0	50·0	54254
G		43·58	53·58	45443
	15	11·49	26·49	54254
D		40·0	55·0	54254
H		41·24	56·24	36576
	17·15	9·89	27·04	54254
		35·0	52·152	54254
I		39·61	56·76	36461
	20	7·8	27·8	54254
		30·0	50·0	54254
P		35·0	55·0	50190
J		36·04	56·04	36461
	22·5	6·92	29·42	54254
		25·0	47·5	54254
Q		30·0	52·5	43592
K		30·74	53·24	36461
	25	6·20	31·20	54254
E		20·0	45·0	54254
L		23·35	48·35	36461
N	26·09	15·44	41·53	36461
	27·40	6·27	33·67	15200
H		10·0	37·40	15200
K		14·38	41·78	15152

Power plant capacity and reservoir storage capacity have severely limited the energy production at power plant nodes 37 (Betwa), 41, 42 and 43 (Chambal). At power plant nodes 20 (Rihand) and 30 (Ramganga) the annual hydrological inflows have restricted the energy production.

6.1 *Irrigation level*

(a) The maximum total irrigated acreage (rabi and kharif combined) occurs at point *I* as shown in figure 5. This irrigation level is 56·8 m ha (17.2 m ha in rabi, and 39·6 m ha in kharif) and its corresponding energy output is 36,461 GWh. Breakdown of annual irrigation level (rabi and kharif, surface water irrigation and groundwater irrigation by states inside India) are presented in tables 9, 10 and 11.

At point *I* in figure 5, surface water irrigation is 257.2 billion m^3 annually (38.3, 29.8 and 189.1 for rabi, summer and kharif), groundwater irrigation is 122.5 billion m^3 (65.1, 43.6 and 13.7 for the respective seasons). Groundwater irrigation in the kharif season is only 11% of total annual groundwater irrigation while surface water

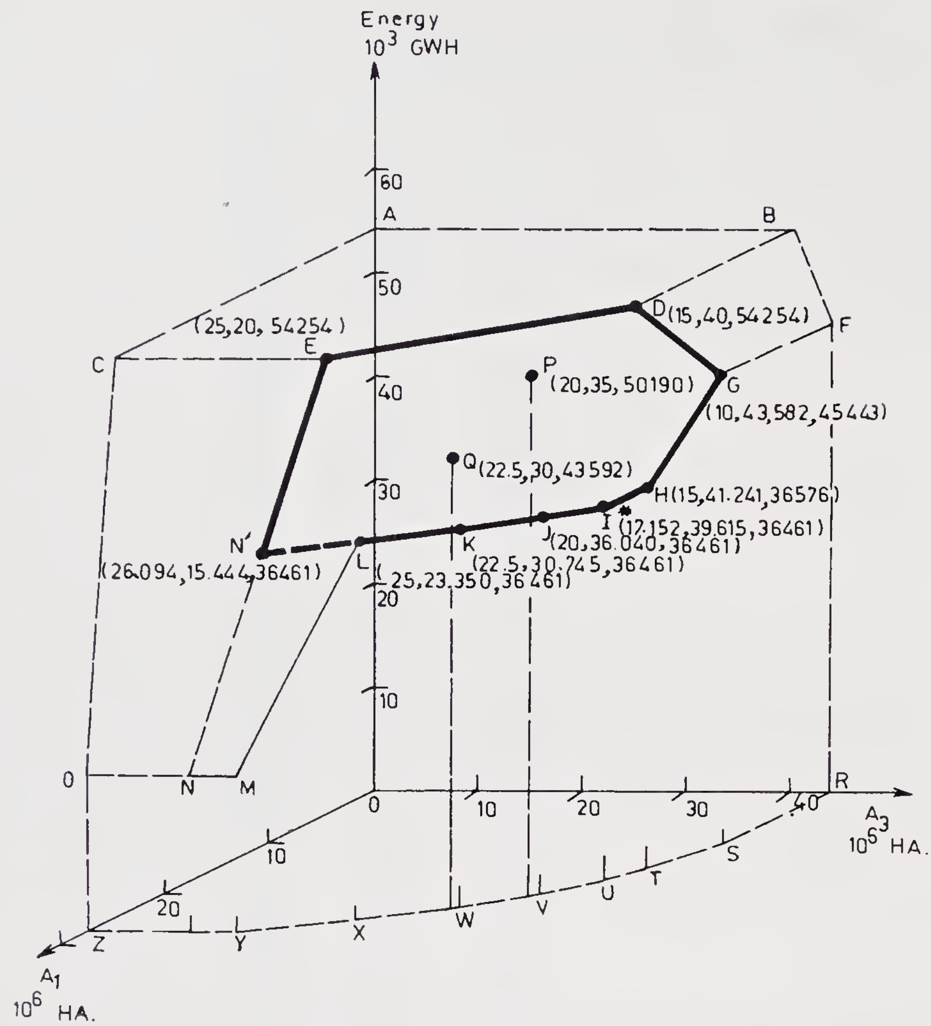

Figure 5. Trade-off among energy, kharif irrigation and rabi irrigation. At point *I*, $A_1 = 17{\cdot}152$, $A_3 = 39{\cdot}615$ and energy = 36,461, where $A_1 + A_3 = 56{,}167$ is the maximum irrigated acreage that can be achieved

irrigation is nearly 74% of the total surface water irrigation. This is because of the monsoon water availability in the kharif season. Surface water and groundwater irrigation relationship is presented in table 12.

(b) Maximum energy production that satisfies the distributional constraints occurs on the line *DE* as shown in figure 5. This energy output is 54,254 GWh and the corresponding irrigation levels are between 45 m ha and 55 m ha.

6.2 *Cropping intensity*

The Irrigation Commission (1972) reported that the agricultural level in the Ganges Basin had a net sown area of 43.824 m ha, a gross sown area of 54.757 m ha, a net irrigated area of 10.817 m ha and a gross irrigated area of 12.544 m ha. Thus, the cropping intensity in 1972 was 125% and the irrigation intensity was 23%.

The cropping and irrigation intensities in the future according to the above solutions are as follows* (a) The cropping intensity is improved to 148% when rabi irrigation is

* In order to calculate these intensities, it is assumed that all culturable land is cultivated in the kharif season with or without irrigation and only the area that is irrigated in the rabi season is cultivated in that season.

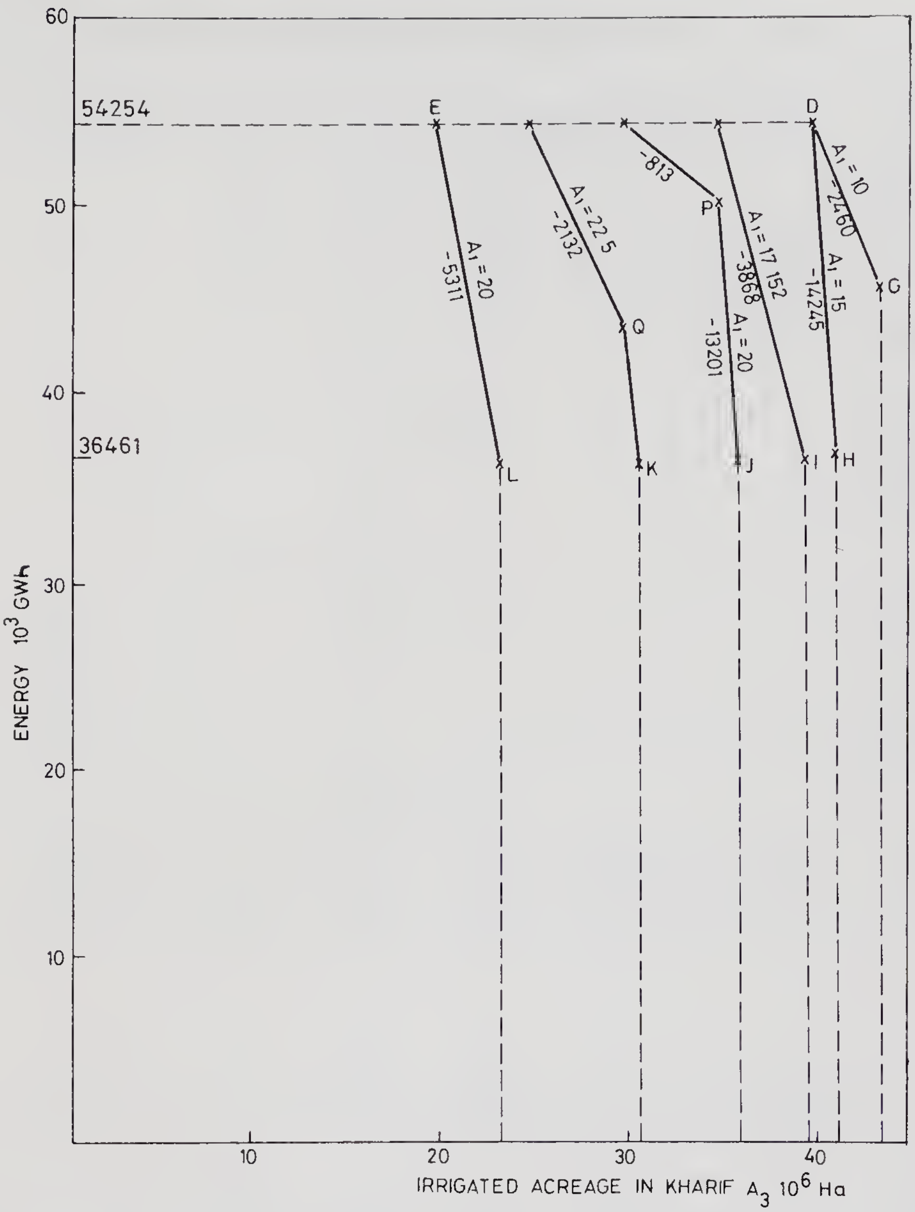

Figure 6. Trade-off among energy, kharif irrigation and rabi irrigation

maximized (point *M* in figure 5). (b) The cropping intensity is 130% when the total irrigation is maximized (point *I* in figure 5).

All the interesting cropping intensities and irrigation intensities from the solutions obtained in this paper can be found in table 13.

6.3 *Degree of complementarity*

It is possible to assess the degree of complementarity of the three-season model by assuming net benefits of energy and irrigation. When these net benefits are absent, ranges of degree of complementarity are obtained.

When the system is operated as a single-purpose one for energy the annual energy production is 54,254 GWh; and when the system is operated for agriculture maximization, the annual irrigation level is 56·8 m ha. Therefore, if the full potential of the

Table 9. Breakdown of irrigation level between states and seasons

Sub-basin		H.P.	Haryana	Delhi	Rajasthan	U.P.	M.P.	Bihar	W.B.	Total by basin
Chambal	A_1				1·428	0·017	1·087			2·532
	A_3				1·908	0·022	1·453			3·383
Yamuna		0·018	0·296	0·010	0·243	0·558	0·526			1·651
		0·106	1·780	0·061	1·463	3·359	3·163			9·932
Ramganga						1·283				1·283
						0·471				0·471
Tons &						0·071	0·081	0·038		0·190
others						0·529	0·607	0·284		1·420
Gomati &						2·260		0·078		2·338
Ghaghara						6·777		0·233		7·010
Son						0·115	0·918	0·417		1·450
						0·296	2·279	1·035		3·600
Gandak &						0·083		3·471	0·696	4·250
others						0·083		3·471	0·696	4·250
Right bank								1·195	0·837	2·032
tributaries								3·191	2·237	5·428
Main Ganga						1·427				1·427
						4·120				4·120
Total by		0·018	0·296	0·010	1·671	5·814	2·612	5·199	1·533	17·153
State		0·106	1·780	0·061	3·'71	15·647	7·502	8·214	2·933	39·614

Table 10. Annual surface irrigation (10^9 m^3/year)

Sub-basin	H.P.	Haryana	Delhi	Rajasthan	U.P.	M.P.	Bihar	W.B.	Total by basin
Chambal				13·814	0·162	10·521			24·497
Yamuna	0·823	13·781	0·469	11·328	26·008	24·493			76·902
Ramganga					5·907				5·907
Tons and others					2·128	2·441	1·141		5·710
Gomati and Ghaghara					48·393		1·667		50·060
Son					1·219	9·707	4·406		15·332
Gandak and others					0·697	29·049	5·827		35·573
Right bank tributaries							7·821	5·482	13·303
Main Ganga					29·959				29·959
Total by State	0·823	13·781	0·469	25·142	114·473	76·211	20·862	5·482	257·243

Table 11. Annual groundwater irrigation (10^9 m^3/year)

Sub-basin	H.P.	Haryana	Delhi	Rajasthan	U.P.	M.P.	Bihar	W.B.	Total by basin
Chambal				13·430	0·157	10·229			23·816
Yamuna	0·175	2·937	0·100	2·414	5·543	5·221			16·390
Ramganga					3·734				3·734
Tons & others					1·058	1·213	0·567		2·838
Gomati & Ghaghara					12·992		0·448		13·440
Son					0·976	7·774	3·529		12·280
Gandak & others					0·245		10·203	2·047	12·495
Right bank tributaries							15·911	11·153	27·064
Main Ganga					10·454				10·454
Total by State	0·175	2·937	0·100	15·844	35·159	24·437	30·658	13·200	122·510

Table 12. Water utilisation of various solutions

Point	Surface water 10^9 m^3	% by season	Ground-water 10^9 m^3	% by season	Water total 10^9 m^3	Irrigated acreage m ha	Energy GWh
I							
rabi	38·6	15·0	64·9	53·0	103·5	17·2	15·70
summer	29·5	11·5	43·9	35·8	73·4	—	7·03
kharif	189·1	73·5	13·7	11·2	202·8	39·6	13·73
total	257·2	100·0	122·5	100·0	379·6	56·8	36·46
D							
rabi	37·5	24·0	114·5	95·3	152·0	25·0	23·36
summer	28·0	17·9	5·4	4·5	33·4	—	10·47
kharif	90·8	58·1	0·2	0·2	91·0	20·0	20·43
total	156·3	100·0	120·1	100·0	276·4	45·0	54·26
E							
rabi	42·7	16·1	48·4	45·1	91·0	15·0	23·36
summer	33·1	12·5	41·2	38·4	74·3	—	10·47
kharif	188·9	71·4	17·7	16·5	206·6	40·0	20·43
total	264·7	100·0	107·3	100·0	371·9	55·0	54·26
N							
rabi	45·3	42·4	121·1	98·8	166·4	27·4	6·55
summer	15·3	14·3	1·2	1·0	16·5	—	2·93
kharif	46·4	43·3	0·2	0·2	46·6	6·3	5·72
total	107·0	100·0	122·5	100·0	229·5	33·7	15·20
N′							
rabi	44·0	23·7	84·7	73·8	128·7	26·1	15·70
summer	24·2	13·0	21·2	18·6	45·4	—	7·03
kharif	117·6	63·3	9·0	7·6	126·6	15·4	13·73
total	185·8	100·0	114·9	100·0	300·7	41·5	36·46

Table 13. Cropping intensities and irrigation intensities in future development

Point	A_1 m ha	A_3 m ha	Gross irrigated area A_1+A_3 m ha	Gross sown area $A_1+57{\cdot}4$*	Cropping intensity	Irrigation intensity
E	25	20	45	82·4	144	55
D	15	40	55	72·4	126	76
G	10	43·6	53·6	67·4	117	80
H	15·4	41·2	56·6	72·8	127	78
I	17·2	39·6	56·8	74·6	130	76
J	20	36	56	77·4	135	72
K	22·5	30·7	53·2	79·9	139	67
L	25	23·4	48·4	82·4	144	59
M	27·4	14·4	41·8	84·8	148	49
N′	26·1	15·4	41·5	83·5	145	50
P	20	35	55	77·4	135	71
Q	22·5	30	52·5	79·9	139	66

* Assuming all the culturable land is sown during kharif season in future development.

Ganges basin for both energy and agriculture is realized the total benefit would reach f_a $56{\cdot}8 + f_p \cdot 54254$. The degree of complementarity of any solution is:

$$\frac{f_a \sum_i (A_{i1} + A_{i3}) + f_p \sum_j \sum_i (P_{ij} K_i)}{f_a \cdot 56{\cdot}8 + f_p \cdot 54254}, \tag{21}$$

and the values for various solutions are given in table 14.

7. Summary

A summary of solutions obtained in this study is presented in table 15. This table lists the objective function, constraint, objective value and remarks for each solution. In each solution, the same hydrological data as shown in tables 2 to 6 are used. This table also indicates the maximum energy production, maximum rabi irrigation and maximum kharif irrigation that can be achieved.

Several solutions are compared with the 1972 agriculture status in table 16.

(i) If the objective is to maximize total irrigation (rabi and kharif) the solution is

Table 14. Degree of complementarity for solutions

Point	A_1 (n ha)	A_3 (m ha)	Energy GWH	Range of degree of complementarity
I	17·2	39·6	36461	0·67–0·99
D	15	40	54254	0·97–0·99
E	25	20	54254	0·79–0·99
Points on DE	15–25	20–40	54254	0·79–0·99
P	20	35	50190	0·93–0·97
Q	22·5	30	43592	0·80–0·92
H	15	41·241	36576	0·69–0·99

Table 15. Summary of solutions

Objective function	Constraints	Objective value	Remarks
1. Maximizing energy $\sum_j \sum_i (P_{ij}; K_i)$	1. Basic constraints (hydrological inputs. . . .)	55,863 GWh	
	2. Minimum water supply, navigation etc.		B
	3. Minimum flow at Farakka		NB
	4. No new power capacity		B
	5. No power distributional constraint.		
2. Maximizing energy $\sum_j \sum_i (P_{ij}. K_i)$	1. Basic constraints	103,932 GWh	
	2. Minimum water supply, navigation etc.		NB
	3. Minimum flow at Farakka		NB
	4. New power capacity		
	5. No power distribution.		
3. Maximizing energy $\sum_j \sum_i (P_{ij}. K_i)$	1. Basic constraints	from	
	2. Minimum water supply, navigation, etc.	36,461 to 54,254 GWh	B
	3. Minimum flow at Farakka		B in rabi season
	4. No new power capacity		B
	5. Power distribution		B
	6. Various levels of irrigation (41·8 to 56·8 m ha)		B
4. Maximizing kharif irrigation $\sum_i A_{i3}$	1. Basic constraints	from	
	2. Minimum water supply, navigation, etc.	14·4 to 43·6 m ha	B
	3. Minimum flow at Farakka		B in rabi season
	4. Various levels of rabi irrigation (10 to 27·4 m ha)		B

Table 16. Present (1972) Irrigation and future irrigation (m ha)

	(1)	(2)	(3)	(4)	(5)	(6)
Rabi			57·42	17·15	40·27	57·42
Summer			57·42	39·62	17·80	57·42
Kharif			57·42	39·62	17·80	57·42
Total*	12·54	102·30	114·84	56·77	58·07	114·84

* Total equals rabi plus kharif. (1) Present (1972) gross irrigated area; (2) Present (1972) gross non-irrigated area; (3) Total = (1) + (2); (4) Future area under irrigation; (5) Future area not under irrigation; (6) Total = (4) + (5)

point I in figure 5. The total irrigation level is 56.8 m ha which is an improvement of 44·2 m ha over the 1972 gross irrigation level (12.5 m ha) or 2.5 times better.

(ii) If the objective is to maximize rabi irrigation, then point M in figure 5 dominates the other solutions. The total irrigation level is 41.8 m ha (27·4 in rabi, 14·4 in kharif) which is a 29.3 m ha improvement over 1972 level.

(iii) In order to avoid substantial energy sacrifice when rabi irrigation is maximized, a compromise solution point N' in figure 5 is obtained. The total irrigation level is 41·5 m ha (26·1 in rabi, 15·4 in kharif). This is a 29 m ha improvement over the 1972 level. In this case, the reduction of rabi irrigation is only 1.3 m ha from that of case (ii) while the energy output is increased from 15,200 GWh to 36,461 GWh.

Since this model of the Ganga basin considers only the benefit to the Indian states it is necessary to understand the water availability when the Ganga enters Bangladesh downstream; River flows at Farakka (which enter Bangladesh) are given in table 17. Values shown in this table are under the maximum irrigation level (56·8 m ha) in Indian states. Table 18 summarizes the results for each of the 9 sub-basins and compares them with the Irrigation Commission (1972) estimates for resource use in 1968–69.

8. Conclusion

The objective of this model is to maximize the net benefit of energy and irrigation:

$$f_a \cdot \sum_i (A_{i1} + A_{i3}) + f_p \cdot \sum_j \sum_i (P_{ij} K_i).$$

This objective function has been replaced by a single-purpose objective (either agriculture or energy) in every solution. It either maximizes energy subject to various irrigation levels or vice versa. However, if the net benefits of energy and irrigation are estimated and the objective function

$$f_a \sum_i (A_{i1} + A_{i3}) + f_P \sum_j \sum_i (P_{ij} K_i)$$

is adopted, the solution should fall upon the plane $DGHIJKLN'E$ as shown in figure 5. Solutions obtained by a comprehensive parametric study on values f_a and f_p will cover points on the same plane $DGHIJKLN'E$ in figure 5.

The model presented in this paper aims to achieve ultimate development for Indian states within the Ganga basin. It is equally important to provide necessary water downstream of the Ganga for optimal development in Bangladesh. This is expressed in the model in the form of minimum irrigation requirements in Bangladesh (XL_2). It is found that the rabi season river flow at Farakka is critical. River flow in this season

Table 17. River flows at Farakka, in Bangladesh, and diversion to Calcutta (million cubic metres)

	River flows at Farakka	Water available after Brahmaputra joins Ganga	Diversion to Calcutta
Rabi	500	81,061	14,680
Summer	6,580	150,471	8,808
Kharif	173,226	520,038	11,744
Total	180,306	751,570	11,744

Table 18. Ganga basin water use and irrigation

Basin	Average annual runoff (m cu m)	Surface water (m cu m)	Ground water (m cu m)	Irrigated areas (ha × 10^6)	
I	24,312	24,497	23,816	K 3·383	(0·886)
		(8,305)	(5,562)	R 2·532	
II	65,621	76,902	16,390	9·932	(3·054)
		(15,523)	(9,513)	1·651	
III	18,626	5,907	3,734	0·471	(0·382)
		(7,144)	(1,446)	1·283	
IV	14,123	5,710	2,838	1·420	(0·394)
		(3,819)	(1,126)	0·190	
V	122,793	50,060	13,440	7·101	(2·143)
		(21,280)	(13,186)	2·338	
VI	42,308	15,332	12,280	3·600	(0·336)
		(10,335)	(838)	1·450	
VII	134,277	35,573	12,495	4·250	(0·374)
		(26,006)	(1,068)	4·250	
VIII	45,145	13,303	27,064	5·428	(1·872)
		(28,366)	(1,552)	2·032	
IX	42,533	29,959	10,454	4·120	(1·914)
		(11,643)	(6,604)	1·427	
Total	509,738	257,243	122,510	39·614	(11·36)
		(132,421)	(40,895)	17·153	

Figures in parentheses represent Irrigation Commission estimates of 1968–69 resource use.

(X_{21}) is binding at the minimum level. It is important to study the relation between the minimum flow requirement at Farakka and the irrigation level in Indian states.

There are few trade-off points found between energy and irrigation in this three-season model. This is because under the assumed system no water is diverted for irrigation upstream of a hydropower plant. The same water that drives the turbine can be used to irrigate an agricultural district downstream as discussed by Basrur (1975). The model in its present form considers the Ganga basin within Indian states as a unit despite possible different local interests. If various targets are required by different states in the basin, then more trade-off points can be expected.

Finally, the power conversion factor is estimated according to one half of the dam height. The real energy production will be less than the solutions obtained in this paper. Although seasonal average height of water surface in the reservoir is more appropriate, it is not used in this present study.

It must be clarified as emphasized at the outset that the study brings out only an approach to analysis and the quantitative figures given above are meant only to illustrate the approach for the decomposition of the system and have no real-life implication. However, it must also be added that the systems approach is a powerful tool for planning and if the currently available data with the various governmental agencies were made available, significant improvements in real-life water resources development could be made. This model is only the starting point for a detailed study.

Appendix A: Mathematics of the Ganga basin model

The complete Ganga basin model is described in this appendix. In the following algebraic equations, j is an index for month or season ($j=1, \ldots, 12$ for a 12-month model and $j=1, \ldots, 3$ for a 3 season model); i is an index for node number ($i = 1, \ldots, 49$). I is a set that contains the nodes of 25 agricultural districts 2, 3, 4, 5, 6, 7, 12, 13, 15, 16, 17, 19, 24, 26, 28, 29, 32, 33, 35, 36, 38, 40, 44, 45 and 49.

The constraints

(i) *Hydrological constraints*

(a) *Continuity constrains*

(1) $X_{1j} = H_{1j} + X_{2j} + D_{2j},$
(2) $X_{2j} + Y_{2j} = X_{3j} + D_{3j} - Z_{2j},$
(3) $X_{3j} = X_{4j} + X_{19,j} + D_{4j} - Z_{3j},$
(4) $X_{4j} = X_{5j} + X_{15,j} + D_{15,j} + D_{5j} - Z_{4j},$
(5) $X_{5j} = X_{6j} + X_{49,j} + D_{6j} + D_{49,j} - Z_{5j} + H_{5j},$
(6) $X_{6j} = X_{7j} + X_{16,j} + D_{7j} + D_{16,j} - Z_{6j},$
(7) $X_{7j} = X_{8j} + X_{17,j} + D_{17,j} - Z_{7j} + H_{7j},$
(8) $X_{8j} = X_{9j} + X_{21,j} + H_{8j},$
(9) $X_{9j} = X_{10,j} + X_{28,j} + D_{28,j} + H_{9j},$
(10) $X_{10,j} = X_{11,j} + X_{32,j} + D_{32,j}$
(11) $X_{11,j} = X_{12,j} + X_{29,j} + D_{12,j} + D_{29,j} + H_{11,j},$
(12) $X_{12,j} = X_{13,j} + Y_{29,j} + D_{13,j} - Z_{12,j},$
(13) $X_{13,j} = X_{14,j} - Z_{13,j},$
(14) $X_{14,j} = H_{14,j},$
(15) $X_{15,j} = H_{15,j} - Z_{15,j},$
(16) $X_{16,j} = H_{16,j} - Z_{16,j},$
(17) $X_{17,j} = X_{18,j} - Z_{17,j},$
(18) $X_{18,j} = X_{20,j} + H_{18,j},$
(19) $X_{19,j} = H_{19,j} - Z_{19,j},$
(20) $X_{20,j} = P_{20,j} + Y_{20,j},$
$X_{20,j} = H_{20,j} - (V_{20,j} - V_{20,j+1}),$
(21) $X_{21,j} = X_{22,j} + X_{24,j} + D_{24,j},$
(22) $X_{22,j} + Y_{22,j} = X_{23,j},$
(23) $X_{23,j} = H_{23,j},$
(24) $X_{24,j} = X_{25,j} - Z_{24,j},$
(25) $X_{25,j} = X_{26,j} + Y_{22,j} + D_{26,j},$
(26) $X_{26,j} = X_{27,j} - Z_{26,j},$
(27) $X_{27,j} = H_{27,j},$
(28) $X_{28,j} = H_{28,j} - Z_{28,j},$
(29) $X_{29,j} + Y_{29,j} = X_{30,j} - Z_{29,j},$
(30) $X_{30,j} = P_{30,j} + Y_{30,j},$
$X_{30,j} = H_{30,j} - (V_{30,j} - V_{30,j-1}),$
(31) $X_{31,j} = H_{31,j},$

(32) $X_{32,j} = X_{35,j} + X_{33,j} + D_{33,j} + D_{35,j} - Z_{32,j}$,
(33) $X_{33,j} = X_{34,j} - Z_{33,j}$,
(34) $X_{34,j} = H_{34,j}$,
(35) $X_{35,j} = X_{36,j} + X_{38,j} + D_{36,j} + D_{38,j} + H_{35,j} - Z_{35,j}$,
(36) $X_{36,j} = X_{37,j} - Z_{36,j}$,
(37) $X_{37,j} = P_{37,j} + Y_{37,j}$,
$X_{37,j} = H_{37,j} - (V_{37,j} - V_{37,j-1})$,
(38) $X_{38,j} = X_{31,j} + X_{39,j} + H_{38,j} - Z_{38,j}$,
(39) $X_{39,j} = X_{40,j} + X_{44,j} + D_{40,j} + D_{44,j} + H_{39,j}$,
(40) $X_{40,j} = X_{41,j} - Z_{40,j}$,
(41) $X_{41,j} = P_{41,j} + Y_{41,j}$,
$X_{41,j} = X_{42,j}$,
(42) $X_{42,j} = P_{42,j} + Y_{42,j}$,
$X_{42,j} = X_{43,j} - (V_{42,j} - V_{42,j-1})$,
(43) $X_{43,j} = P_{43,j} + Y_{43,j}$,
$X_{43,j} = H_{43,j} - (V_{43,j} - V_{43,j-1})$,
(44) $X_{44,j} = X_{45,j} + D_{45,j} + H_{44,j} - Z_{44,j}$,
(45) $X_{45,j} = X_{46,j} + H_{46,j} - Z_{45,j}$,
(46) $X_{46,j} = X_{47,j} + X_{48,j}$,
(47) $X_{47,j} = H_{47,j}$,
(48) $X_{48,j} = H_{48,j}$,
(49) $X_{49,j} = H_{49,j} - Z_{49,j}$.

(b) *Groundwater returns*

$$D_{ij} = \xi_j \left[\theta_i AG_i - \sum_j T_{ij} \right] i \in I, \forall_j$$

(ii) *Agricultural constraints*

(a) Field irrigation requirements

$$T_{ij} + Z_{ij} = \alpha_{ij} A_{ij},\ i \in I,\ \forall_j$$

(b) Culturable land and current irrigation level

$$AL_i \leqslant A_{ij} \leqslant AH_i,\ i \in I,\ \forall_j$$

(c) Artificial constraints

$$A_{i2} = A_{i3},\ i \in I$$

(iii) *Capacity constraints*

(a) Irrigation channels

$$Z_{ij} \leqslant m_j(ZH_i + Z\text{NEW}_i),\ i \in I$$

(b) Groundwater storage

$$\sum_j T_{ij} \leqslant \theta_i AG_i,\ i \in I.$$

(c) Diversion channels

$$Y_{ij} \leqslant m_j Y H_i,\ i \in I, \forall_j.$$

(d) Reservoir live storages

$$V_{ij} \leqslant V H_i,\ \ i = 20, 30, 37, 42, 43, \forall_j$$

(e) Hydropower plant capacity

$$P_{ij} \leqslant m_j (PH_i + P\text{NEW}_i),\ \ i = 20, 30, 37, 41, 42, 43, \forall_j.$$

(iv) *Municipal water supply*

$$Y_{ij} \geqslant m_j Y L_i, i = 2, \forall_j.$$

Diversion to Calcutta for municipal water supply.

(v) *Economic constraints*

$$\sum_i (P_{ij} K_i) \geqslant \eta_i \sum_j \sum_i (P_{ij} K_i)$$
$$i = 20, 30, 37, 41, 42, 43, \forall_j$$

This is the power demand distributional constraint.

(vi) *Environmental and other constraints*

Minimum river flow

$$X_{ij} \geqslant m_j X L_i,\ i = 2, 5, 7, 10, 44, 45\ \forall_j$$

The objective function

The objective of this model is to maximize the net benefit

$$\max Z = f(f_a, A_{ij}, f_p, P_{ij}, K_i; f_a, f_P, K_i, i, j),$$
$$\text{or} = f_a \sum_i [A_{i1} + A_{i3}] + f_p \sum_j \sum_i [P_{ij} K_i].$$

Appendix B. Field irrigation requirements

In this appendix field irrigation requirements (α_{ij}) in the Ganga basin are examined. Only the Chambal sub-basin (node 40) is illustrated because the procedure for obtaining these requirements is similar. The monthly or seasonal field irrigation requirement is a function of (i) evaporation; (ii) cropping pattern; (iii) rainfall and (iv) soil type, conveyance, storage and operational losses.

Evoporation

Christiansen *et al* (1966) have developed an empirical formula for estimation of a class A pan evaporation:

$$E_p = 0{\cdot}459\ R C_t C_w C_h C_s C_e,$$

where E_p is class A pan evaporation, R is extraterrestrial radiation; C_t, C_w, C_h, C_s and C_e are coefficients of temperature, wind velocity, relative humidity, sunshine percentage and elevation. These coefficients for node 40 are presented in table B.1.

Cropping pattern

Evapotranspiration (consumptive use) of a crop is the product of evaporation (E_p) and the consumptive use coefficients (k) of each crop. Consumptive use coefficients of the kharif crop (mainly rice) and the rabi crop (mainly wheat) are taken from Ministry of Agriculture (1971) estimates.

The consumptive use coefficients of rice are 0·97, 1·21, 1·24 and 0·80 for the four months of the kharif season July to October respectively. The consumptive use coefficients of wheat are 0·26, 0·75, 0·90, 0·81 and 0·61 for the months November to March respectively. During the summer season the consumptive use coefficient of 0·8 is assigned to June irrigation for land preparation. There is no irrigation requirement in the months of April and May.

Rainfall

Net irigation requirements (NIR) are the differences of evapotranspiration and effective rainfall. Effective rainfall depends on the normal rainfall and the consumptive use. These effective rainfalls (R_e) in table B.1 are estimated from Ministry of Agriculture (1971) data.

Table B.1. Field irrigation requirements in Chambal sub-basin (node 40)

Month	R	T_c	C_T	E_p	E_t	Rainfall	R_e	NIR (mm)	FIR (mm)
Jan.	304	15	0·839	119	107	10·47	7·54	99	132
Feb.	321	19	0·965	145	117	7·46	5·50	111	148
Mar.	422	24	1·135	224	137	5·83	4·60	132	176
Apr.	464	27·5	1·250	272	—	3·74	—	—	—
May	513	29	1·305	313	—	9·08	—	—	—
Jun.	507	31	1·370	325	260	91·42	88·68	171	228
Jul.	520	32·5	1·425	347	337	283·42	280·00	57	76
Aug.	496	31	1·370	318	385	252·65	252·00	133	177
Sep.	434	29	1·305	265	329	137·26	137·00	192	256
Oct.	381	27·5	1·250	223	178	19·73	17·00	161	215
Nov.	309	25	1·167	169	44	9·30	6·00	38	51
Dec.	289	20	1·000	135	101	5·42	4·00	97	129
Total	4959	25·88 mean		2855	1995	835·78	802·32	1191	1588

R radiation in mm at latitude of 26° N; T_c monthly average temperature in °C; C_T temperature coefficient in Christiansen formula; E_p class A pan evaporation (assuming $C_wC_hC_s = 1$) in mm; E_t evapotranspiration (consumption use) in mm, $E_t = k\,E_p$.
Rainfall: monthly rainfall in mm (weighted average 58% of East Rajasthan and 42% of West Madhya Pradesh); R_e effective rainfall in mm; $\alpha_{40,1} = 636$ mm, $\alpha_{40,2} = 228$ mm, $\alpha_{40,3} = 724$ mm.
Node 40—Latitude 26°N, Elevation 500 m, Mean temperature 25·88°C, Annual rainfall 835·78 mm

Monthly rainfall of the Chambal sub-basin is a weighted average of East Rajạsthan (about 58 %) and West Madhya Pradesh (42 %). Rainfall statistics of Chambal and other sub-basins are obtained from the Ministry of Irrigation and Power (1972) report.

Losses

Due to the unavoidable water losses through soil percolation, conveyance, storage and operation, more irrigation water than the estimated net irrigation requirement (NIR) is required. This field irrigation requirement (FIR) is determined by NIR and the field application efficiency (FAC). The efficiency is assumed to include all the losses for simplicity.

$$\text{FIR} = \text{NIR}/\text{FAC}.$$

An FAC of 75 % is assumed for the Ganga basin model. The field irrigation requirements of Chambal sub-basin are given in the last column (FIR) in table B.1. Thus the FIRs at node 40 for a three-season model are 0·636, 0·228 and 0·724 meters per unit area for the rabi, summer and kharif seasons respectively.

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List of symbols

AG_i area (10^6 m^2) at node *i* over which groundwater is available

AH_i culturable land (10^6 m^2) at district *i*

AL_i	minimum irrigation level (current irrigation level) at districi i
D_{ij}	quantity of water (m cu m) left from upstream river node i that returns to the river node downstream
H_{ij}	hydrological inputs (m cu m) at river node i during jth period
K_i	power converson factor (MW/m cu m/mon) at power plant i
m_j	parameter specifying use constraint of a system capacity
PH_i	capacity of watcr (m cu m/mon) driving the turbine at power plant i
P_{ij}	quantity of water (m cu m) driving the turbine at power plant i
$P\text{NEW}_i$	new capacity (m cu m/mon) to be added at power plant i
T_{ij}	quantity of groundwater (m cu m) pumped for irrigation district i during jth period
VH_i	capacity (live storage in m cu m) at reservoir i
V_{ij}	storage (m cu m) at reservoir i during jth period
X_{ij}	quantity of water in 10^6 m^3 (m cu m) flowing through a river away from node i downstream during jth period
XL_i	minimum monthly flow (m cu m) at node i
Y_{ij}	quantity of water (m cu m) diverted from node i in jth period
YH_i	capacity of diversion channel from node i
YL_i	minimum water diversion requirement from node i
Z_{ij}	quantity of water (m cu m) diverted for irrigation from node i during jth period
ZH_i	capacity of diversion channel (irrigation) from node i
$Z\text{NEW}_i$	new capacity of diversion channel to be added to irrigation
α_{ij}	field irrigation requirement (m cu m/$10^6 \times m^2$) at district i
η_j	power demand distribution for jth period
θ_i	quantity of annual groundwater availability (m cu m/$10^6 \times m^2$) at district i
ξ_j	the fraction of total unpumped groundwater returns to river system in jth period

Decentralized planning for the Ganga basin: Decomposition by river basins

PETER ROGERS and SHYANG-LAI KUNG*

Department of Environmental Engineering, Harvard University, Pierce Hall, 121 Cambridge, Massachusetts 02138, USA

* Argonne National Laboratory, 9700, S. Case Avenue, Argonne, Illinois 60439, USA

Abstract. Ths use of the decomposition principle in analysing large and complex systems is demonstrated through its application to the Greater Ganga Basin. The decomposition principle consists of three models (i) the consistency model, (ii) the sub-problem model and (iii) the master problem model. The consistency model tries to identify a feasible solution and sends this information to all the sub-basins. In the sub-problem model each sub-basin optimises the water use according to local conditions subject to meeting the mandatory releases in the Ganga and/or energy targets. After gathering information from the two models the master problem model adjusts the water release requirements and energy targets according to shadow prices. The iterative process is carried out between the sub-problem model and the master problem model to obtain the best solution. The difficulties in getting convergence in the iterative process and the drawbacks of this approach are also highlighted.

Keywords. Decomposition; large scale system; decentralized planning; consistency model; sub-problem model; master problem.

1. Introduction

In this paper a case study of the Ganga Basin is taken up to explore some possible approaches that a river basin authority could use to ensure more efficient use of the water resources and also meet requirements at various downstream points, at such specific locations as tributary nodal points, state frontiers and international boundaries. The underlying data and the basic models are the same as those by Chaturvedi *et al* (1985) but they are now rearranged in various ways to decentralize the decision-making. The actual numerical results are slightly different from those reported by Chaturvedi *et al* (1985) and these differences are due to changes made to simplify the computational procedure.

The approach taken is to assume that there is some central agency responsible for water resources planning in the Ganga basin. We call this the Ganga Basin Authority (GBA). The structure of the assumed authority is not relevant at present. The studies by Chaturvedi *et al* (1985) were carried out as though the GBA had the authority to make water allocations as it liked in all parts of the Ganga Basin. We now modify this in two ways. The first modification assumes that detailed planning decisions will be made by separate river basin authorities for each of the major tributaries. These authorities could all be from one state or could be interstate management boards where more than one state is involved. The role and the responsibility of the central agency, the GBA, is to coordinate all of these independent river basins in such a way as to meet the upstream-downstream requirements. This is to be implemented by the GBA authorizing the minimum seasonal flows out of each of the river basins. In other words the individual basins can do what they like with the water within their own basin provided they meet the outflow requirements.

The second approach dealt with by Karady & Rogers (1985) takes the political unit of the State as the basis of the decentralized decision-making. Under this approach a variety of different algorithms for allocating water use are explored. Essentially, they deal with the total inflows and outflows of the water to and from a State set as targets by the GBA.

This paper is an extension of the coordinating-screening model for the Ganga river basin in which the water resources allocations are made using the decomposition principle of large scale economic optimization models. A different approach has been taken by Chaturvedi (1974). The coordinating-screening model is decomposed into smaller mathematical programs by solving sub-basin problems. A hypothetical GBA is assumed as a central agency who will govern the main Ganga Basin and regulate the river flows to the sub-basins subject to meeting the low-flow requirements down-stream at Farakka for water supply, salinity control, navigation, irrigation, etc.

Several assumptions in constructing the decomposition model are described as follows:

(i) *Main basin and sub-basins* The Ganga Basin is divided geographically into nine basins: the main Ganga Basin and 8 sub-basins. Each sub-basin is a major tributary or a set of smaller streams that join the main Ganga. These sub-basins including the main Ganga Basin (shown in figure 1 and in more detail in figure 2) are:

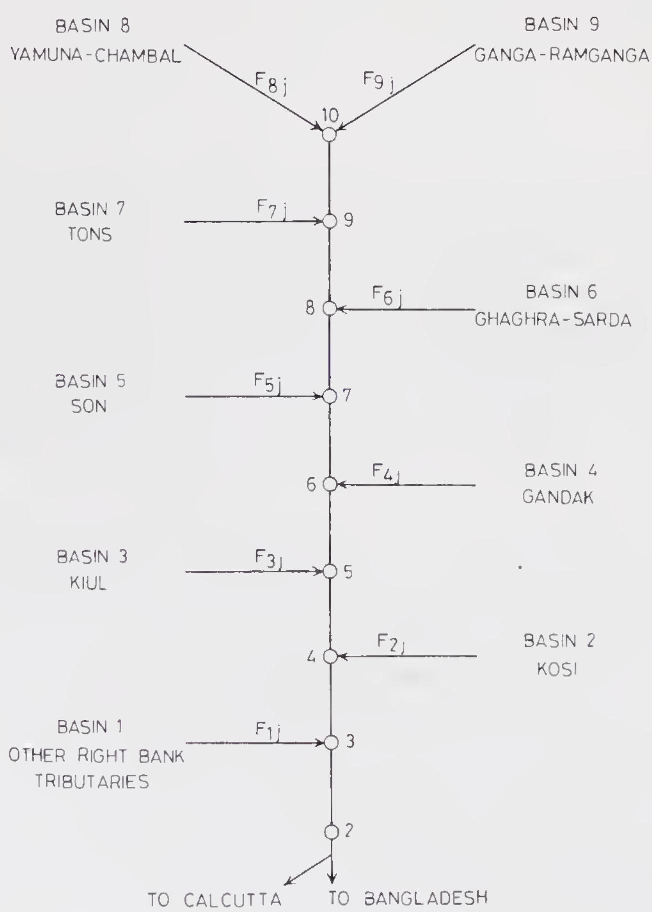

Figure 1. Decentralization of Ganga basin into 9 sub-basins

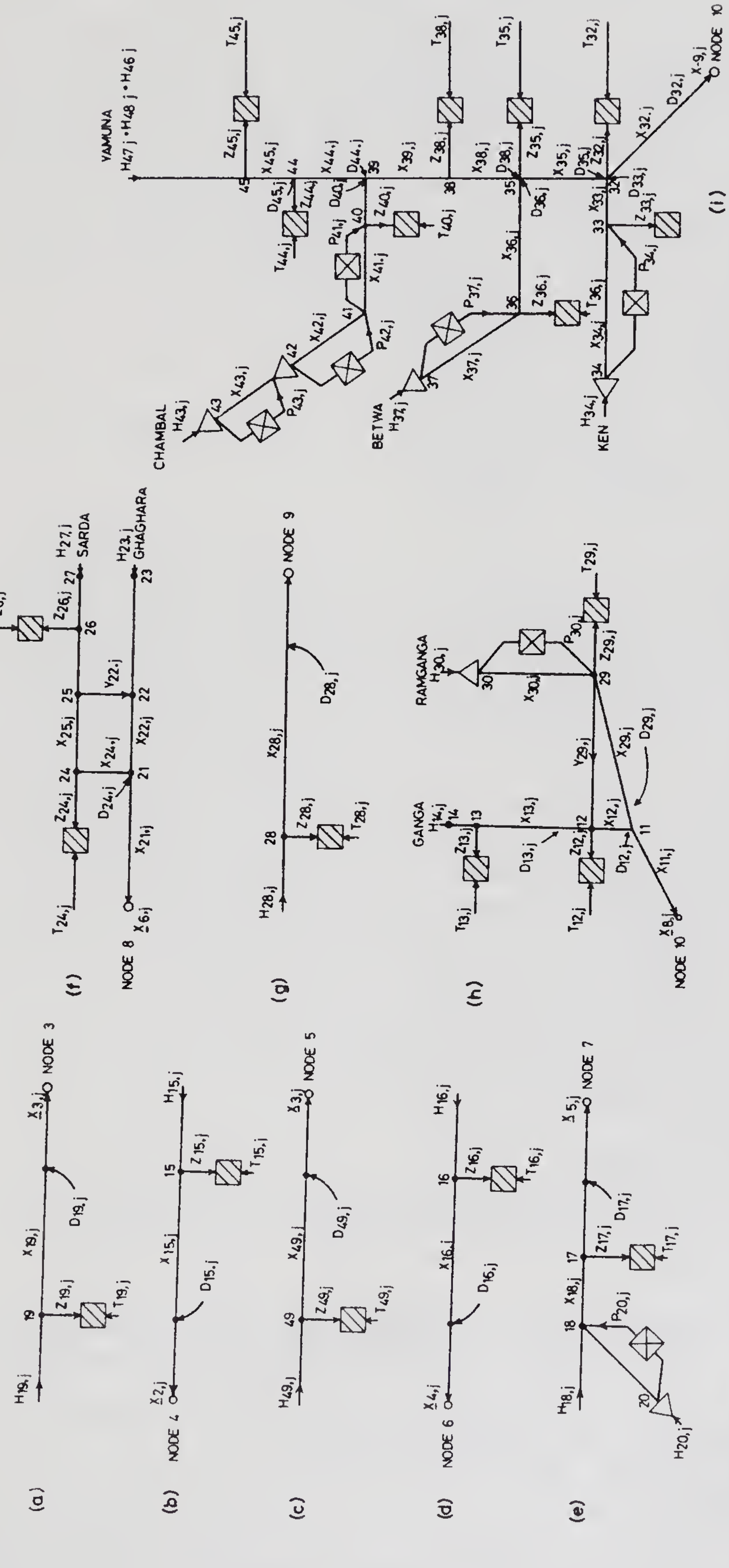

Figure 2. **a.** Sub-basin 1, right bank tributaries east of the Kiul. **b.** Sub-basin 2, the Kosi basin. **c.** Sub-basin 3, Kiul basin. **d.** Sub-basin 4, Gandak basin. **e.** Sub-basin 5, Son basin. **f.** Sub-basin 6, Ghaghra–Gandak **g.** Sub-basin 7, Tons basin. **h.** Sub-basin 8, Yamuna–Chambal basin **i.** Sub-basin 9, Ganga–Ramganga basin

(a) Right bank tributaries east of Kiul; (b) Kosi; (c) Kiul; (d) Gandak; (e) Son; (f) Ghaghara and Sarda; (g) Tons; (h) Yamuna, Chambal, Betwa and Ken, (i) Ganga and Ramganga.

There is irrigation in each sub-basin. Hydropower plants and storage reservoirs are located in Son, Yamuna–Chambal, Ken, Betwa and Ganga–Ramganga sub-basins.

(ii) *Hydrology* A deterministic hydrology of average monthly flows of a typical single year in the past is used. For flood protection and other purposes, a hydrology of extreme events which would have a chance of realization in one year out of every 50 or 100 years would be more appropriate. This has not been considered at present. For the groundwater hydrology it has been assumed, as in Chaturvedi *et al* (1985), that the annual recharge is a proportion of the cultivable area, and that a fraction of the unpumped groundwater becomes available as surface flow.

(iii) *Time periods* The year is divided into three seasons; rabi: November–March, summer: April–June, kharif: July–October.

(iv) *Crops* Two major cropping systems can be used annually, one each in the rabi and the kharif season. Irrigation in summer is restricted to June irrigation for land preparation for the following kharif season.

(v) *Assumptions on decomposition principle* (a) The decomposition principle presented in this paper is composed of three models: the consistency model; the sub-problem model; and the master problem model. A feasible solution is identified in the consistency model and is used as a starting point in the sub-problem and the master problem models. The decomposition model iterates between the two models of the sub-problem and the master problem until a convergent solution or a stopping rule is reached. In each iteration, the GBA sends the minimum water releases and/or energy production targets to each sub-basin; and the sub-basins, after optimizing their own sub-problems, feed back to the central authority the shadow prices and ranges on the minimum water releases and/or energy production. (b) Each sub-basin adopts similar technology in constructing its sub-problem model (its constraints and objective function). The objective function in the sub-basins is to maximize the irrigation level of the total of rabi and kharif seasons. (c) Each sub-basin makes its best efforts to utilize the available water for agricultural developments and/or energy production. Each sub-basin maintains at least the minimum river flows (water releases required by GBA) and keeps perfect communication with the Authority.

2. The decomposition model

The three components of the decomposition model are described in detail as follows:

2.1 *Consistency model*

The GBA tries to identify a feasible solution and sends this information to all the sub-basins (see figure 3). This model has the three major constraint sets described below.

2.1a. *Continuity equation*: The amount of water that flows into a river node equals the amount of water that flows away from the node:

$$f(X, Y, D, F) = H. \tag{1}$$

2.1b *Irrigation constraints*: These are: (a) The amount of water from surface irrigation(Y) and tubewell irrigation (T) equals the product of the irrigation acreage (A)

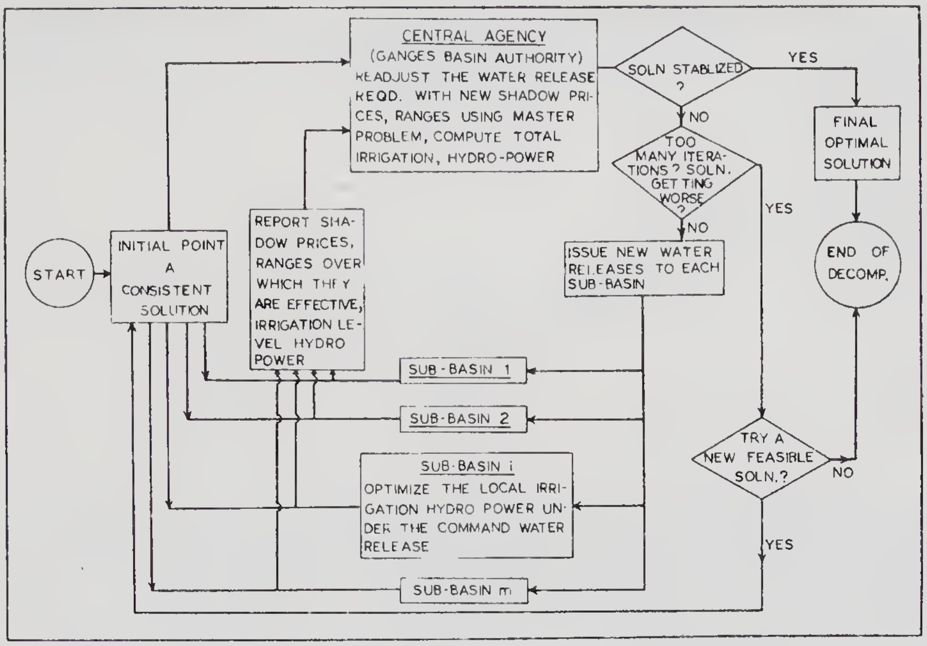

Figure 3. Information flows in river basin decentralisation

and the local field irrigation requirements (α). (b) The irrigation level of the summer season equals the level of the following kharif season. (c) Annual groundwater pumping (ΣT) is less than the groundwater storage (θAG), and groundwater recharges its storage annually. (d) The unpumped groundwater returns to the river at a downstream node according to a seasonal distribution (ξ)

$$I(Y, T, D, A_j, \alpha, \theta AG, \xi) = 0. \tag{2}$$

2.1c *Capacity constraints*: Surface diversion (Y) groundwater pumping (T), and irrigation acreage must be less than their respective capacities ($\overline{Y}$, $\overline{T}$, and $\overline{A}$). In addition, the irrigation acreage must exceed the current irrigation level (**A**) and the river flows at Farakka (X_2) and must meet the low flow requirements (F_2).

$$(\mathbf{X}, \mathbf{Y}, \mathbf{T}, \mathbf{A}; F_2) \leqslant (X, Y, T, A) \leqslant (\overline{X}, \overline{Y}, \overline{T}, \overline{A}) \tag{3}$$

where X, river flows with lower limit **X** and upper limit $\overline{X}$; X_2, river flows at Farakka; Y, canal diversions for irrigation ($\mathbf{Y}, \overline{Y}$); T, tubewell irrigation ($\mathbf{T}, \overline{T}$); D, groundwater and drainage returned to the river; F, water releases from sub-basin; F_2, minimum river flows at Farakka; H, hydrological inputs, A, irrigation acreage ($\mathbf{A}, \overline{A}$), α, field irrigation requirements, θAG, groundwater storage and ξ groundwater return distribution.

To attain a feasible solution of the above constraint set, a linear program that maximizes the irrigation level $\left(\sum_{l,j} A_{lj}\right)$ can be used*. The water releases from each basin are called $F^{(0)}$ (where (0) denotes the initial point).

2.2 *Sub-problem model*

In the sub-problem model, each sub-basin optimizes the water uses for local agricultural development within each sub-basin subject to meeting the command

* In fact a consistent solution is easily found by assuming several feasible releases (F) and computing the remaining releases.

water releases to the main Ganga, and/or energy target levels issued by the GBA.

The objective functions of the sub-problem model takes the following form:

Objective function $\max Z_i = \sum_k (A_{k1} + A_{k3}), \qquad \forall_i.$ (4)

The constraints are:

(a) Continuity equations,

$$f^i(X, Y, D, P, V) = H^i, \qquad \forall_i; \tag{5}$$

(b) Irrigation constraints,

$$I^i(Y, T, D, A; \alpha, \theta AG, \xi) = 0; \tag{6}$$

(c) Capacity constraint,

$$(\mathbf{X}, \mathbf{Y}, \mathbf{T}, \mathbf{A}, \mathbf{P}, \mathbf{V}; F_i, E_i) \leqslant (X, Y, T, A, P, V) \leqslant (\overline{X}, \overline{Y}, \overline{T}, \overline{A}, \overline{P}, \overline{V}), \qquad \forall_i. \tag{7}$$

In this capacity constraint, the river flows from each sub-basin to the main Ganga must exceed the requirements ($X_{ij} \geqslant F_{ij}$) and/or the energy production must meet the issued target levels ($k_m P_{mj} \geqslant E_{mj}$), where, i is sub-basin number, j is season number, k_m is the conversion factor for flow through turbines to energy for sub-basin m, m is the sub-basin with energy production, F_{ij} is water release requirements from sub-basin i during season j, E_{mj} is the energy production target in sub-basin during season j.

After the optimization is reached each sub-basin reports the shadow prices (defined as the reduction of irrigation acreage for every unit of increment of water releases and/or of energy target levels) and their effective ranges on F_{ij} and/or E_{mj}, irrigation acreage, and/or energy production to the central organization.

2.3 *Master-problem model*

With the information gathered from the sub-basins and from the consistency model, the GBA adjusts the water release requirements and energy target levels for the sub-basins according to the shadow prices. Sub-basins that have more important shadow prices (*i.e.* larger negative shadow prices) will have reduction in the water release requirements and vice versa. This is also true in adjusting the energy target levels.

To facilitate this adjustment process, a linear program is constructed to maximize the incremental irrigation acreage, while honouring the minimum flow at Farakka and the energy constraints.

The objective function of maximising the incremental irrigation acreage takes the following form,

$$\max \Delta_w^{(k)} = \sum_{i,j} \frac{\partial Z_i}{\partial F_{ij}} \Delta F_{ij} + \sum_{m,j} \frac{\partial Z_m}{\partial E_{mj}} \Delta E_{mj} + \sum_{l,j} \Delta A_{lj}. \tag{8}$$

Several simple constraints are constructed to ensure that the low flow requirements, increasing irrigation level and distribution of energy production are met.

(a) Low flow requirements at Farakka (F_2): The changes in increases (or decreases) of water releases from sub-basins and the changes in Main Ganga irrigation must not violate the minimum flow requirements at Farakka,

$$\sum_i \Delta F_{ij} - \sum_l (\alpha_{lj} \Delta A_{lj}) \geqslant F_{zj}^{(k-1)} - F_{zj}, \qquad \forall_j. \tag{9}$$

(b) Energy production should maintain its seasonal distribution and improve over the previous level if possible.

$$\sum_m \Delta E_{mj} - \eta_j \sum_k \Delta E_{mk} = 0, \qquad \forall_j, \tag{10)*}$$

$$\sum_m \Delta E_{mj} \geqslant 0, \qquad \forall_j. \tag{11)**}$$

(c) Upper and lower bounds on the changes (ΔF, ΔE, ΔA),

$$\begin{aligned} &\underline{\Delta} F_{ij} \leqslant \Delta F_{ij} \leqslant \overline{\Delta} F_{ij}, \\ &\underline{\Delta} E_{mj} \leqslant \Delta E_{mj} \leqslant \overline{\Delta} E_{mj}, \qquad \forall_{j,m,l,i} \\ &\underline{\Delta} A_{lj} \leqslant \Delta A_{lj} \leqslant \overline{\Delta} A_{lj}, \end{aligned} \tag{12}$$

and ΔF_{ij}, ΔE_{mj} and ΔA_{lj} are unrestricted as to sign, where $\Delta_w^{(k)}$, is the objective function of the incremental irrigation acreage in the kth iteration; $\partial Z_i/\partial F_{ij}$, the shadow price of water release requirement in sub-basin i in the season j; $\partial Z_m/\partial E_{mj}$, the shadow price of energy target level in sub-basin m in season j; ΔF_{ij}, the change of water release in sub-basin i in season j; ΔE_{mj}, the change of energy target level in sub-basin m in season j; ΔA_{ij}, the change of irrigation level in main basin at node l in season j; η_j the seasonal energy production distributions; $\overline{\Delta} F$, $\overline{\Delta} E$, $\overline{\Delta} A$, are the upper bounds on changes determined by the smaller value of upper bounds over which the shadow prices are effective and logical upper bounds; $\underline{\Delta} F$, $\underline{\Delta} E$, $\underline{\Delta} A$, are the lower bounds on changes determined by the larger value of lower bounds over which the shadow prices are effective and logical lower bounds.

These upper bounds ($\overline{\Delta} F, \overline{\Delta} E, \overline{\Delta} A$) and lower bounds ($\underline{\Delta} F, \underline{\Delta} E, \underline{\Delta} A$) are deduced from two sources: ranges reported from sub-basins, over which the shadow prices are effective and logical constraints. For example, when the upper bound of a shadow price is larger than the water that can be regulated from the surface, groundwater and reservoirs, then the upper bound should only consider the amount of water that the surface, groundwater and reservoir can regulate. Another example is when the lower bound is negative infinity, it has to be set at zero to avoid negative river flows.

The solution of this master problem model in the kth stage is the adjustment of the new water releases and energy target levels:

$$\begin{aligned} &F_{ij}^{(k)} = F_{ij}^{(k-1)} + \Delta F_{ij}, \\ &E_{mj}^{(k)} = E_{mj}^{(k-1)} + \Delta E_{mj}, \qquad \forall_{i,m,l,j} \\ &A_{lj}^{(k)} = A_{lj}^{(k-1)} + \Delta A_{lj}. \end{aligned} \tag{13}$$

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* Because the initial solution has enforced this seasonal distribution (η_j), and if the changes in energy production $\left(\sum_m \Delta E_{mj}\right)$ also satisfy the seasonal distribution, then the new energy production will satisfy the seasonal distribution automatically.

** This constraint should not be enforced when the trade-off between agriculture and energy is very obvious (*i.e.*, irrigation gains a lot by sacrificing a little energy).

3. Iterative decomposition process

The iterative process of the decomposition model takes place as shown in figure 3 by repeating the sub-problem model and the master problem model. This iterative process is described below:

(i) The initial feasible solution is attained by solving the consistency model. The GBA then issues the initial water releases and/or energy target levels to all the sub-basins.
(ii) Each sub-basin solves the sub-problem model by optimizing the irrigation level under the given water releases and/or energy target levels. Each sub-basin then reports to the central organization its optimal irrigation level, and/or energy production, shadow prices and their effective ranges on the water releases and energy target levels.
(iii) The central organization solves the master problem based on the information reported from the sub-basins by:
(a) Evaluating the appropriate upper and lower bounds on ΔF, ΔE and ΔA, (b) solving the optimization equations (8) to (12), (c) adjusting the water releases and/or energy target levels and issuing them to the corresponding sub-basins, (d) computing the new total irrigation level and the energy production of the whole basin.
(iv) Stopping rule: This iteration procedure is checked to see whether it should go to step (v) or repeat steps (ii) and (iii) by; (a) Going to step (v) if the water releases have stabilized from iteration to iteration, or the total irrigation level no longer improves (*i.e.* all shadow prices are zero or both their upper or lower bounds are equal); (b) Going to step (v) if the iteration number has reached a pre-specified allowable number (presumably a large number). (c) Going to step (ii) and repeating the iteration if neither (a) nor (b) occurs.
(v) Stop iteration and report current values as the best solution.

It is possible that no feasible solution can be reached in step (ii) when a sub-basin tries to solve the sub-problem model while honouring the new increased water releases and energy target levels because the ranges are estimated on the basis of individual constraints. When this happens parametric programming is adopted reducing the energy target levels (according to seasonal distribution η_j) successively, until a feasible zone appears. This parametric programming will reduce the energy production but maintain the seasonal energy production distribution.

4. Solutions

Two solutions under conditions similar to those specified by Chaturvedi *et al* (1985) were made: (i) to maximize the irrigation and generate hydropower with available water; and (ii) to maximize the irrigation and insist on the maximum achievable power (with both distributional and power plant capacity constraints). The initial feasible solution obtained from the consistency model for both the examples given above is presented in table 1.

In the first example, the decomposition process gives the solution (total irrigation 57·69 m ha) after the third iteration. The increments and decrements of each sub-basin and the main basin are shown in tables 2 to 4 and the centrally administered low flows are shown in table 5.

Table 1. Feasible solution to consistency model

	Seasonal releases		
Sub-basin	Rabi Fi_1	Summer Fi_2	Kharif Fi_3
1	50	—	—
2	1,500	5500	—
3	50	—	—
4	1,500	4500	—
5	1,000	—	—
6	10,000	1500	—
7	70	—	—
8	1,000	100	1000
9	3,500	2000	—

In the second example, the iterative decomposition process reaches an irrigation level of 54 m ha in the fourth iteration and stops because the improvement on irrigation from the third iteration is slightly negative (see table 6). The energy generated is 26,479 GWh/year (see tables 6 and 7).

5. Conclusions

The decomposition principle presented in this chapter is very powerful in reducing the size of the computational problem to smaller sub-problems of manageable size that can be solved by a time-sharing computer system. Necessary changes from iteration to iteration are easy to arrange. However, it is not clear from the particular cases that we have solved whether it would always achieve such rapid convergence. The choice of our feasible solution (table 1) was conditioned by the previous solutions made by Chaturvedi *et al* (1985). Hence we started with a very good solution to the problem and converged quickly to near optimal solutions. This is not really a fair test of the methodology.

There are a few serious drawbacks associated with this approach. The first is that for the method to converge towards the optimum the river basins have to report their shadow prices and ranges over which they are applicable correctly. If the basins misrepresent their requirements for some reason or the other there is no guarantee that the planning approach is efficient. Unfortunately, there is a large incentive for misrepresentation in this administrative set-up and, hence, some additional method to control it may be needed. The second major drawback is that the individual sub-basins cross state lines and, hence, there is little reason to believe that the sub-basins would themselves be able to agree upon the "best" solutions given the flow requirements. This issue is dealt by Karady & Rogers (1985).

Table 2. Maximization of irrigated area–first iteration

Basin	Rabi				Summer				Kharif			
	$\partial Z_i/\partial Fu_1$	$1Fu$	$1F_L$	ΔFi_1	$\partial Z_i/\partial Fi_2$	$2Fu$	$2F_L$	ΔFi_2	$\partial Z_i/\partial Fi_3$	$3Fu$	$3F_L$	ΔFi_3
1	−1·873	259	0	−50	0	0	0	0	−1·873	913	0	0
2	−1·613	6502	−317	0	5541	0	+41	0	0	30,241	0	0
3	−1·873	259	0	−50	0	0	0	0	0	0	0	0
4	−1·613	8338	1011	−488	0	4740	0	+240	0	46,190	0	0
5	−1·577	10,100	6179	+1666	0	2865	0	0	0	6447	0	0
6	−1·629	10,781	5551	−4449	−1·629	4113	0	−1500	0	27,302	0	0
7	−1·942	150	0	−70	0	0	0	0	0	0	0	0
8	−1·608	6578	0	+968	−1·608	335	91	−100	0	1326	0	0
9	−1·919	6788	2990	−3299	−1·919	3016	1001	−1213	0	10	0	0

Total area $56{\cdot}07 \times 10^6$ ha.

Table 3. Maximization of irrigated area–second iteration

Basin	Rabi				Summer				Kharif			
No.	$\partial Z_i/\partial Fi_1$	$1Fu$	$1F_L$	ΔFi_1	$\partial Z_i/\partial Fi_2$	$2Fu$	$2F_L$	ΔFi_2	$\partial Z_i/\partial Fi_3$	$3Fu$	$3F_L$	ΔFi_3
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1182	657	0	0	555	0	0	0	30,241	0	0
3	−1·873	259	0	0	0	0	0	0	0	0	0	0
4	−1·613	1011	562	0	0	4740	0	0	0	46,190	0	0
5	−1·577	7297	0	0	0	0	0	0	0	2628	0	0
6	−1·629	5551	0	0	0	0	0	0	0	27,302	0	0
7	−1·942	0	0	0	0	123	0	0	0	0	0	0
8	−1·608	6659	0	+201	−1·608	220	0	+787	0	1326	0	0
9	−1·83	6202	2379	−201	−1·92	1612	152	−787	0	10	0	0

Total area $57{\cdot}65 \times 10^6$ ha.

Table 4. Maximization of irrigated area–third iteration

Basin	Rabi				Summer				Kharif			
	$\partial Z_i/\partial Fi_1$	$1Fu$	$1F_L$	ΔFi_1	$\partial Z_i/\partial Fi_2$	$2Fu$	$2F_L$	ΔFi_2	$\partial Z_i/\partial Fi_2$	$3Fu$	$3F_L$	ΔFi_3
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1182	657	0	0	555	0	0	0	30,241	0	0
3	−1·873	254	0	0	0	0	0	0	0	0	0	0
4	−1·613	1011	562	0	0	4740	0	0	0	46,190	0	0
5	−1·577	7297	0	0	0	0	0	0	0	2628	0	0
6	−1·629	5551	0	0	0	0	0	0	0	27,302	0	0
7	−1·942	0	0	0	0	123	0	0	0	0	0	0
8	−1·608	6678	1326	0	−1·608	19	0	0	0	1326	0	0
9	−1·873	2791	1416	0	−1·873	852	2	0	0	10	0	0

Total area $57{\cdot}69 \times 10^6$ ha.

Table 5. Centrally administered low flows during rabi (Fi_1) without power targets.

Basin	Start	After 1 iteration	After 2 iteration
1	50	0	0
2	1,500	1183	1183
3	50	0	0
4	1,500	1012	1012
5	1,000	2666	2666
6	10,000	5551	5551
7	70	0	0
8	1,000	1968	2169
9	3,500	201	0

Table 6. Maximizing irrigation with power targets

	Iteration			
Iteration	1	2	3	4
Total area irrigated (m ha)	51,048	53,854	54,052	54,000
Total energy produced (GWh)	20,889	23,134	24,468	26,479

Table 7. Maximizing irrigation with power targets (MW)

Basin iteration	Son				Yamuna				Ganga-Ramgamga			
power targets	1	2	3	4	1	2	3	4	1	2	3	4
Ei_1	753	931	1134	1222	1722	1776	1776	1776	430	491	444	633
Ei_2	337	327	558	704	722	774	774	774	193	332	193	148
Ei_3	658	0	0	0	1506	2544	2976	3303	376	252	0	0

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Decentralized planning for the Ganga Basin. Decomposition by political units

GEORGE KARADY and PETER ROGERS*

Temple, Barker and Sloane Inc., 33, Hayden Avenue, Lexington, Massachusetts 02173, USA

*Department of Environmental Engineering and City Planning, Harvard University, Pierce Hall, 121, Cambridge, Massachusetts 02138, USA

Abstract. In this study the greater Ganga Basin is decomposed by political units for analysis instead of by hydraulic sub-basins. This method is more logical because water-resources-use planning is under the individual state jurisdiction but the Central Government is responsible for meeting the low flow requirement at Farakka. Maximisation of national benefits is taken in terms of total area irrigated. The solution technique proposed is an iterative procedure.

The problem is analysed under two schemes (i) flow quota scheme and (ii) resource allocation scheme. These schemes are worked out by three algorithms. The first algorithm requires that minimum flow at any point in the Ganga should be greater than the sum of the minimum quota fixed by the central Government for all the states above that point. Under algorithm two, water that leaves an upstream state may be used by a downstream neighbour provided that this neighbour allows a flow greater or equal to the sum of its and all the upstream states quota to pass into the next state. In algorithm three the restriction of algorithm two has been lifted. The merits and demerits of each algorithm are discussed.

Keywords. Large scale systems; decomposition; decentralized planning; flow quota scheme; resource allocation scheme.

1. Introduction

The purpose of this study is to apply a decentralized planning solution technique to the coordinating-screening Ganga river basin model developed by Chaturvedi *et al* (1985). Their large, deterministic linear programming model, which describes in detail the water in the Ganga basin, was solved in its entirety. Later, a decomposition by river basin solution was proposed by Rogers & Kung (1985). This latter approach assumes the existence of river basin authorities, which solve their own, much smaller resource allocation problems and whose action is coordinated by some central planning agency. The method presented here addresses the more complicated but realistic issue of decomposition by provinces or states. The motivation for such a scheme is as follows. Water resources use planning is under the jurisdiction of individual states, but it is the central government which is responsible for meeting the low flow requirements at Farakka. The central government's (CG) objective is presumably to meet this above constraint while coordinating the state governments' (SG) work in such a way that the total national benefits, in our case rabi and kharif season irrigation of agricultural land, are maximized.

The technique proposed is an iterative one, in which the CG decrees some initial allocation of water for each state so that the low flow constraints are met at Farakka. The states solve their own, pertinent water allocations and report back to the CG some shadow price on the initial allocation. The CG then reallocates in such a way that there is a net increase of total area irrigated in the states. This back and forth exchange of information goes on until the CG cannot engineer a further improvement in its objective. Hopefully, as was the case in the basin-wise decomposition, the iterative process will terminate in a few steps. These iterations are equivalent to "rounds of discussions" between the CG and the SG, each of which has conflicting goals and is trying to secure the best possible solution for itself.

One of the broad schemes proposed calls for the CG to ask each SG to contribute a certain amount of water to the national and international cause of satisfying the low flow requirements at the Bangladesh border. Apart from this intervention the CG allows the states to use their water resources in the most efficient way possible. The states do this by solving their water allocations subject to the CG imposed quota and to other minimum flow requirements negotiated among themselves.

A second scheme, which will henceforth be referred to as the "resource allocation scheme" requires that the CG tell the states how much water they can divert for irrigation in each season. Under this proposal the CG must be aware of the hydrological inputs to each of the states, so that it can check that the states do not misrepresent the quantity of water they use. The advantages and disadvantages of this latter decomposition method will be further expounded below.

The major assumptions and simplifications made to the coordinating-screening model are restated as follows: (i) The objectives are to maximize rabi and kharif season irrigation subject to the constraint that during one month of the summer season, the same area be irrigated as during the kharif season (this summer irrigation is to prepare the soil for sowing), (ii) no consideration is given to power generation.

Other simplifications and their justifications are presented in § 4. A simplified view of the Basin considered as 6 states plus Bangladesh is shown in figure 1.

2. Description of the decomposition algorithms

Each of the algorithms considered is of the primal feasible type, for it was deemed important to be able to stop the process, if necessary, before the optimal solution was found and still end up with a feasible set of operating rules. A further requirement was that the operating policy be relatively easily implemented and enforced.

The greatest difficulty in connection with the decomposition by state scheme was dealing with the serially-coupled nature of the problem. If a state decides to use less water, *i.e.* allow more to pass into the downstream states, the question arises as to what the optimal strategy is for the use of the extra water by these states. The algorithms presented attempt more or less successfully to decouple the states from each other. The situation is further complicated by the fact that the model considers not one, but three, seasons among which there is also considerable coupling. For this reason at each iterative step only one parameter of one season is changed.

3. Flow quota scheme

Under this scheme, each state contributes a certain amount of water, set by the CG, to the quantity required at Farakka. The CG communicates an initial quota, $F_{Nj}^{(0)}$, (where N refers to one of the states, j refers to the season) to each of the state governments. The SG solves its problem, and returns shadow prices on its input and output constraints, as

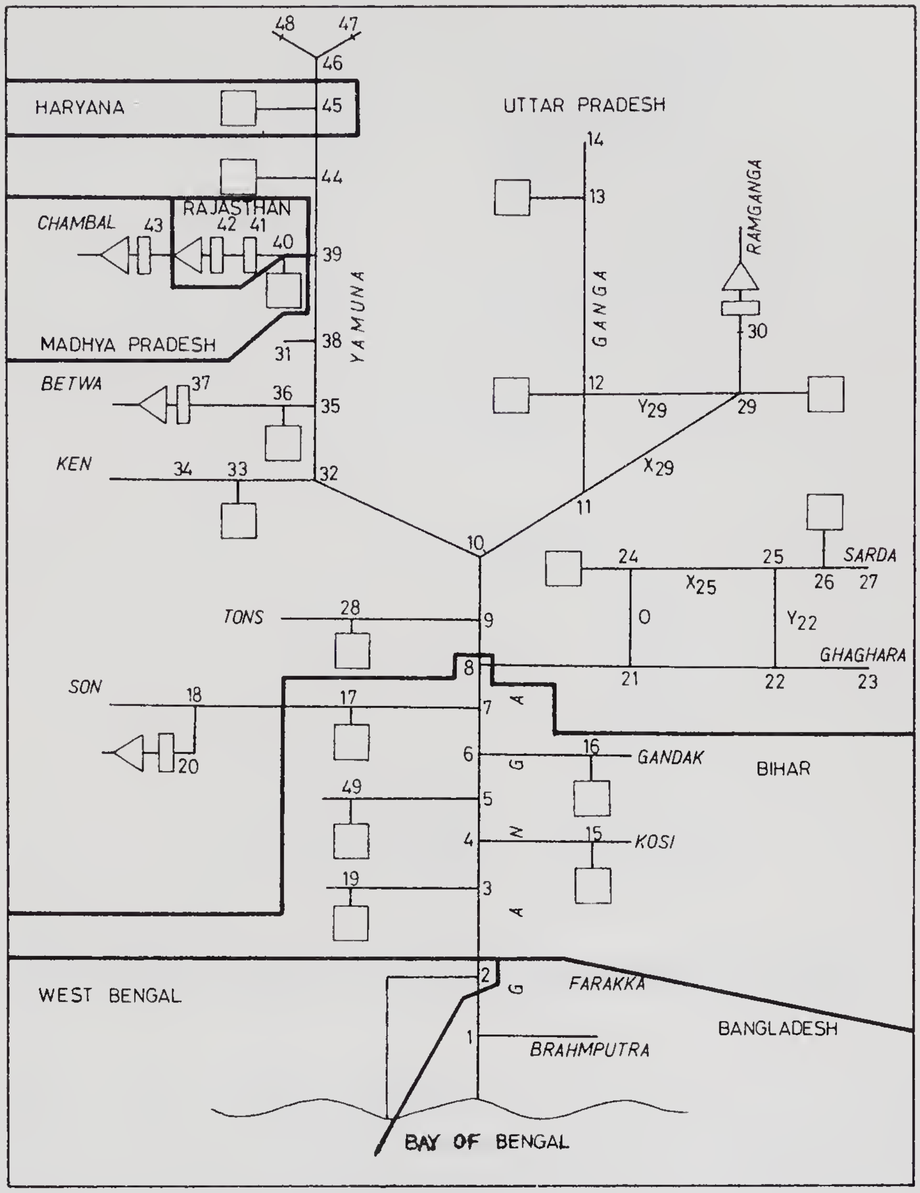

Figure 1. Line diagram of the Ganga basin

well as the range of the relevant right hand sides, over which the shadow prices are unchanged, to the CG. The CG reassesses the data and changes the $F_{Nj}^{(k)}$, where k is the iteration number, in such a way that the sum total of the irrigated area in the states increases. This usually means that states with a high shadow price for water are required to contribute less, while states with a low shadow price for water are to contribute more to the common cause. The iterations are carried out until one of the following criteria is met: (i) all shadow prices are equal; (ii) further increase or decrease of some of the $F_{Nj}^{(k)}$ would result in system infeasibilities.

A block diagram of this scheme is shown in figure 2 along with arrows depicting the information flow between CG and SG. The CG sets the $F_{Nj}^{(k)}$ and enforces or at least checks them by occasionally measuring the actual flow of water across the states' borders. The SG relays information concerning the shadow prices on its input and output of water and the right hand side ranges over which these shadow prices are constant. Information as to

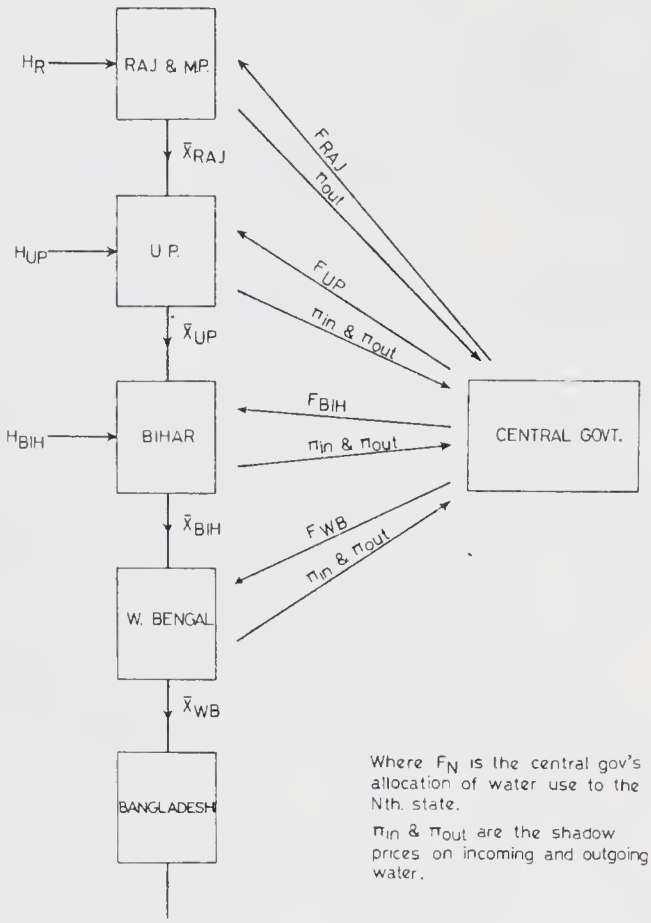

Figure 2. Schematic diagram and information flow between Central Government and State Government.

each state's optimal irrigation for a given $F_{Nj}^{(k)}$ is also released to the CG. This is the extent to which information is exchanged among the different hierarchies of government.

Unfortunately, the algorithms considered below are very much subject to misrepresentation by the SGs. While the CG can ascertain, by direct measurement, that each state allows at least $F_{Nj}^{(k)}$ amount of water to leave its territory, it cannot be sure whether the shadow prices or ranges on their right hand sides have been falsified or not. In the analysis that follows, it is assumed that the state governments do not misrepresent these data. The problem of the CG in finding the optimal $F_{Nj}^{(k)}$ when misrepresenting is considered should be investigated at a future date, for it may represent a more realistic situation than the one considered here. It should be noted that the CG possesses no direct mechanism by which it could force the states to comply with the required $F_{Nj}^{(k)}$, should their output fall short of this targeted value.

3.1 *Algorithm I*

Complete decoupling of the states, if not of the seasons, may be achieved by requiring that the minimum flow anywhere in the main stream of the Ganga be greater than the sum of the F_{Nj}'s of all of the upstream states. See figure 3a for illustration. This is a very restrictive constraint, for under this scheme downriver states can in no way utilize the water released upstream. The system is effectively separated into one similar to that

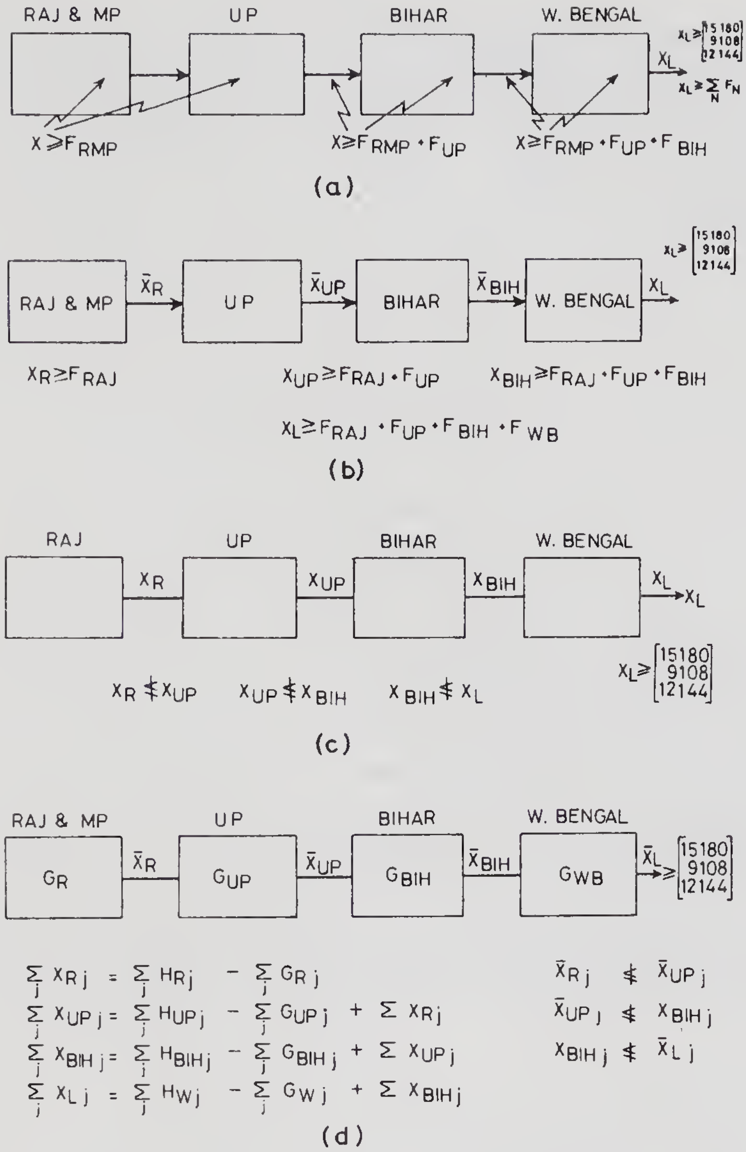

Figure 3. **a.** Outflow quota scheme, algorithm I. **b.** Outflow quota scheme, algorithm II. **c.** Low flow quota scheme, algorithm III. **d.** Resource allocation algorithm.

considered by Rogers & Kung (1985) in their basinwise decomposition. They showed that convergence was rapid; only three iterations were required. From a practical, implementational point of view, algorithm I is infeasible, for it requires that the flow of water be regularly checked at each main stem node, and the final solution may be socially inefficient, since it could allow a situation in which Northern UP is underirrigated, but Southern UP has too much water. If the above constraint were relaxed within UP and were only enforced at its border with Bihar, UP may be able to increase its irrigated areas considerably. These considerations bring us to a second, more realistic algorithm.

3.2 *Algorithm II*

Under this algorithm, water that leaves an upstream state may be used by its downstream neighbour provided that this neighbour allows a flow greater or equal to the sum of its and all the up-stream states' F_{Nj} to pass into the next state. The situation is illustrated in figure 3b. While the algorithm may lead to higher overall irrigation levels, it also poses some major computational difficulties. Monotonic convergence to the global optimum is not assured anymore. It also becomes difficult to ascertain whether after a seemingly last iteration a global optimum has in fact been attained. At the heart of these difficulties lies the fact that the ranges on the right hand sides are computed assuming that only that this side is changed. This means, for example, that one either changes the inflow or the outflow constraints of a state. Changing both or changing one in more than one season may lead to erratic results because a shift in one of the constraint's right hand side may lead to a changed shadow price or range for another constraint. With all this in mind, consider the situation encountered in the first computational example after the ninth iteration. The status of the model after this iteration is shown in figure 4a. Briefly then, the shadow prices indicate that it would be beneficial to increase either the input to UP and/or to reduce its output to Bihar. Neither of these possibilities is open to the CG, for UP's output already equals Rajasthan's quota with $F_{UPj} = 0$ in the first season. Is one at an optimum? In a sense a local optimum has been reached, but can a still higher optimum be reached by first increasing UP's output (a sub-optimal move) and then increasing the input to it from Rajasthan? Will such a move lead to a better solution, and if yes, by how much should one increase UP's output? These questions may only be answered by actually performing the calculations. It is because of considerations like these that the convergence is not monotonic and is heavily dependent on the 'path' or decisions that were taken by the CG to get to the 'local maxima'. At each iteration the CG chooses from among a number of decisions, all of which will improve the overall solution. It does not know *a priori* which of the choices will take it the "farthest", along the decision tree. It may have to decide to "skip from one branch to another" in a sub-optimal iterative step in order to progress further towards the global optimum. The fifth iterative step was such a 'skipping' move. See figure 5 for further details.

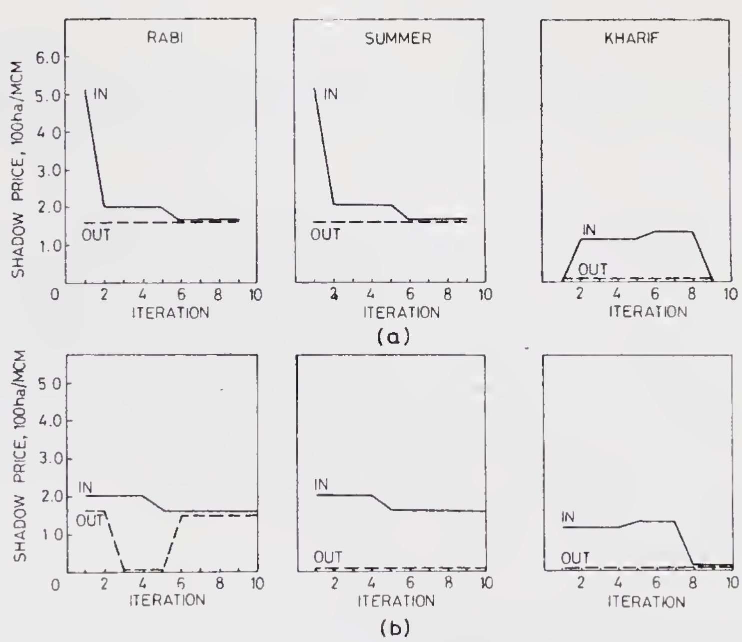

Figure 4. Shadow prices for Uttar Pradesh. **a.** Algorithm II. **b.** Algorithm III.

In defence of the algorithm, it must be pointed out that there was very little improvement to the objective function value after the fourth iteration. Familiarity with the system would also tend to make one doubt that the solution after the ninth iteration may be significantly improved. Nevertheless, it is entirely plausible that the relative success of algorithm II on the Ganga basin problem is due to the insensitivity of the model to changes in the input and output parameters. In the light of these difficulties, one ought to exercise great caution when applying the algorithm to an unknown general system.

3.3 *Algorithm III*

In the second algorithm, Rajasthan's quota, for example, could be used by UP but had to be accounted for at its border with Bihar. In the algorithm considered here, this restriction is lifted. The F_{Nj}'s are no longer the Nth state's contribution to the quota to be met at Farakka, but it is the actual amount of water the Nth state is required to release to its neighbour. In effect the CG is not only seeking the best solution subject to the Farakka constraint, it also takes upon itself to redistribute the water of the Ganges among the six states in such a way as to maximize the sum of the areas irrigated in all of the states. Because this algorithm is less restrictive than algorithms I and II, one expects it to yield the highest solution of the three. Figure 3c illustrates the situation. While this method suffers from fewer computational difficulties than the second algorithm, one wonders whether or not it constitutes a grave infraction on the part of the CG on the states' sovereignity, to dictate the redistribution of their resources in such a manner.

This third algorithm converges monotonically to what is believed to be the global maximum for the system. As yet, this statement has not been proved. The path to the maximum does not seem to be unique, just as the solution, as far as the decision variables are concerned, is not unique.

In summary then, algorithms were presented for the decomposition by state of the Ganges basin. All the three are susceptible to misrepresentation by the SGs. Algorithm I, which is the least difficult to solve, is almost impossible to implement in practice. Algorithm II, while most palatable in a political sense (contributions to a national cause) has difficulties in converging to a global optimum. Algorithm III performs well mathematically, but may promote animosity between the states and the CG.

4. Resource allocation schemes

Instead of prescribing the low flow requirement F_{Nj}, the CG allocates a certain amount of water $G_{Nj}^{(k)}$ to be used by the Nth state in the jth period. The explicit form this constraint takes is

$$\sum_{ij} Z_{ij} = G_{Nj}^{(k)}, \tag{1}$$

where Z_{ij} is the amount of water diverted for irrigation at node i in period j. The sum over i runs over all the nodes in state N. Apart from minor modifications, the CG's strategy is as before. An initial feasible solution is chosen, which is improved upon by adjusting the $G_{Nj}^{(k)}$ with contributions from the respective shadow prices.

If the scheme of algorithm II is used, this problem is even harder to solve than algorithm II. If the method adopted in algorithm III is the basis of the CG's actions, then complete decoupling may be achieved among the states. This happens because there is now only one constraint for each state. The input and output constraints that plagued the 'low flow quota' methods have been eliminated in favour of (1). If, for example, G_{RAJ} is reduced; but none of the other states' G's is changed, the extra water released by Rajasthan will manifest itself as increased flow at Farakka. This seems to be the most desirable feature of this method.

In order to minimize the chance of changing a G in such a way that infeasibilities occur, the initial G's should be set high enough such that no water flows out from any one of the states. The situation is summarized in figure 3d.

The algorithm requires that the CG know the hydrological inputs to all the states. It can then ascertain that the states are not misrepresenting the amount of water they use by evaluating the following relationships;

$$\sum_{ij} H_{ij} = \sum_{j} F_{Nj} + \sum_{j} G_{Nj} - \sum_{j} X_{Nj}, \tag{2}$$

where $\sum_{ij} H$ is the annual hydrological input to the Nth state, $\sum_{j} F_{Xj}$ is the amount of water flowing out of the state and $\sum_{j} X_{Nj}$ is the input of water to the Nth state from its upstream neighbour.

After the CG chooses an initial allocation of G_{NJ}'s such that the constraints are met at Farakka, the SGs solve their problems and relay back to the CG their shadow prices on the G_{Nj}, the ranges and their output F_{Nj}. The reason for the CG's inability to determine the F_{Nj} *a priori* is because of the season-to-season coupling by groundwater pumping and the operating of reservoirs. This is precisely where the shortcomings of the algorithm lie. The CG is unable to determine, short of having the states do the calculations, how the seasonal output of UP, for example, will change if both G_{RAJ} and G_{UP} are changed. Because of this seemingly insurmountable difficulty it was decided not to investigate the method any further. It is conceivable, however, that because of the general stiffness of the Ganga model, the season-to-season coupling would not be strong enough to seriously interfere with the workings of the algorithm.

From a political point of view, the algorithm may not be a favourite of the SGs, as it may be construed to infringe on state autonomy.

5. Computational experience

5.1 *General remarks*

Calculations were made using the Harvard Business School's DEC 1070 system. The linear programming sub-problems were solved by the highly convenient and adaptable HPSLP subroutine available on this computer. Because of software, hardware, time and fiscal limitations, it was necessary to make a few simplifications in the original model to reduce the sizes of the sub-problems to solvable ones by the HBSLP program. Even so, the largest of the linear programs, that for UP, had 121 variables and 123 constraints. Admittedly, the input matrix was sparse, but such a large problem is still just about as big as the existing time-shared software can handle. The CG's master program was solved by hand.

5.2 *Assumptions and simplifications*

Since in both the solutions presented by Rogers & Kung (1985), the groundwater reserves were completely exploited at the end of the third season, it was decided to set the D_{ij}'s to be identically zero (D_{ij} is the quantity of groundwater and irrigation drainage at node i that is returned to the river at a downstream node). Further reductions in the size of UP's sub-problem were achieved by fixing the irrigation levels of nodes 13, 24, 33, 44 and 45 at the levels calculated by the previous two methods. The particular areas were chosen because their abundant water supplies assure their being irrigated at a constant level for not too drastic changes in F_{RAJ} and F_{UP}.

Node 40 irrigates roughly equal areas in Madhya Pradesh and Rajasthan. Since power generation was not considered in the objectives of the states, it was assumed that the reservoirs at nodes 42 and 43 were operated in unison to derive the maximum irrigation benefits for both states.

Because of similar considerations UP's reservoir at node 20 was operated in such a fashion as to aid the irrigation of Bihar. Of course if power generation were one of the objectives, operating policies would be drastically different.

5.3 *Notes on iterations*

Figure 5 represents the progress of the iterations for algorithms II and III.

5.3a *Algorithm II*: It proceeded smoothly until iteration four, at which point it was realized that a 'skip to another branch' was necessary if one was not to get stuck at a sub-optimal solution. This was done by increasing the first season output of UP from 3000 to 6500·8 m cum, which was the limit dictated by the range of Bihar's shadow price for incoming water. This skip resulted in a slight decrease in the total area irrigated, but permitted a yet higher level to be reached in subsequent iterations. A similar procedure would have been performed after the ninth iteration, but as already pointed out earlier, the value of such a procedure at this stage would have been questionable. The optimization procedure was thus terminated at what is no doubt a sub-optimal solution. The value of the primal feasible feature of the algorithm is thus amply demonstrated. Figure 5 and table 1 summarize the status of the model after each iteration and indicate what changes were made from iteration to iteration.

Table 1. Algorithm II: Gross area irrigated (million hectares)

Iteration	Rajasthan and M.P.	U.P	Bihar	West Bengal	Total
1	7·42	28·96	18·90	1·11	56·39
2	7·37	29·08	19·11	1·11	56·67
3	7·38	29·22	19·12	1·11	56·83
4	7·18	29·46	19·12	1·11	56·87
5	7·18	28·89	19·68	1·11	56·86
6	7·02	29·07	19·68	1·11	56·88
7	6·53	29·58	19·68	1·11	56·90
8	6·36	29·83	19·68	1·11	56·98
9	6·33	29·87	19·68	1·11	56·99

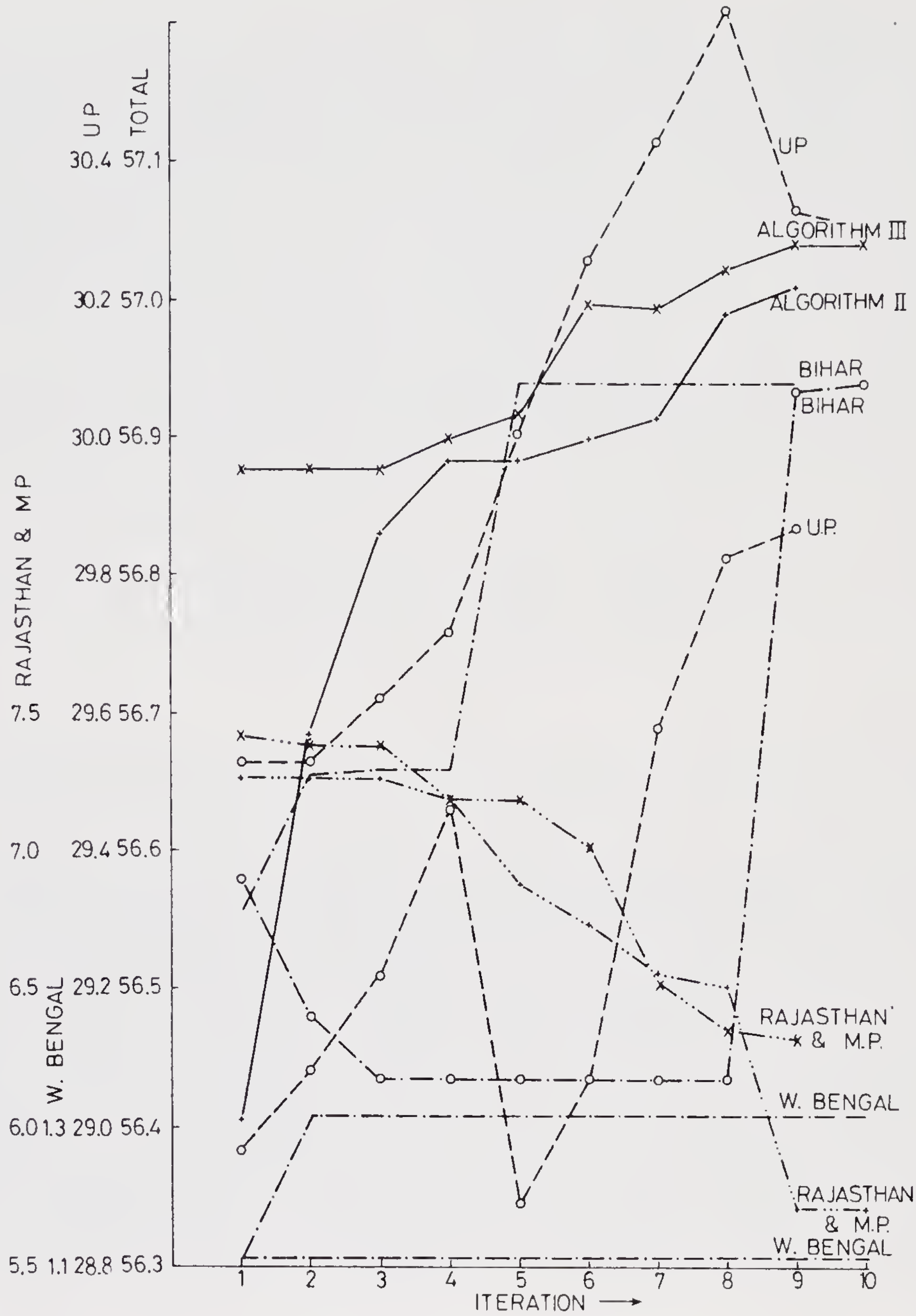

Figure 5. Iteration results of different algorithms.

5.3b *Algorithm III* It proceeded slowly and uneventfully. An effort was made at the eighth iteration to speed up convergence by increasing the third season input to UP by 2000 m cu m rather than the 679 m cu m that was indicated by the range on the shadow price. The attempt was a failure. The value of 2000 was promptly reduced to 679 in the ninth iteration. The progress of the algorithm and final results are summarised in table 2 and figure 5.

6. Conclusions and discussions

The foregoing discussion should illuminate the complications encountered when a

Table 2. Algorithm III: Gross area irrigated (million hectares)

Iteration	Rajasthan and M.P.	U.P.	Bihar	West Bengal	Total
1	7·26	29·53	18·96	1·11	56·86
2	7·26	29·53	18·76	1·32	56·87
3	7·26	29·62	18·67	1·32	56·87
4	7·18	29·72	18·67	1·32	56·89
5	6·87	30·05	18·67	1·32	56·91
6	6·73	30·26	18·67	1·32	56·98
7	6·56	30·43	18·67	1·32	56·98
8	6·51	30·52	18·67	1·32	57·02
9	5·71	30·33	19·67	1·32	57·03
10	5·71	30·31	19·68	1·32	57·02

large river basin is decomposed into sub-problems that are serially coupled to each other. Both of the algorithms that were tested on the Ganga basin model seemed to work adequately, but their limitations, as discussed in § 3, must never be lost sight of. It is not at all certain, for example, that algorithm II would lead to satisfactory solutions within a reasonable number of steps were it applied to a more flexible model than the one used here for the Ganga basin. As has been already suggested, a game-theoretical approach may be applicable here. Future studies should cover the behaviour of the resource allocation algorithm of § 4, and should refine the model by including power generation in the objective functions. The effects of misrepresentation and how it may be precluded by the CG or how the CG can actually force the states to release a certain quantity of water to be used at Farakka should also be studied in detail.

One wonders whether algorithm II or algorithm III is the more socially equitable one. Were they equivalent computationally, the decision to use one or the other should be arrived at jointly by the central and state governments. As Kornai (1973) pointed out, it is unreasonable to expect real world planning processes to follow the confined ways and means of an elegant mathematical algorithm. While the results presented in this paper are numerically correct, the way in which they were arrived at, the iterative process between the CG and SGS, should not be taken too literally. There is so much that the algorithms ignore. Economic and political pressures, corruption, bribery, behind-the-scenes negotiations are all vastly more powerful forces in choosing what the actual allocations will be, than the naive decisions taken by our hypothetical CG based entirely on the computed shadow prices.

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An unconventional approach to integrated ground and surface water development

ROGER REVELLE and V LAKSHMINARAYANA*

Department of Political Science, University of California, San Diego, California 92093, USA

*Department of Civil Engineering, Indian Institute of Technology, Kanpur 208 016, India

Abstract. The conjunctive use of surface water with groundwater development in the Ganga Basin is considered more desirable due to unacceptable environmental conditions created by using all the low flows and the limited possibilities of surface storages. There are several ways to increase infiltration during the monsoon season. One method is to create groundwater storage by pumping during the non-monsoon period. A procedure for estimating the extent and the rate of pumping such that it is replenished in 120 days of the monsoon season and equilibrium is achieved, is outlined in this study. The areas in the Ganga Basin suitable for such groundwater storage schemes have been marked out and the economic aspects of the scheme have also been studied. It is concluded that with this scheme of underground storage of flood water the total potential irrigation in the Ganga Basin may be limited by the area of irrigable land rather than the water supply.

It is suggested that this potentially advantageous scheme should be systematically studied and investigated in detail and factors like sediment transportation which may reduce the infiltration rate, the possible hazards of subsidence due to lowering of the water table, the possible ecological effects, and other relevant issues should also be considered.

Keywords. Groundwater; conjunctive use; surface water; underground water storage.

1. Introduction

The various Ganga models have suggested that large increases in irrigated area are only obtained at the expense of good low flow conditions. Deteriorating low flow conditions would be unacceptable from environmental considerations and are not likely to be accepted by downstream users of the Ganga.

One approach to the problem of the low flow of the Ganga grew out of the work of Revelle & Herman (1972) and Lakshminarayana & Revelle (1975) which has been labelled "The Ganges Machine". It is an approach based on groundwater development in the Ganga basin in conjunction with surface water.

Besides the limited possibilities of surface storage, there are at least five ways in which a portion of the monsoon flow could be stored underground. Infiltration into the water table in the monsoon season could be increased by (i) water spreading in the piedmont deposit north of the Terai belt of the springs and marshes; (ii) constructing bunds at right angles to the flow lines in uncultivated fields to slow down run-off and increase infiltration; (iii) pumping out the underground aquifers during the dry season in the neighbourhood of nullahs (natural drains) which carry water during the monsoon (Rama 1971); (iv) pumping out groundwater during the dry season along certain tributaries of the Ganga to provide space for groundwater; and (v) increasing seepage from irrigation canals during the monsoon season by extending the network of canals, distributaries, and water courses for kharif irrigation and pumping out this seepage water during the dry season. In addition, evaporation losses from the water table might be reduced by lowering it below the level of appreciable evaporation. Finally, it may be beneficial to export some monsoon water from the Basin to areas in the south and the west where irrigation could be extended if firm water supplies were available.

In table 1 we have estimated the likely increase in irrigation water supplies produced by some of these devices. A large increase could be obtained by constructing barrages and "leaky" canal systems for surface irrigation of a large part of the cultivated area, including an increased area of rice cultivation during the kharif season, and wells to recover the underground seepage during the rabi season. Recharge of aquifers along certain Ganga tributaries could provide an equally large increase of rabi irrigation supplies.

There is good reason to believe that in many places the underground aquifers are well-connected to the rivers and are highly permeable. For example, in one region where a groundwater survey was made (Pathak 1969) the seasonal contours of the water table on both sides of a large tributary show that this river is a drain which carries off perhaps $0{\cdot}12 \times 10^6$ ha m of water that seeps into it during the dry months from the underground aquifers. If these contours could be reversed by large-scale pumping of the underground waters in the dry season, the aquifers could receive and store a large

Table 1. Possible future water budget for the Ganga plain

	Volume ($\times 10^6$ ha m) during	
Source or sink	Low flow season (November to June)	High flow season (July to October)
Supplies		
Present average river flow at Bangladesh boundary	7·3	28·9
Evapotranspiration from present surface storage and river diversion (1968–1969)	1·8	1·8
Evapotranspiration from present well irrigation (1968–1969)	1·3	0·7
Additional surface storage (under construction or potential)	1·5	−1·5
Reduction of groundwater evaporation by pumping down watertable	0·8	
Increased infiltration of rainfall by bunding in uncultivated areas	0·7	−0·7
Potential additional underground storage	6·0‡	−6·0‡
Transfers out of basin (such as "Ganga-Cauvery Link")		−1·8
Total supplies	19·4	21·4
Uses and excess flows		
Consumptive use in present irrigation (1968–1969)	3·1	2·5
Consumptive use in potential additional irrigation	9·0	6·0
Diversion to Hooghly River at Farakka Barrage for Calcutta maintenance	2·3‡	
Needs for irrigation in Bangladesh	1·8‡	
River navigation and waste disposal	3·2‡	
Monsoon flow at Bangladesh boundary		12·9*
Total uses and excess flows	19·4	21·4

‡ See text. *Estimated by difference.

part of the monsoon flow of the river. We believe that similar underground storage of river floodwater could be carried out along many tributaries of the Ganges.

It would be necessary to lower the water table at the beginning of the monsoon season to a greater depth than that required simply to produce the storage volume. Moreover, the aquifer directly under the river would need to be pumped down close to the average depth. In the rivers of the western part of the plain, where the dry season flow comes largely from groundwater seeping out of the river banks, the low flow discharge during the first year would be removed by the pumping, and thereafter the river would be virtually dry from November to June. Several years would be required to obtain the full storage potential. Each year the water table at the beginning of the monsoon season would be pumped deeper than the year before, until an equilibrium is ultimately reached.

2. Pumping out groundwater during the low flow season

For a rough estimate we may assume that along 3200 km of the system of the larger tributaries of the Ganga (about a quarter of the total length) large well fields could be constructed which would produce storage space by pumping out the groundwater during the low flow season. With well fields 6 km wide on either side of the river, the area covered would be $3{\cdot}8 \times 10^6$ ha. If we assume that the well field capacity is 2·25 cumecs/km (that is, 1·12 cumecs/km of length on each side of the river) and the storage coefficient of the aquifer is 0·25, then the water table will be lowered, on the average, about 12 m at the end of 8 months of continuous pumping. All the wells need not be of the same capacity. It is necessary only to design the well spacings and discharges in such a way that we pump out a trough of 12 m below the river bed. The method used for finding the depressions of the water table is given below.

The drawdown due to pumping in an aquifer is given by

$$s = \frac{Q}{4\pi T}\int_{r^2S/4Tt}^{\infty} \frac{\exp(-u)}{u}\,du, \tag{1}$$

where the drawdown $s = h_i - h$ (m), h_i is the initial saturated thickness of the aquifer (m), h is the height of the water table during pumping (m), Q is the discharge (m^3/day), T is the coefficient of transmissibility (m^2/day,) S is the storage coefficient (dimensionless), t is time since pumping started (days), and r is the distance from the pumping well (m).

Equation (1) holds strictly only for a confined aquifer which is isotropic and homogenous. However, it can be used for an unconfined water table aquifer (as in the present case) provided drawdown is small compared with the original saturated thickness of the aquifer. In the Ganga plain the aquifers are quite thick, and the drawdown of the water table will be small compared to the initial saturated thickness of the aquifer; consequently, we can apply (1), which also has other assumptions involved in its derivation. Revelle & Herman (1972) showed that although these assumptions are not strictly valid in the present case, the equation can still be used to give a fairly good solution.

Equation (1) is the solution of the differential equation

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t}, \tag{2}$$

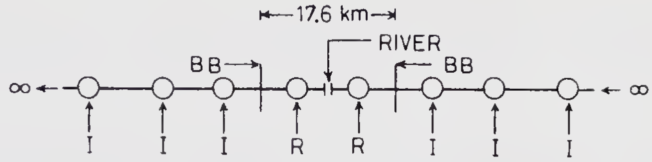

Figure 1. Location of real and image well groups. BB, barrier boundary; R, real well group centre; I, image well group centre

subject to certain simple boundary conditions. Since (2) is linear, the superposition principle can be used to find the solution when more than one well is being pumped in the aquifer. Equation (1) is obtained assuming that the aquifer is really infinite. If we have boundaries, we must use the method of images

In the present calculation we have assumed that there is a natural groundwater divide at a distance of 8 km on either side of the river. This is approximately true for many of the tributaries that feed the main tributaries of the Ganga. The natural groundwater divide acts as an impervious barrier. The presence of the river itself can be ignored in the computations, since during the dry season the quantity of flow in many Ganga tributaries will be small compared to the quantity of pumping. Grouping the wells in pumping centres, we will have the real and image wells shown in figure 1. Because of the assumed existence of an impervious boundary on either side of the river, there will be an infinite number of images. However, only a few need to be considered, since the effect of image wells very far off will be small near the river.

Equation (1) is applied repeatedly for all the real and image wells, and we obtain a lowering of the water table, on the average, of about 12 m at the real wells.

3. Recharge of groundwater mound by monsoon flow

When pumping stops at the end of the dry season there is some flow into the trough from the sides. It is, therefore, assumed that we have a net trough with an average depth of 10 m to be partly filled by monsoon flow in the river.

The growth of the groundwater mound resulting from infiltration of the monsoon flow in the river is computed by using the following equations given by Hantush (1967),

$$h^2 = h_1^2 + \frac{WT}{KS} t\{2 - 4i^2\, Erfc\,(L-x)(4Tt/S)^{-1/2}$$

$$- 4i^2\, Erfc\,(L+x)(4Tt/S)^{-1/2}\} \qquad \text{for } x < L, \tag{3}$$

$$h^2 = h_1^2 + \frac{WT}{KS} t\{4i^2\, Erfc\,(x-L)(4Tt/S)^{-1/2}$$

$$- 4i^2\, Erfc\,(L+x)(4Tt/S)^{-1/2}\} \qquad \text{for } x > L, \tag{4}$$

where the symbols other than the ones already used are: W, recharge rate through the bed of the river (m/day); K, coefficient of the permeability in the aquifer (m/day); t, time during which recharge takes place (days); L, half width of river (m); x, distance from centre of river (m); and

$$Erf(x) = \frac{2}{\pi^{1/2}} \int_0^x \exp(-\xi^2)\, d\xi,$$

$$Erfc(x) = 1 - Erf(x);\ 4i^2\, Erfc(x) = Erfc(x) - 2xiErfc(x).$$

Since (3) and (4) are implicit, a trial and error procedure or a graphical method has to be adopted for the solution. For example, assume $t = 15$ days. Then, using $T = 4650\,\text{m}^2/\text{day}$, $L = 150$ m, $W = 0{\cdot}61$ m/day, $K = 15{\cdot}2$ m/day, $S = 0{\cdot}25$, $h_i = 300$ m, and $t = 15$ days, we get $(4Tt/S)^{\frac{1}{2}} = 1055$ m and $L/(4Tt/S)^{\frac{1}{2}} = 0{\cdot}144$. From (3) we find

$$h^2 = (300)^2 + \left(\frac{0{\cdot}61}{15{\cdot}2} \times \frac{4650}{0{\cdot}25} \times 15\right)(0{\cdot}56) = 96{,}270\,\text{m}^2,$$

Therefore, $h = 310$ m and $h - h_i = 10$ m.

Thus the time for the water to rise 10 m at the centre of the recharging strip is 15 days.

The height of the groundwater at a distance of 600 m from the centre of the river can be computed as follows:

$$(x - L)(4Tt/S)^{-1/2} = 450/1055 = 0{\cdot}43,$$

$$(x + L)(4Tt/S)^{-1/2} = 750/1055 = 0{\cdot}72.$$

Using (4) we obtain

$$h^2 = (300)^2 + \left(\frac{0{\cdot}61}{15{\cdot}2} \times \frac{4650}{0{\cdot}25} \times 15\right)(0{\cdot}35 - 0{\cdot}14) = 92{,}350\,\text{m}^2.$$

Therefore, $h = 303{\cdot}5$ m and $h - h_i = 3{\cdot}5$ m. Similarly at 1500 m, we obtain

$$h^2 = (300)^2 + \left(\frac{0{\cdot}61}{1512} \times \frac{4650}{0{\cdot}25} \times 15\right)(0{\cdot}016 - 0{\cdot}005) = 90{,}123\,\text{m}^2,$$

$$h = 300{\cdot}2\,\text{m} \quad \text{and} \quad h - h_1 = 0{\cdot}2\,\text{m}.$$

Thus, assuming that the rate of recharge is 0·61 m/day, which is rather conservative, the height of the water mound at the end of 15 days will be 3·5 m at a distance of 600 m and 0·2 m at a distance of 1500 m. From this we can compute the quantity of monsoon water abstracted as 1×10^6 ha m. After 15 days there will still be some recharge, because some of the bank flow from the river will continue to fill the trough. Thus, during the first year of operation a little more than 1×10^6 ha m will be extracted from the monsoon flow. When this is spread over the groundwater basin 17·5 km wide, it will raise the water table by 0·75 m. To this we may add a rise of the water table by 0·6 m caused by 15 cm of net rainfall infiltrating to the water table. Thus, at the beginning of the second year of operation the water table will be about 8·6 m below the level at the beginning of the first year.

During the second year of operation, the water table will be lowered by 10 m to a depth of about 18·6 m before the monsoon flow begins. The time taken to raise the water table 18·6 m at the centre of the river bed during the monsoon works out to 33 days. At this time the height of the groundwater mound will be 7·5 m at a distance of 600 m and 1·5 m at a distance of 1500 m. The total quantity of monsoon water extracted will be about 2×10^6 ha m, again ignoring the contribution from bank flow. This will raise the water table by about 1·5 m. Adding about 0·6 m due to infiltration of rainfall, the depth of the water table at the beginning of the dry season in the following year will be 16·5 m below the initial level.

During the third year of operation, this will again be lowered by 10 m, leaving the water table at a depth of about 26·5 m at the beginning of the monsoon. The time taken for the water table under the river to rise 26·5 m is about 70 days. At this time the height of the groundwater mound will be 15 m at a distance of 600 m, 5 m at a distance of 1500 m, and 0 m at a distance of 3000 m. Thus, the amount of water extracted from the monsoon flow, ignoring the contribution from bank flow, will be about 6×10^6 ha m. At the end of the monsoon the water table will be at an average depth of about 22 m over the cross section of 17·5 km.

By similar computation, we can show that during the fourth year of operation the depth of the water table at the end of the pumping season will be 32 m, and in the 120 days of the monsoon season we will extract from the monsoon about 9×10^6 ha m. The depth of the water table at the end of the monsoon will be about 25 m below the initial level 4 years earlier.

From the following year onwards, the water table will be stabilized at these levels by pumping out a quantity equal to consumptive use, surface drainage and return infiltration to the groundwater table.

Figure 2 shows the growth of the groundwater mound under uniform recharge from the river for the stated values of the parameters. Because different scales have been used in the horizontal and vertical directions, the slope of the water table appears to be steep.

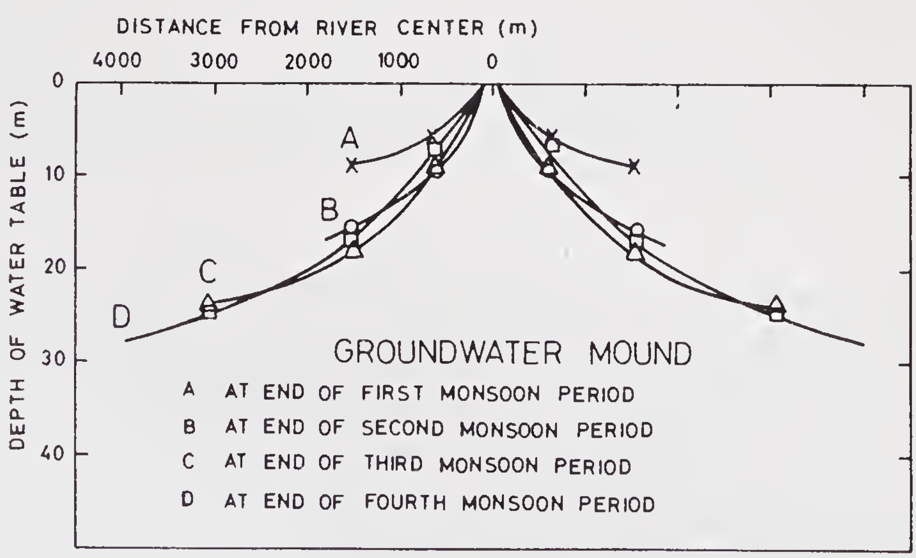

Figure 2. Growth of groundwater mound under uniform recharge from river.

Actually its profile will be very flat. For instance, at the end of the first monsoon period the slope will be approximately 1 to 170; at the end of the fourth monsoon period it will be approximately 1 to 140. We can therefore use the bank storage equations given by Cooper & Rorabaugh (1963) for a horizontal water table, as shown in the next section.

With any particular set of assumed parameters, equilibrium will be reached in the number of years required to lower the water table to a depth such that 120 days (the length of the monsoon season) will be required for the infiltration mound to reach the bed of the river. For example, assuming a storage coefficient of 0·15, a transmissibility of 2800 m^2/day, and a pumping rate of 1·35 cumecs km^{-1}, an equilibrium depth of 35 m at the end of the monsoon season will be reached in about 12 years. From that time onward, 6×10^6 ha m will be stored each year.

During the monsoon season the rivers in northern India always carry some water, with flood peaks occurring after every heavy storm. Thus, even if the duration of the flood wave is short, say 6 to 12 hr in the smaller streams (longer in bigger tributaries), recharge will continue under the lesser flow that prevails before and after its passage. Hence we can assume that about 120 days are always available for recharge during the monsoon season.

4. Advantages of aquifer storage

4.1 *Flood amelioration*

During the flood wave there will be much more bank storage than there is now along the tributaries where the water table has been lowered by pumping. This will supplement the aquifer storage described above in reducing downstream flooding. The amount of bank storage can be computed from the equations of Cooper & Rorabaugh (1963).

Assuming a flood duration of 3 days, a flood crest of 3 m, aquifer transmissibility of 4650 m^2/day, and a storage coefficient of 0·25, the amount of bank storage 2 days after the beginning of the flood will be $2{\cdot}3 \times 10^5$ m^3/km. This temporary bank storage is 50 % of the water entering the aquifer during the same 2-day period; 75 % of the bank storage will return to the river during the following 7 days.

4.2 *Use of stored monsoon waters in irrigation*

The area to be irrigated with the pumped waters would be larger than that of the well fields. Assuming 6×10^6 ha m of storage from the monsoon flow, and adding the rainfall infiltration of 0·15 m, the gross irrigated area would be 17·5 to 19 m ha. Here we assume that an amount of water equal to 10 % of consumptive use by evapotranspiration is allowed for drainage to maintain a salt balance, or alternatively the original dry season flow of the river is returned downstream of the well fields in order to maintain the low flow. If the irrigated areas, including the zone of intense pumping, were located in strips along both sides of the rivers used in the scheme, the average width on each side of the rivers would be roughly 27 to 30 km.

Allowing for 20 % return infiltration of the pumped water, the total pumping from the irrigated area during the dry season is about $10{\cdot}5 \times 10^6$ ha m, requiring a total well capacity of around 5000 cumecs. If the well fields are 6 km wide on either side of the river, more than half the net volume pumped would need to be transported to the outer

21- to 24-km strip in surface conveyance channels. Since unlined channels inevitably leak into the ground a considerable fraction of the water they carry, this surface distribution system could, with proper management, also be used as a groundwater storage mechanism. For example, if the channels extended to the river, they could be used as inundation canals for irrigation during the monsoon season, and 30–50 % of the water carried in them would be expected to seep downward to the aquifer.

5. Possible tributaries for monsoon storage

Table 2 shows possible river reaches along which the underground storage scheme for the monsoon waters might be used, and table 1 shows a possible future water budget for the Ganga plain. It will be seen that in the western tributaries the initial dry-season flow would be about 25 % of the water coming from the rivers into the aquifer. A portion of pumped water would be needed for water supply and waste disposal for cities and towns along these rivers; return flows from irrigation could also be used for waste disposal. In either case, conveyance channels or pipes for the pumped water would be required. In the central and eastern plain, the dry-season flow probably comes largely from the Himalayas and equals 42 to 77 % of the quantity of stored monsoon water. For economy in pumping and ease in maintaining the low flow water supplies for cities and towns, it would probably be desirable to construct diversion barrages upstream of the well fields and lined channels to carry the diverted water downstream of these fields.

Table 2. Possible river reaches for underground storage of monsoon flows

River	Length of well fields (km)	Monsoon flow ($\times 10^6$ ha m)		Dry-season flow ($\times 10^6$ ha m)	Ratio of dry-season to stored flow (%)
		Stored underground	Remaining in river		
Ganga to Yamuna	720	1·3	0·1	0·3	23
Ramganga	560	1·0	0·1	0·2	20
Yamuna system	1440	2·6	0·3	0·7	27
Gomti and Sai	610	1·1	0·1	0·3	27
Gagra, Sarda, and Rapti	1280	2·3	3·2	1·2	52
Son	640	1·2	1·0	0·5	42
Buhri, Gandak and Baghmati	720	1·3	3·2	1·0	77
Below the Kosi, including Mahananda	400	0·7	1·1	0·4	57
Totals	6370	11·5	9·1	4·6	42
Sum of 1 to 4	3330	6·0	0·6	1·5	25
Sum of 5 to 8	3040	5·5	8·5	3·1	56

Note:—Estimated monsoon and dry-season flows are based on UN data.

6. Costs and benefits of the storage scheme

6.1 *Power requirements for pumping stored monsoon waters.*

Assuming an average pumping lift of 30 m, the net electrical energy required to pump $10{\cdot}5 \times 10^6$ ha m would be $8{\cdot}75 \times 10^9$ kWh. With an overall efficiency of 67 % including transmission losses, the energy required at the generating plant would be 13×10^9 kWh, corresponding to an installed power capacity of 3000 MW at 50 % load factor.

The electrical power requirement could be supplied by pit head electric generating plants in the Raniganj-Jharia coal fields in Bihar, or by utilizing a small fraction (possibly less than 15 %) of the enormous potential hydroelectric capacity of Nepal.

All the methods we have described for underground storage of monsoon waters would involve use of electric or diesel power for pumping. Because of the greater depth of pumping, the energy requirements for the river storage scheme would be larger than for other methods, but the ratio of benefits to costs would still be high.

6.2 *Annual costs and benefits of the storage scheme*

At \$0·02 per kWh, the annual power cost would be \$260 million, or about \$14·50 per gross irrigated hectare. At \$0·005 per kWh, the power cost would be \$3·65 per gross irrigated hectare.

Construction costs of tube wells per unit of capacity diminish with increasing well capacity. Compared with larger wells, the maximum cost should be for wells pumping 0·03 cumecs. Assuming that the cost is \$ 10,000 per well, the total cost for 170,000 wells would be \$1·7 billion. Amortized over 10 years at 8 %, the annual costs of well construction would be roughly \$14·00 per gross irrigated hectare. To these fuel and capital costs should be added the cost of land for the tube wells and the drainage conveyance channels, the cost of constructing these channels, and the labour costs for maintenance and operation of the system. With our present information we are unable to estimate these costs, but we believe they should be less than \$15 per year per gross irrigated hectare.

The total annual costs would thus be about \$40 to \$45 per gross irrigated hectare. With adequate water management and proper use of fertilizers and other inputs, it would be possible to obtain high productivity from high-yielding crop varieties on the irrigated fields in contrast to the present yields from traditional varieties, which must be used on unirrigated lands. The gross value of cereal crops would be of the order of \$500 per hectare, ten times the annual costs of irrigation water supplies.

Of equal importance would be the increased food production from the newly irrigated lands. For the entire Ganga plain, the storage of monsoon waters along tributaries by the pumping scheme we have proposed would provide a basis for an increase in production of 55×10^9 kg per year. All storage methods combined, together with increased kharif irrigation from canals, would give more than 110×10^9 kg above present production, enough by itself to provide a greatly improved diet for 400 million people.

In table 1 we estimate that 6×10^6 ha m would be used for irrigation during the kharif season of monsoon rainfall and high river flows. The necessity for irrigation in this season is due both to the large variation from year to year in total monsoon rainfall and to the intraseasonal irregularity of the rainfall. In many areas, water supplies for monsoon irrigation could be obtained by construction of barrages across the Ganga tributaries, which will divert waters into systems of canals, distributaries, and water courses. About 35 to 50 % of this water will seep into the ground and can be used for well irrigation during the dry season. Thus, the possibilities for total underground storage are much larger than our estimates of the storage than can be obtained by pumping out the aquifers along tributaries. The total potential irrigation in the Ganga plain may be limited by the area of irrigable land rather than the water supply.

7. Need for further investigation

The choice between systems for storage of underground water will vary from region to region, and possibly with the stage of development of the integrated system of surface and groundwater irrigation. Further detailed field investigations and systematic analysis are required to determine the choice and sequence of investments for irrigation. Among the factors which should be considered are: the effects of sediment transportation and deposition which might reduce infiltration rates from the rivers, the possible hazards of subsidence resulting from lowering the water table, and possible ecological effects. Special attention should be paid to design and construction of irrigation projects that are compatible with the long-range objectives of storing monsoon waters and maintaining the present volume of flow during the dry season. Projects that are incompatible with these objectives should not be initiated.

Appendix. A Consumptive use of irrigation water

The consumptive uses of irrigation water as of 1968–69 are computed as follows: $4{\cdot}15 \times 10^6$ ha are irrigated from storage reservoirs and canal systems, $1{\cdot}55 \times 10^6$ ha from tanks and other minor surface storage, and $4{\cdot}41 \times 10^6$ ha from wells. This gives a total net irrigated area of $10{\cdot}1 \times 10^6$ ha. Assuming that the depth of water consumed in field evapotranspiration and drainage is 45 cm, 20 % of water diverted for irrigation from large reservoirs and canal systems is lost by evaporation, mainly in the reservoirs, and 90 % is lost from tanks, the total consumptive use is $3{\cdot}6 \times 10^6$ ha m for surface irrigation and 2×10^6 ha m from wells. The allocation of irrigation waters between kharif and rabi seasons is our best estimate based on irrigation practices in the Ganga plain. It is generally recognized that present irrigation supplies are inadequate. In considering modification of present systems and future irrigation, we have assumed that average field evapotranspiration and drainage will be 50 cm, including nonbeneficial uses. For $37{\cdot}5 \times 10^6$ gross irrigated hectares, consumptive use plus other evaporation losses would be about $20{\cdot}6 \times 10^6$ ha m.

The average amount of water evaporating from the water table is probably between 2 and 3 cm. A reduction of 2 cm over an area of 40×10^6 ha might be obtained if the average depth to the water table were lowered by a few metres. This should not seriously interfere with the seepage of groundwaters into the rivers, which is the source of much of the river flows during the dry season. We estimate that construction of a sufficient number of low bunds at right angles to the flow lines in uncultivated areas might increase rainfall infiltration by 10 % or $0{\cdot}7 \times 10^6$ ha m.

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Storage of surface flows through groundwater recharge

M C CHATURVEDI* and V K SRIVASTAVA

*Applied Mechanics Department, Indian Institute of Technology, Hauz Khas, New Delhi 110016, India.

†Raipur Engineering college, Raipur, India.

Abstract. The Ganga basin in India has a serious problem of water availability. The basin, which is only one twelfth of the United States in area, has a population greater than the total US population, and is increasing at a rate of 2·5% per annum. About 77% of the population is engaged in agriculture which is totally dependent on irrigation, as almost 85% of the rainfall comes down in 2–3 monsoon months. Surface storage possibility is extremely limited, but groundwater recharge appears feasible, since sedimentary alluvial formations extend to depths of thousands of metres. Three alternative schemes of groundwater recharge have been proposed. One involves pumping heavily along perennial rivers prior to the monsoon so as to lower the water-table and promote induced groundwater recharge. The second proposes a similar approach along nonperennial rivers. The third involves irrigation during the monsoon with groundwater lowered adequately in the non-monsoon period so that enough induced groundwater recharge takes place to provide adequate supplies for non-monsoon months. A simulation-optimization model has been developed to study the surface flow-groundwater interaction and has been applied to study comparative cost effectiveness of the three alternate approaches. Sensitivity analysis has also been carried out. It is shown that the third scheme is the most attractive.

Keywords. Surface flows; induced groundwater recharge; groundwater simulation; sensitivity analysis; simulation-optimization model.

1. Introduction

The Ganga basin has a serious problem of water availability. Surface storage possibilities are extremely limited but groundwater recharge appears feasible as sedimentary alluvial formations extend to thousands of meters depth.

Of the several ways of groundwater recharge, three schemes of groundwater recharge appear to be particularly promising. The first involves pumping heavily along perennial rivers prior to the monsoons so as to lower the groundwater level to promote induced groundwater recharge. The second proposes a similar approach along non-perennial rivers. The third involves irrigation during monsoons with groundwater lowered adequately in the non-monsoon period so that enough induced groundwater recharge takes place to provide adequate supplies for non-monsoon month requirements.

A simulation-optimization model has been developed to study the surface flow-groundwater interaction and has been applied to study the feasibility and comparative cost-effectiveness of the three alternatives. Sensitivity analysis has also been carried out and the third scheme appears to be the most attractive.

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2. The issue

The water availability in the Ganga basin in India is acute from several considerations. It covers an area about one-twelfth of, and has a population almost that of the U.S.A. or roughly one-tenth of the world's population. The population growth rate of about 2·0% is one of the highest in the world and the GNP per capita of about $100 is one of the lowest. About 77% of the population is engaged in agriculture. The average foodgrain yields of 1000 kg/hectare are low, comparing unfavourably even with yields of 2500 kg/hectare in neighbouring regions of Punjab in India itself or 1800 kg/hectare in China, or 5000 kg/hectare in Japan (Chaturvedi 1976).

Irrigation is crucial for scientific agriculture as over the years there is a long arid period, punctuated by a short monsoon period of heavy rains and floods, when nearly 84% of the rainfall takes place. Storage of monsoon waters is essential but surface storage possibilities are very limited. The plains have, however, alluvial deposits thousands of meters deep. Thus storage of the monsoon waters through induced groundwater recharge is quite feasible. The physiographic and hydrologic features of the basin are shown in figure 1 and figure 2 respectively.

2.1 *Possible alternatives for surface water storage*

Revelle & Herman (1973) suggested storing of monsoon flows of the perennial rivers through induced groundwater recharge by lowering of the groundwater table in the adjoining areas by heavy pumping for irrigation prior to monsoons. A schematic layout of tube wells is shown in figure 3. This has been designated scheme I for induced groundwater recharge along perennial rivers (PR). It may be noted that there is no pumping during the monsoon period. Independently, Rama (1971) had also suggested a similar scheme along non-perennial rivers. This has been designated as scheme II for induced groundwater recharge along non-perennial rivers (NR). A third possibility, suggested by Chaturvedi (Srivastava 1976), is through conjunctive surface irrigation during monsoons and pumped groundwater irrigation during arid winter and summer months. The monsoon irrigation is proposed through unlined canals with the capacity to carry the demanded monsoon irrigation (called kharif) plus surplus water designed to recharge the groundwater. The groundwater pumping in the previous arid months is designed so that the natural rainfall recharge and induced monsoon flow recharge equals the irrigation demand during this period (called rabi). The groundwater level is also a decision variable to be suitably designed to obtain satisfactory induced groundwater quantity and optimal pumped quantity. The monsoon irrigation channels shall be unlined while the non-monsoon channels shall be lined as shown in figure 4. This has been designated scheme III and is called kharif channel conjunctive use (KC). This study relates to the development of a mathematical simulation-optimization model and a comparative cost effectiveness study of the three schemes.

3. The model

Analytically, the problem is of modelling the stream-aquifer response given the stream dimensions, flow specification and pumpage capacities. Next, for several pumpage configurations, the optimal pumping policy has to be determined. On this basis, preliminary selection can be carried out between the three alternative schemes. Having

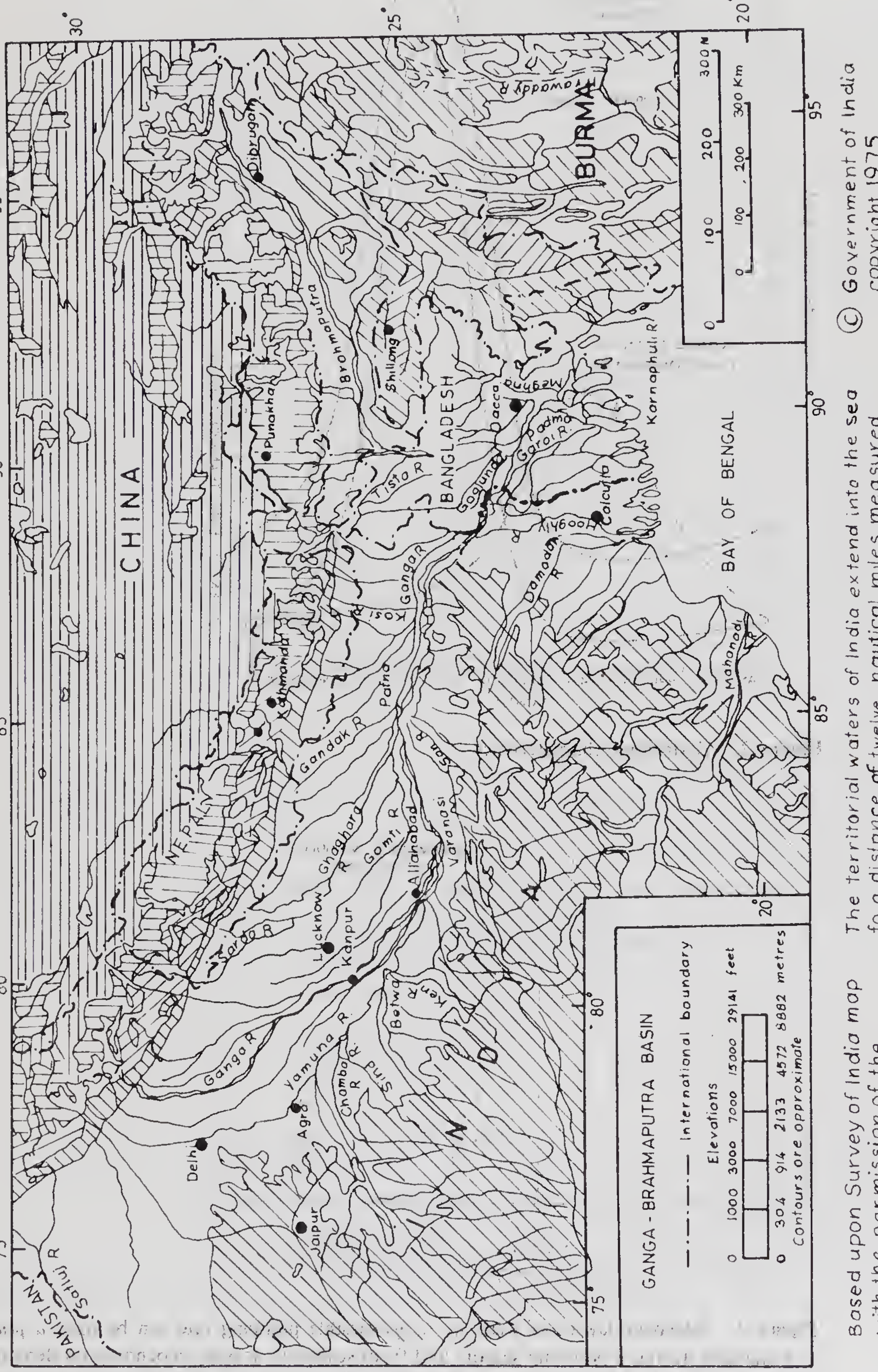

Figure 1. Ganga river basin.

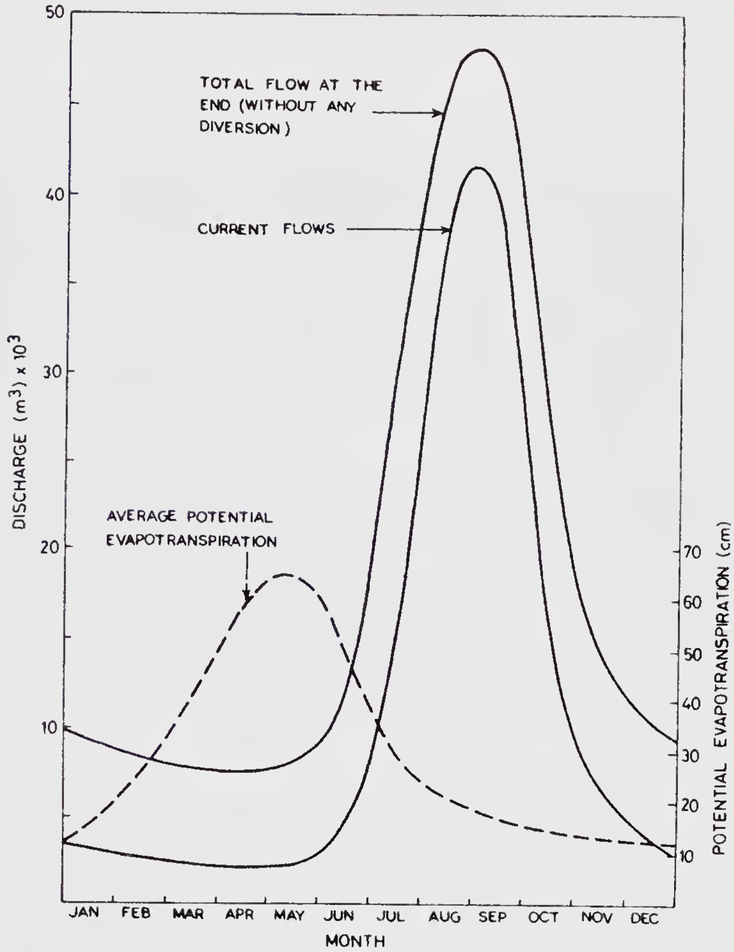

Figure 2. Hydrologic characteristics.

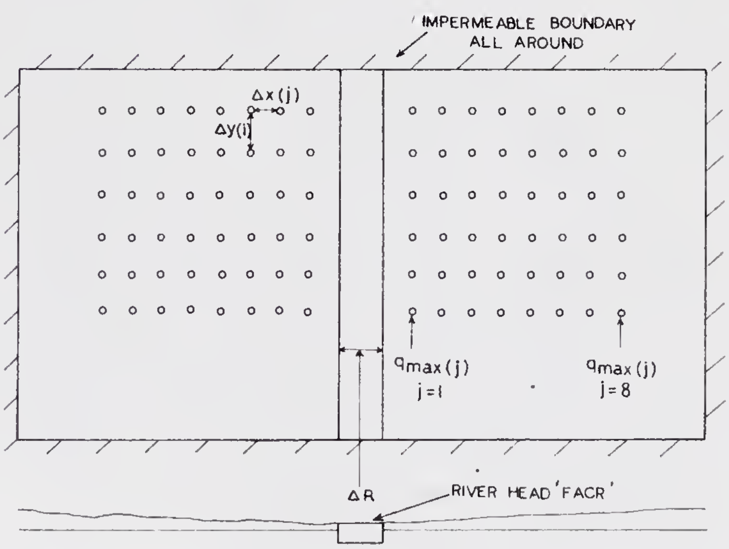

Figure 3. Schematic layout of wells: $q_1 \ldots q_8$-variable pumping rate can be fixed *a priori* and changed during a pumping season, and from season to season, depending on demand; $\Delta x(j)$, $\Delta y(i)$, $\Delta R(j)$-grid spacing in x direction, y direction, and width of river respectively, variable from node to node but fixed during a particular simulation study; FACR-variable but fixed during a pumping period simulated.

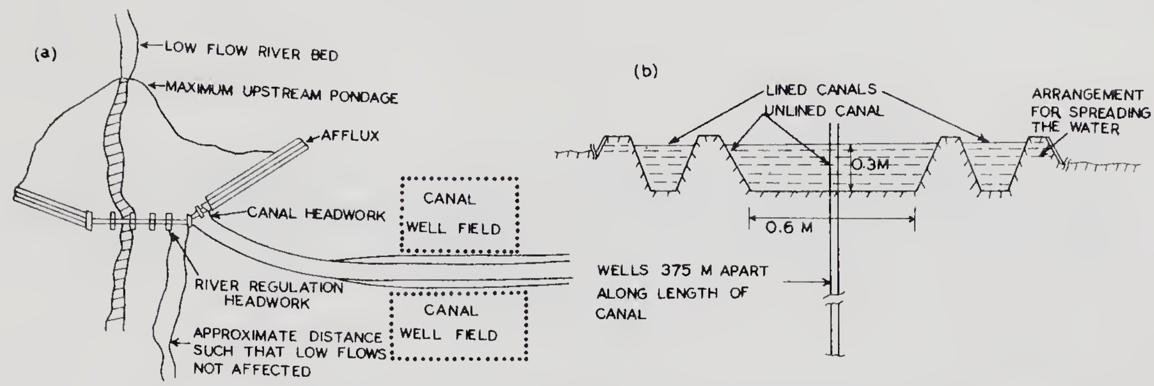

Figure 4. Canal offtake and schematic plan of induced groundwater recharge through kharif canal. a) Plan, b) Section of a typical field distributary.

chosen the preferred candidate system, a second study for optimal system configuration can be designed by having other studies give production functions for various capacity tubewells, or lateral wells, etc. The present study has been confined to the first part only.

Stream aquifer interaction models using the finite difference approach have been developed lately by many researchers (Pinder & Bredehoeft 1968, Maddock 1969; Pinder 1970; Prickett & Lonnquist 1971; Trescott 1973; Bredehoeft & Young 1970; Young & Bredehoeft 1972, etc.). The two techniques which have found favour in the solution of the partial difference equation are the Peacemen & Rachford (1955) and the Duglas & Rachford (1956) alternating direction implicit (ADI) techniques. A number of modifications of the basic ADI method have been devised (Birkhoff *et al* 1962; Wachspress 1965) but have not been used in groundwater modelling. The ADI technique was used in this study.

Mathematical programming models have been coupled to simulation models to determine the optimum policy (Young & Bredehoeft 1972; Maddock 1974). Drawing on earlier work and incorporating suitable features, a simulation-linear programming model was developed by Srivastava (1976) to model the three proposed schemes. The simulation model is essentially as developed by earlier researchers though some improvements in the coupling to a linear programming model, have been made.

The basic equation of motion of water through a porus medium oriented colinear with the principal components of hydraulic conductivity K_{xx} and K_{yx} is,

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t}+Q_{(x,y,t)}-q^1_{(x,y,t)}+q^2_{(x,y,t)} \tag{1}$$

where $T =$ non-homogeneous transmissivity (L^2/T), $h =$ hydraulic head (L), $S =$ coefficient of storage or storativity, $Q_{(x,y,t)} =$ rate of pumping per unit area (L/T) $q^1_{(x,y,t)} =$ rate of leakage from confining layer having storage capability such as leakage from lake or stream bed (L/T), $q^2_{(x,y,t)} =$ rate of evapotranspiration as discharge from water-table aquifer (L/T). The leakage given by Pinder & Bredehoeft (1968) and evapotranspiration given by Trescott (1973) are approximated as follows:

$$q^1 = \frac{k_z}{M}(H_0 - H), \tag{2}$$

where $k_z =$ vertical permeability of the bed (L/T), $M =$ thickness of bed through which leakage takes place (L), $H_0 =$ water-level in the river (L), $H =$ starting level of groundwater table held fixed (L), and

$$q^2 = \frac{k_E}{H_y}(H_y - H_L) \tag{3}$$

where k_E = maximum evapotranspiration rate (L/T), H_y = depth below top of the land surface at which evapotranspiration ceases (L), H_L = depth of water table below the top of the land surface (L). The finite difference equations and solution methodology is given in appendix A. The grid is shown in figure 5.

A simple linear programming model has been formulated with an objective function which optimises the pumping schedule and computes the overall cost of pumping which consists of simulation of the cost of pumping at each individual well. The goal of the basin management authority is the minimisation of the average annual cost of pumping to meet the demand for water. Alternative development solutions to the problems are therefore ranked according to the criteria

$$\min Q = \frac{1}{T}\sum_{t=0}^{t=T}\sum_{j=1}^{N}(h_{(j)} \cdot qw_{(j)})\,\Delta t, \tag{4}$$

in which t is the total pumping period broken up into several parts of Δt over which the objective function is evaluated, N, the number of pumps which exist in a row, $qw_{(j)}$, the pumping rate of pump at jth column node across the direction of flow of the river with the pump nearest to the river being $qw_{(1)}$, h_j, the total pumping head or lift at column node j determined from the aquifer model, and Q, the measure of the average annual net operating cost of pumps.

The objective function is minimized subject to the following constraints:

$$qw_{(j)} \geqslant 0 \quad (j = 1, 2, \ldots, N), \tag{5}$$

in which $qw_{(j)}$ is the pumping rate of the well at column node j in each row, and N is the total number of installed pumps in a row and is the number of independent variables to each of which $q_{(j)}$ as the pumping capacity is assigned. In the cases studied N takes a maximum value of up to 8 pumps in a row.

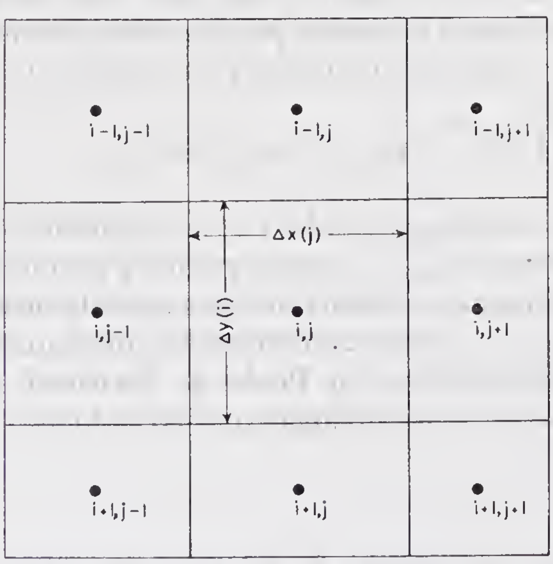

Figure 5. Nodal array for digital model.

Equation 5 has the non-negativity restrictions or constraints

$$qw_{(j)} \leqslant q_{\max(j)}, \tag{6}$$

or

$$q_{\max(j)} - q_{(j)} = 0,$$

in which $q_{\max(j)}$ is the maximum installed capacity of the pump at column node j, which means that the pumping capacity assigned by the linear program solution cannot exceed the installed pumping capacity at that node. Also

$$\sum_{j=1}^{j=N} qw_{(j)} = q_{\text{total}}, \tag{7}$$

in which q_{total} is the maximum pumping rate permitted of producing water, with the combined capacity of all pumps not to produce more than this water for each row of wells being the same for all rows.

Constraints of the type

$$qw_{(j)} \geqslant q_{\min(j)}, \tag{8}$$

or

$$q_{\min(j)} - q_j = 0,$$

in which $q_{\min(j)}$ is the minimum pumping capacity which must be assigned to each group at column node j, have not been considered. The reason for not including such constraints is that a pump which is uneconomical to operate can be shut down or assumed to be non-existent to find the optimal well field geometry. Such constraints can, however, be included by a simple modification of the program to include such a condition when the situation requires it.

It may be noted that the objective ranking function is not an economic function in the usual sense as the monetary value term and discounting function have not been incorporated in it. It is, however, quite adequate for ranking purposes. The generalised flow chart is given in figure 6. The computer listing is given by Srivastava (1976).

4. Analysis

As a preliminary estimate Revelle & Herman (1973) had proposed installing a battery of tubewells of capacity 0·0285 cumecs each at 0·4 km distance, at right angles and parallel to the river. Eight wells on either side were proposed to give the requisite discharge. Considering the river as 0·8 km wide and the nearest point where the wells can be placed as also 0·8 km away from the river bank, we get the total width of 0·8 km on either side with a discharge of 2·25 cumecs per km length of river. The schematic representation of the well field is given in figure 7.

For non-perennial rivers the same scheme (river dimensions) and geo-hydrologic parameter were adopted. Only the water availability time was assumed as 120 or 240 days for two hydrologic conditions. This is not entirely representative as the dimensions will be smaller and flow will not be constant for the entire period. Alternatively, these time periods could be obtained through small storage works. For the perennial river also discharge was assumed constant over the year although flow would vary with time. These alternative details could be modelled but at this stage the objective was only to develop an analytical tool and to get an idea of the comparative and general order of magnitude under the three possible schemes, and their sensitivity

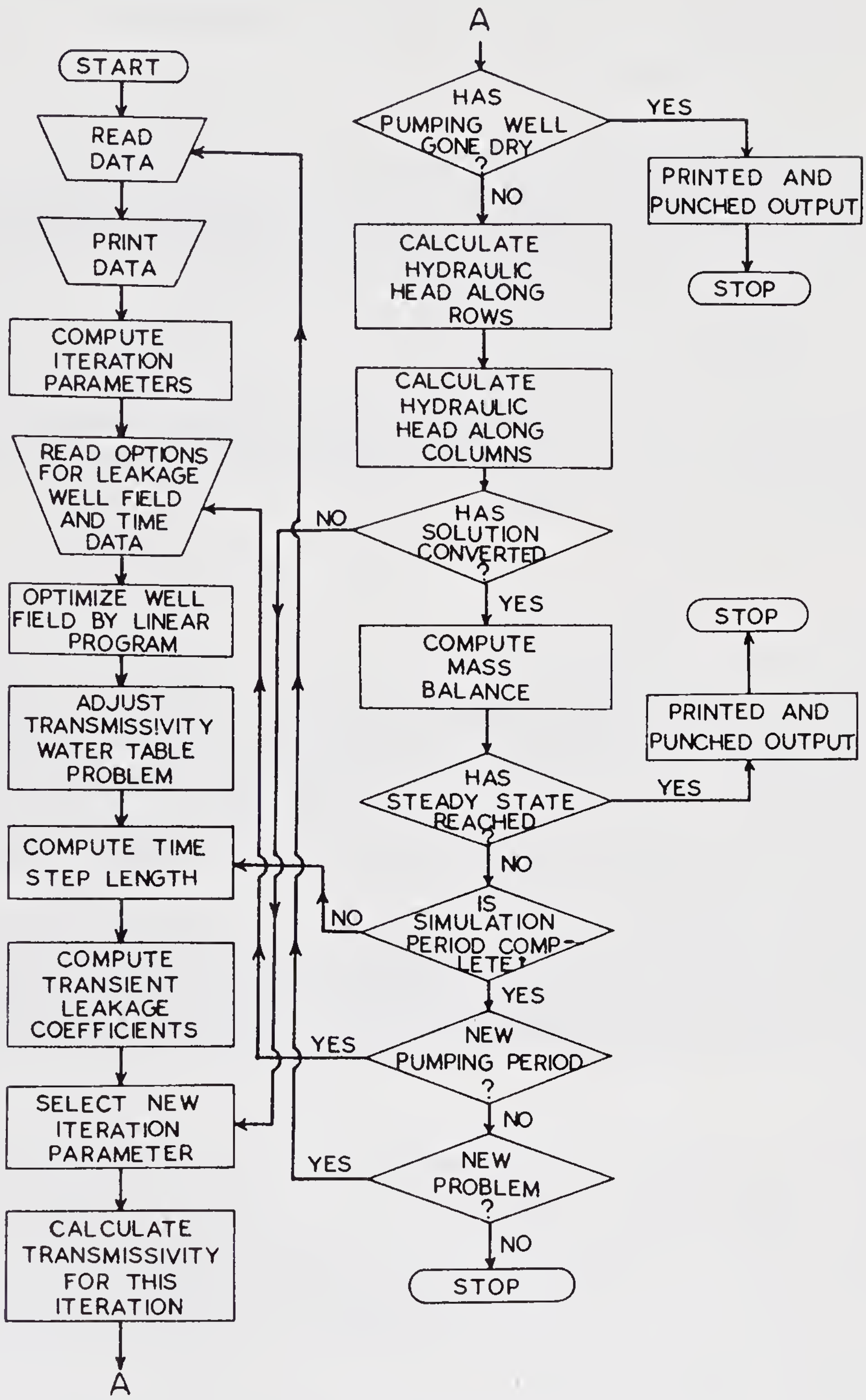

Figure 6. Generalized flow chart for combined hydrologic and economic digital simulation model.

to hydrogeological parameters. Many design improvements can be made. Instead of vertical tubewells radial wells could be used. Duration of water availability in non-perennial streams during monsoon periods could be increased by having some storage structure as stated above. Naturally, these issues were not considered at this stage.

In scheme I (PR), during summer season pumping, some of the low flows can be withdrawn due to heavy pumping along the rivers at this time. These have to be

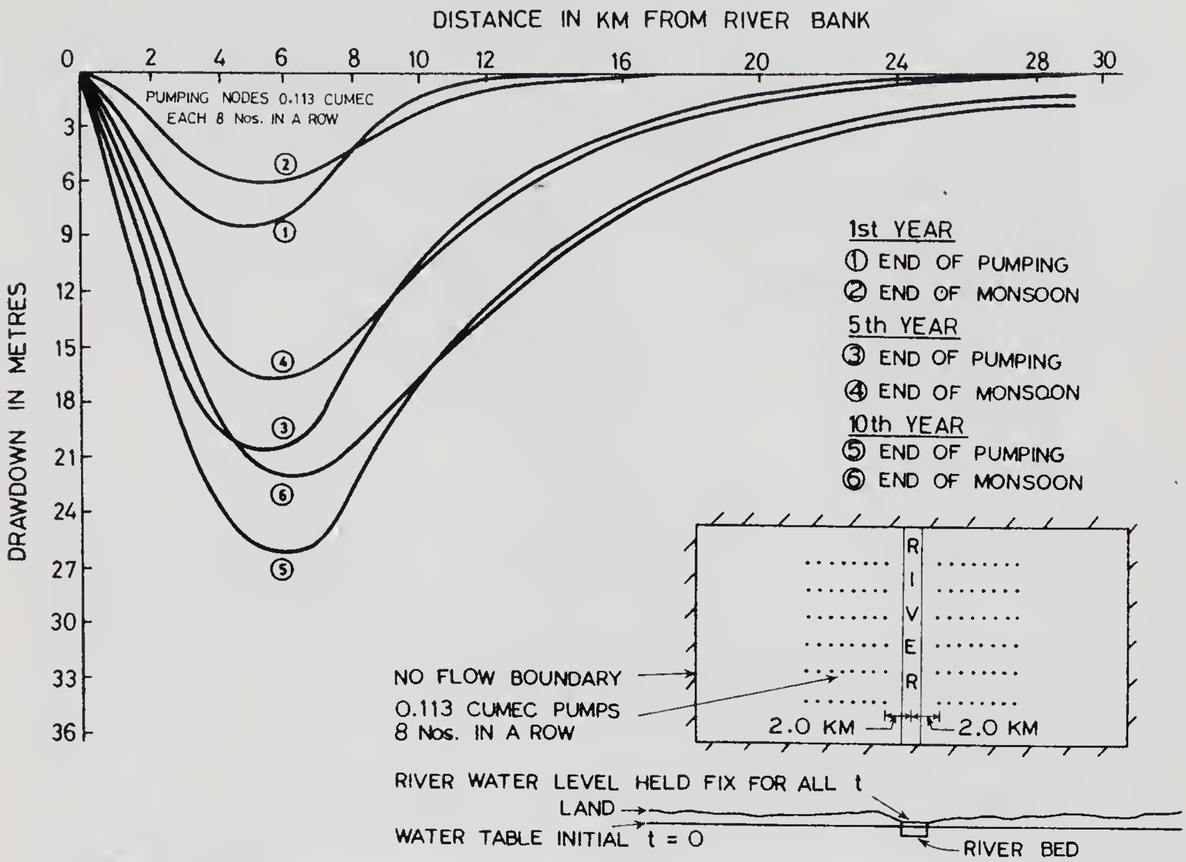

Figure 7. Drawdown with no rainfall recharge for perennial river.

returned and the net utilizable groundwater recharge will be the total withdrawals minus these low flow withdrawals. The low season withdrawals given by the model are on the higher side as real life low flows are almost one-fiftieth of monsoon flows, and the scheme is unfavourably penalised. Further, these low season withdrawals can be completely avoided by having a pumping scheme at a distance from the river on a diversion canal. These issues were not considered at this stage.

The river, aquifer and pumping characteristics for scheme I and II are given in table 1. In scheme III, a typical kharif channel proposed for irrigation will carry a discharge of 0·09 cumecs for kharif requirements of irrigation. If a channel is designed to carry a discharge of an additional 0·056 cumecs during the kharif season of 120 days which will leak into the aquifer which was pumped during the dry season of 240 days, the kharif channel will work as a recharging channel during the kharif season. (Additional discharge for a pumping and recharge season of 180 days will be 0·028 cumecs only).

The objective is to get water at minimum cost. The costs include the cost of conveyance of water to areas needing irrigation. An associated objective is to capture as much monsoon water as possible per unit length (net low flow returns in each perennial case). The issue has multi-objectives but in the first instance we have compared the alternatives from the point of view of cost, developing a design that shall enable us to recharge targeted amounts of water. Conveyance costs were neglected as this did not affect the comparative ranking. The multi-objective analysis has to be in terms of appropriate well field intensity and may be taken up later when more detailed design

Table 1. River, aquifer, pumping characteristics of schemes I and II.

A.	*River*	
	Width	800 m
	Bed thickness	15·3 m
	Hydraulic conductivity	2·5 m per day
	Depth of flow	3 m
	Duration of flow	120 days for non-perennial river
	Specific storage of river bed.	0·0000656 per m.
B.	*Aquifer*	
	Hydraulic conductivity	15·3 m per day
	Specific yield	0·25
	Thickness	305 m
	Initial water table	305 m above impervious datum
C.	*Pumping*	
	Rate of withdrawal	1·25 cumecs/km length of river on either side
	Duration	240 days for non-perennial river; 240 and 180 days for perennial river for reasons discussed later
	Distance between pumps	Grid size 6 × 39 square grid

Table 2. Comparative operating performance of the three schemes.

Type of scheme	Average annual objective function at steady state mm^3/s	Usable water for same quantity pumping ha m $\times 10^3$
Perennial river	64·00	1·680
Non-perennial river	66·40	4·675
Recharging kharif channel	21·03	4·675

Note: (1) Pumping duration 240 days, recharge duration 120 days (2) Total pumping 2·250 cumecs (3) Aquifer parameters same for all three schemes (4) Rainfall recharge not taken into account in any scheme.

analysis is carried out as part of a systems study. For the preliminary comparative analysis the objective function of (4) was used as surrogate for cost. The results of the comparative analysis are shown in table 2. The results show that scheme III, the kharif channel conjunctive scheme, is much more efficient than scheme I or II, *i.e.* the induced groundwater schemes along perennial or non-perennial rivers. On detailed analysis, scheme III will turn out to be even better, as favourable assumptions about availability of water in schemes I and II have been made and conveyance costs will be minimal in scheme III.

Both schemes I and II have almost the same cost for gross induced groundwater recharge but scheme I is comparatively inefficient in terms of conserving the resources and correspondingly uneconomical as the low flow seasons are diverted and have to be returned in scheme I. These figures are only indicative as scheme I is penalised and scheme II is favourably supported. The low flow diversions will be much less as flow breadth and depth will be much less during this period than what is assumed. On the other hand, much more pumping will be required in scheme II as flow dimensions and availability period corresponding to scheme I during monsoons shall not be available unless storage structures are constructed which will naturally increase the unit cost. Creative solutions for scheme I are also possible for increasing the efficiency by pumping along diversions. Therefore, for taking decisions more detailed hydrologic, hydraulic and engineering-economic analyses are needed. Furthermore, these schemes are not mutually exclusive.

The important issue of long-term salt-balance has not been analysed in this case and must be studied in any further study. Reference may therefore be made to the classic study of the Indus basin by the Harvard group (Thomas & Burden 1965).

5. Sensitivity analysis

Analysis has been carried out for a range of configurations and parameters in each of these three cases to get an idea of the dynamics of the system. Some of the results for scheme I are given in table 3. First, keeping the capacity constant, what is the effect of the location of the wells? It is seen that the optimal case has two tubewells near the river. Based on this result, radial wells appear to be attractive. Secondly, for the perennial case net usable groundwater recharge increases, but at increased unit cost for a spread out field. The implication is that if pumps are proposed to be spread out along the length of the river to reduce groundwater lowering, there is a corresponding penalty in the increased lateral dimension to maintain unit availability per unit length of river. Thirdly, increased pumping time increases unit costs as drawdown increases while groundwater recharge decreases, as proportionately larger amounts of water have to be returned during the low flow season. Similar studies have also been carried out for the other two schemes.

The sensitivity of the objective function to change in the aquifer parameters was also carried out for each of these three cases. For one case, *viz* the non-perennial case, the results are shown in table 4.

The changes for other cases are of the same order of magnitude. It will be seen that the objective function is most sensitive to changes in aquifer hydraulic conductivity, next to the specific yield, and comparatively insensitive to river bed hydraulic conductivity.

The drawdown, yearly recharge and pumped withdrawal per kilometre length of river for some of the configuration and aquifer parameters are shown in figure 13.

Figure 7 shows that drawdown varies spatially and temporarily for a given configuration. No rainfall recharge was assumed. The specific yield value adopted was 0.25. If a different value of specific yield or additional rainfall recharge is adopted general characteristics remain the same and only the drawdowns vary.

For a specific yield of 0·1 the drawdown at the end of the tenth year changed from 26 to 35 metres while with normal rainfall recharge of 15 cm annually, the drawdown at the tenth year was changed only marginally to 23 from 26 metres. The yearly recharge and pumped withdrawal per kilometer length of river is shown in figure 8. It will be seen that a steady state is not reached even after 10 years. The drawdown will go down further and objective function worsen, apparently asymptotically. Even if normal rainfall recharge is taken into account, although the yearly recharge is increased, a steady state is not reached after 10 years. However, if the value of the specific yield was 0·25, steady state would be reached with normal rainfall recharge in about 10 years.

The effect of well configuration has also been studied by replacing eight wells by only

Table 3. Alternative operating configuration and policy for perennial river.

Run Number	Starting-end node from bank of river of first-last pump.	No. of wells	Average objective function mm^3/s	Usable water per km ha m $\times 10^3$	Percent of usable water: Monsoon diversion	Percent of usable water: Rainfall recharge	Remarks
A. *Pumping period* 180 *days from end of monsoon. Specific yield* 0·25							
1.	2–2	1	40·2	1·616	66·2	33·8	Steady state reached in 10 yrs
2.*	2–3	2	39·6	1·780	68·0	32·0	Steady state reached in 10 yrs
3.	2–5	4	42·5	2·000	53·2	34·0	Steady state not reached by 10th yr
4.	2–9	8	49·5	2·250	44·2	38·8	Steady state not reached by 10th yr
B. *Pumping period* 240 *days from end of monsoon. Specific yield same as above.*							
5.	2–2	1	56·8	1·342	59·3	40·7	Steady state reached in 10 yrs
6.	2–3	2	58·0	1·487	61·5	38·5	Steady state reached in 10 yrs
7.	2–5	4	64·0	1·680	60·8	39·2	Steady state not reached by 10th yr
8.	2–9	8	76·0	2·070	39·0	38·35	Steady state not reached by 10th yr
C. *Pumping period same as above, specific yield* 0·1							
9.	2–2	1	61·6	1·356	59·60	40·4	Steady state reached in 5 yrs
10.	2–3	2	63·1	1·500	55·30	44·7	Steady state reached in 5 yrs

Note: 1. Aquifer hydraulic conductivity 15·2 m per day. River bed vertical hydraulic conductivity 2·5 m per day.
* Probable optimal operating policy and well field configuration.

Table 4. Sensitivity of objective function to changes in aquifer parameters for non-perennial rivers

Specific yield	Aquifer hydraulic conductivity (m/day)	River bed hydraulic conductivity (m/day)	Average objective function (m m³/s)	Remarks
0·1	15·2	2·5	120·0	Well field geometry, operating policy, and other specifications remain constant.
0·25	15·2	2·5	82·3	
0·1	22·8	2·5	93·8	
0·1	22·8	3·75	93·6	

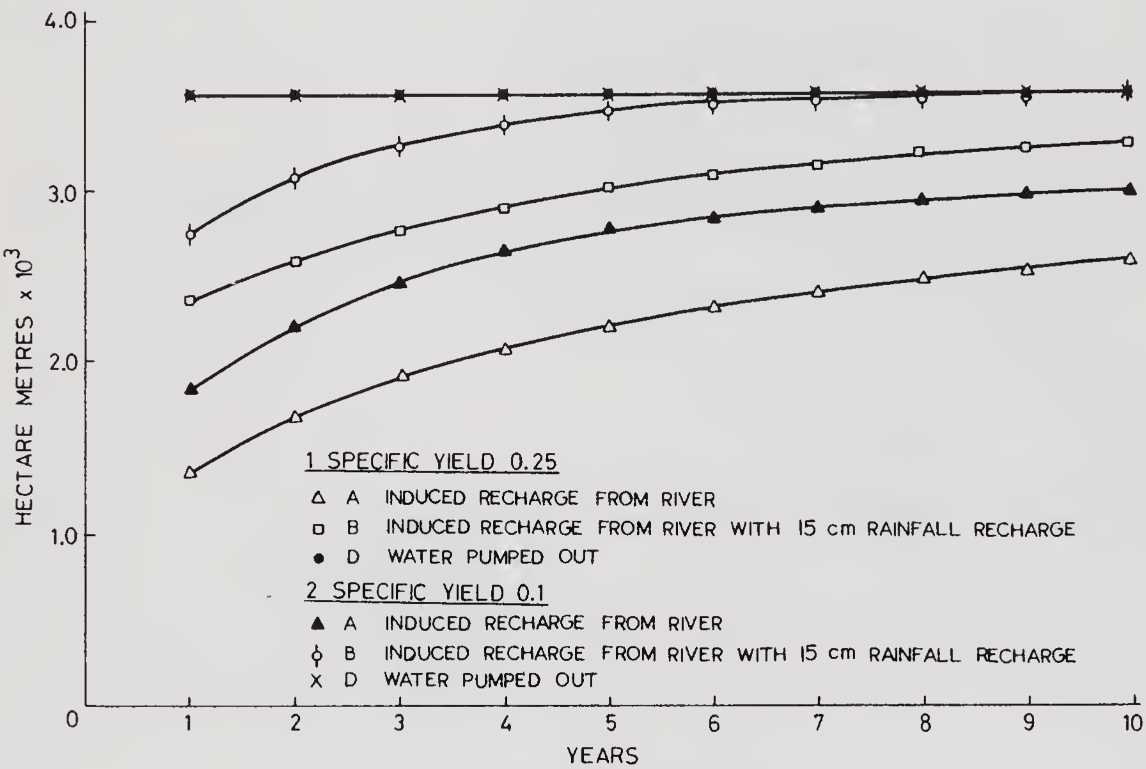

Figure 8. Yearly recharge and pumped withdrawal per kilometer length of perennial river.

one well of equivalent capacity. The drawdown with rainfall recharge in this case is shown in figure 9. The corresponding values of objective function and induced groundwater recharge have been given in table 3. Obviously, in actual designs appropriate configurations dependent on geophysical characteristics and natural as well as engineered hydrological conditions would have to be developed.

Corresponding to the conditions of the perennial case presented in figures 7 and 8, the response for the non-perennial case is shown in figures 10 and 11, respectively. Although the annual recharge was much higher than in scheme I, the steady state was far from being obtained even after 10 years. The implication is that the objective function is going to be worse than that shown in table 2.

The corresponding figures for scheme III, the kharif channel, are shown in figures 12 and 13 respectively. It is to be noted that the pumps installed are of very low pumping

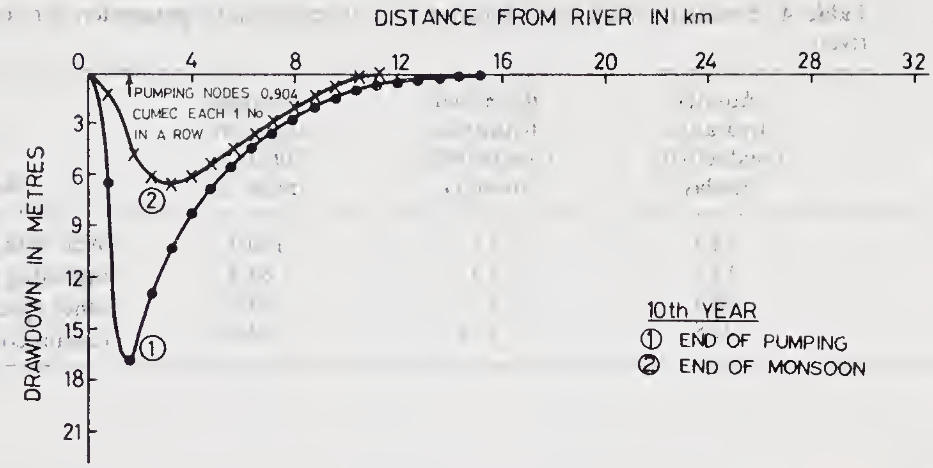

Figure 9. Drawdown with rainfall recharge for perennial river.

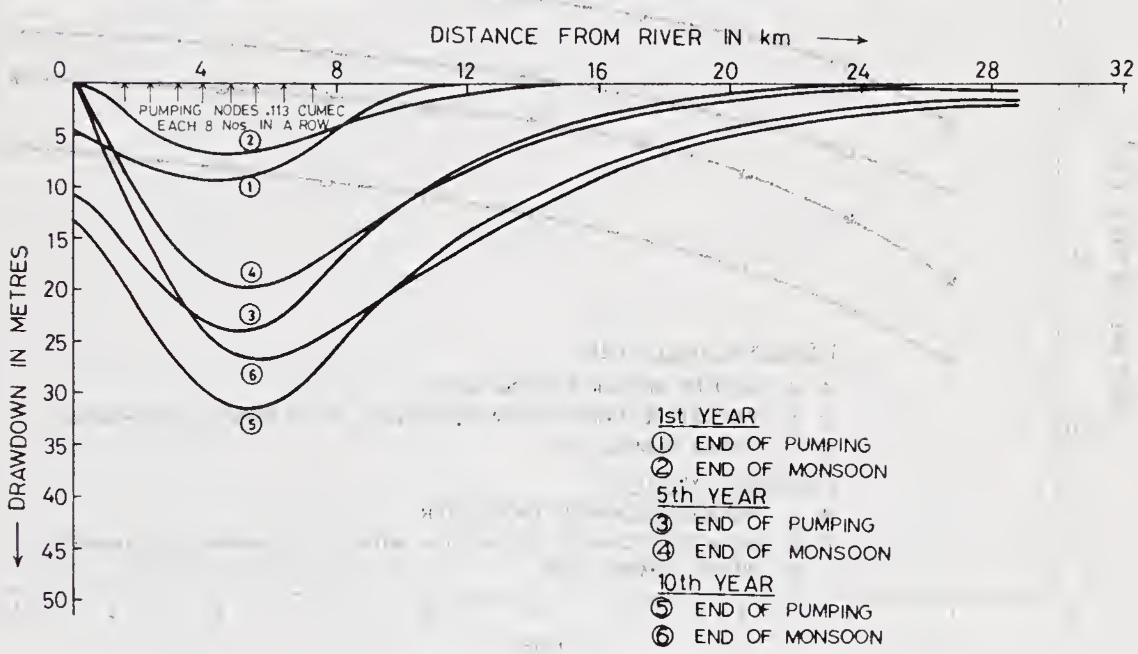

Figure 10. Non-perennial river drawdown with no rainfall recharge.

capacity and uniformly spread over the whole area and therefore the water table goes down uniformly all over the aquifer due to the pumping stress. The drawdown, therefore, is a horizontal line in all cases at the end of both pumping and the recharge cycle. Steady state is reached, in contrast to the earlier two schemes, within five years.

6. Conclusion

The study is exploratory. An aquifer-stream flow interaction simulation-linear programming model has been developed. Order of magnitude behaviour for three schemes designed to conserve the monsoon flows in the Ganges basin by induced groundwater recharge and the sensitivity to engineering decisions, hydrogeological parameters and hydrological conditions has been quantified. Technical feasibility of storage of large monsoon flows has been demonstrated.

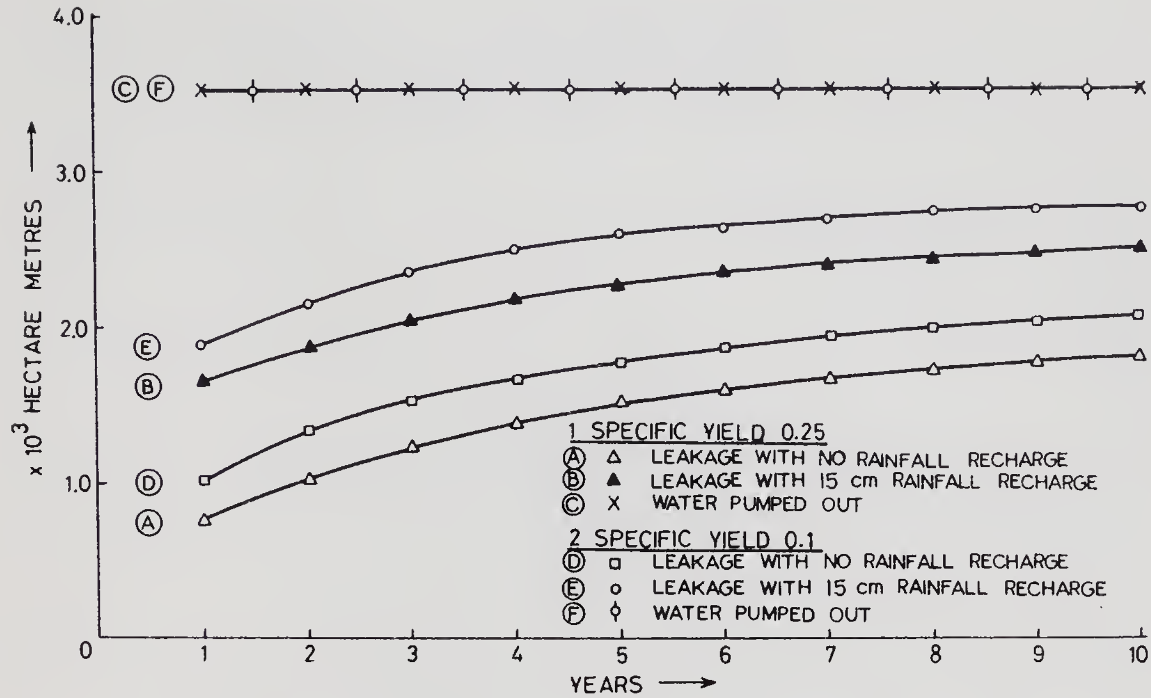

Figure 11. Yearly recharge and pumped withdrawal per kilometre length of non-perennial river.

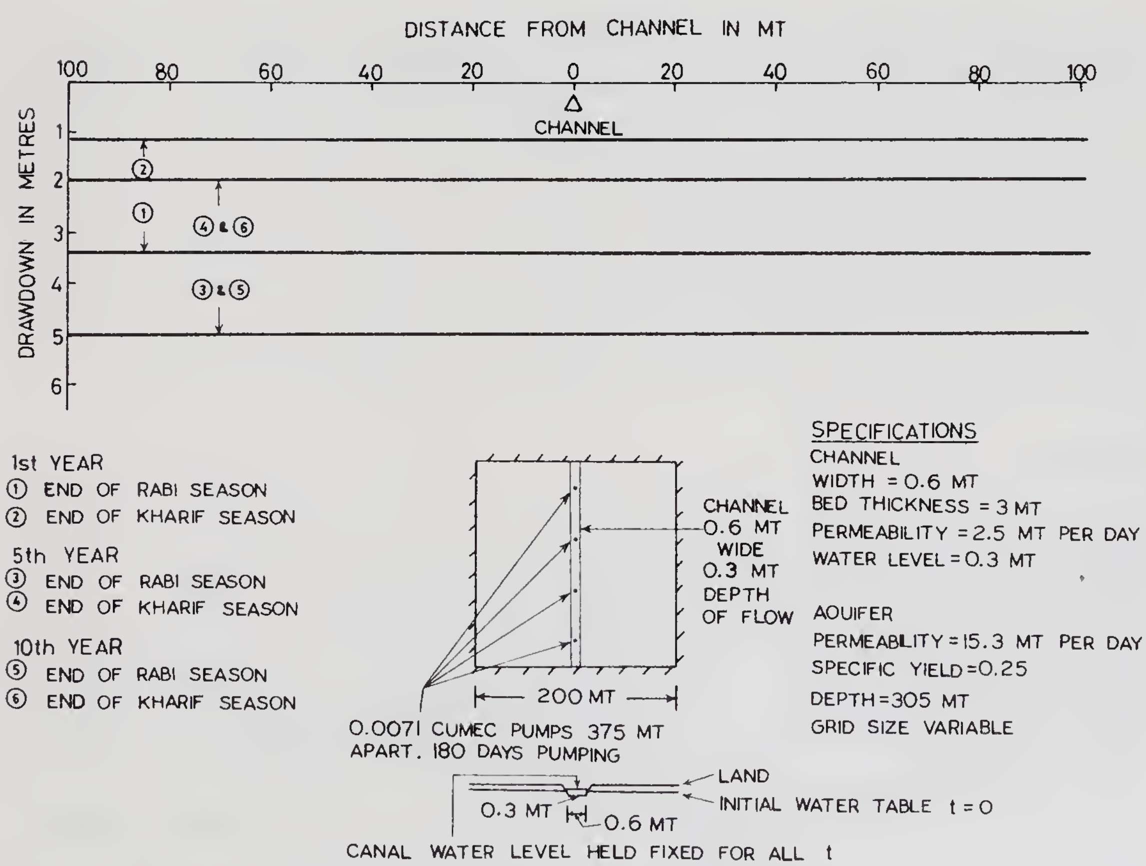

Figure 12. Drawdown with recharge during kharif season and pumping during rabi season.

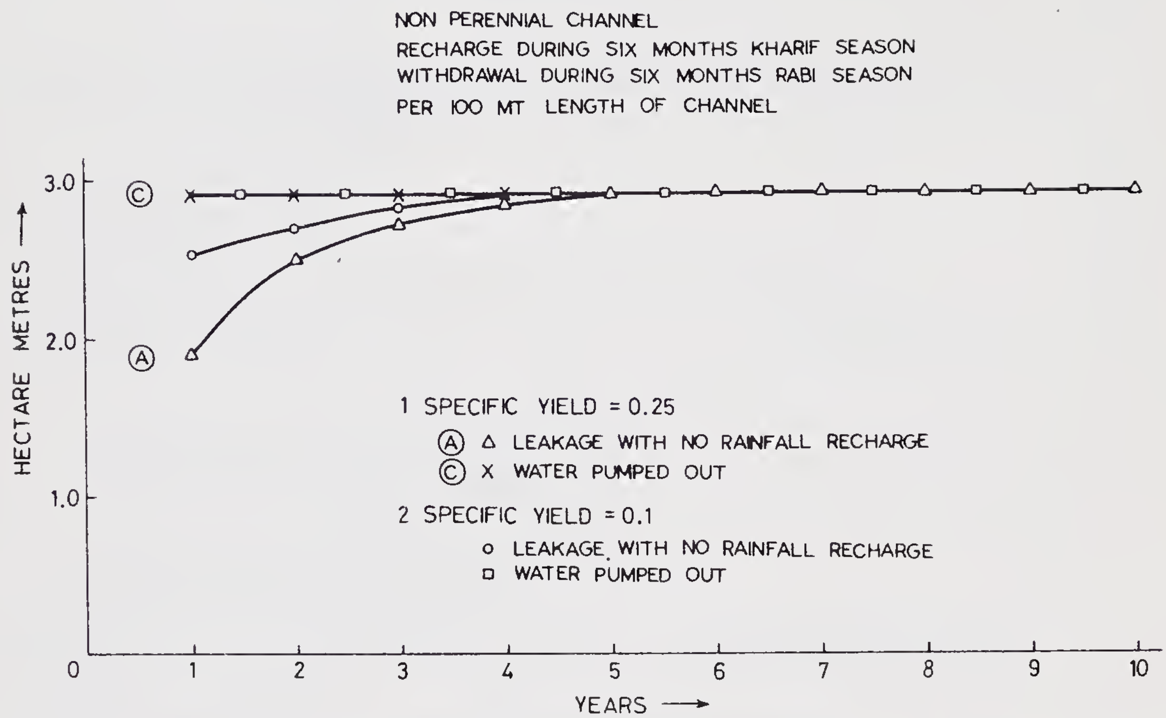

Figure 13. Yearly recharge and pumped withdrawal per kilometre length of non-perennial river.

Economic feasibility is a matter of detailed systems planning and design. Of the three schemes, the third, *viz* kharif channel conjunctive groundwater development appears to be very attractive. The schemes are not mutually exclusive and their choice depends upon general hydrologic-physiographic situations. For instance, in the three continuous areas of the Indo-Gangetic basin, each has some advantage over the other. In Punjab, at the western end where all the perennial river flows have been stored, scheme II is being explored. In Uttar Pradesh and Bihar, *viz.*, the western and central Ganges basin, where even after conserving all possible monsoon flows considerable excess supplies shall be left over, scheme III or I is being proposed for adoption. In Haryana, in the south-west, where groundwaters are saline, scheme II is being proposed.

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Appendix A. Finite difference formulation and solution methodology

The discretization of the basic equation of motion leads to the finite difference equation

$$T_{xx}|i-\tfrac{1}{2}j|\left|\frac{h_{i-1jk}-h_{ijk}}{(\Delta x)^2}\right|+T_{xx|i+\frac{1}{2}j|}\left|\frac{h_{i+1jk}-h_{ijk}}{(\Delta x)^2}\right|$$
$$+T_{yy|ij-\frac{1}{2}|}\left|\frac{h_{ij-1k}-h_{ijk}}{(\Delta y)^2}\right|+T_{yy|ij+\frac{1}{2}|}\left|\frac{h_{ij+1k}-h_{ijk}}{(\Delta y)^2}\right|$$
$$= S\left|\frac{h_{ijk}\,h_{ijk-1}}{\Delta t}\right|+\left|\frac{Q_{ijk}}{\Delta x\,\Delta y}\right|-q^1_{ijk}+q^2_{ijk} \tag{A.1}$$

for a rectangular grid, as shown in figure 5.

The index k represents the kth time step and i and j represent row and column respectively to produce the discretized form. The index i represents the discrete form of y and j represents the discrete form of x.

Half-node expansions of transmissivity variable are defined as given by Saul'yev (1964).

$$T_{|i-\frac{1}{2}j|}=\frac{T_{|i-1j|}+T_{|ij|}}{2}, \tag{A.2}$$

$$T_{|i+\frac{1}{2}j|}=\frac{T_{|i+1j|}+T_{|ij|}}{2}, \tag{A.3}$$

$$T_{|ij-\frac{1}{2}|}=\frac{T_{|ij-1|}+T_{|ij|}}{2} \tag{A.4}$$

$$T_{|ij+\frac{1}{2}|}=\frac{T_{|ij+1|}+T_{|ij|}}{2} \tag{A.5}$$

The finite difference form of (A.2) and (A.3) become

$$q^1_{|ijk|}=\frac{k_{Z|ij|}}{M_{|ij|}}\left[H_0-H_{|ijk|}\right] \tag{A.6}$$

and

$$q^2_{|ijk|}=\frac{k_E}{H_y}\left[H_y-H_{L|ijk|}\right] \tag{A.7}$$

An ADI procedure is used to solve the equation after substituting the discretized values of the various terms of (A.4). An iterative procedure used by Ruben (1968) is used to increase the accuracy of the method. Application of these techniques to (A.4) leads to two new equations.

$$\frac{T_{xx|i-\frac{1}{2}j|}}{(\Delta x)^2} h_{i-1jk}^{(n+1)} - \left[\frac{T_{xx|i-\frac{1}{2}j|}}{(\Delta x)^2} + \frac{T_{xx|i+\frac{1}{2}j|}}{(\Delta x)^2} + \frac{S}{\Delta t} - I_{|ij|}^{(n)}\right] h_{ijk}^{(n+1)} + \frac{T_{xx|i+\frac{1}{2}|}}{(\Delta x)^2} h_{i+1jk}^{(n+1)}$$

$$= \frac{T_{yy|ij-\frac{1}{2}|}}{(\Delta y)^2} h_{ij-1k-1}^{(n)} + \left[\frac{T_{yy|ij-\frac{1}{2}|}}{(\Delta y)^2} + \frac{T_{yy|ij+\frac{1}{2}|}}{(\Delta y)^2} - \frac{S}{\Delta t} I_{|ij|}^{(n)}\right] h_{ijk-1}^{(n)}$$

$$+ \frac{T_{yy|ij+\frac{1}{2}|}}{(\Delta y)^2} h_{ij+1k-1} + \frac{Q_{ijk}}{\Delta x\, \Delta y} - q_{ijk}^1 + q_{ijk}^2 \tag{A.8}$$

and

$$\frac{T_{xx|ij-\frac{1}{2}|}}{(\Delta x)^2} h_{ij-1k}^{(n+1)} - \left[\frac{T_{xx|ij-\frac{1}{2}|}}{(\Delta x)^2} + \frac{T_{xx|ij+\frac{1}{2}|}}{(\Delta x)^2} + \frac{S}{\Delta t} - I_{|ij|}^{(n)}\right] h_{ijk}^{(n+1)}$$

$$+ \frac{T_{xx|ij+\frac{1}{2}|}}{(\Delta x)^2} h_{ij+1k}^{(n+1)} = \frac{T_{yy|i-\frac{1}{2}j|}}{(\Delta y)^2} h_{i-1jk-1}^{(n)} + \left[\frac{T_{yy|i-\frac{1}{2}j|}}{(\Delta y)^2} + \frac{T_{yy|i+\frac{1}{2}|}}{(\Delta y)^2} - \frac{S}{\Delta t} - I_{|ij|}^{(n)}\right] h_{ijk-1}^{(n)}$$

$$+ \frac{T_{yy|i+\frac{1}{2}j|}}{(\Delta y)^2} h_{i+1jk-1}^{(n)} + \frac{Q_{ijk}}{\Delta x\, \Delta y} - q_{ijk}^1 + q_{ijk}^2 \tag{A.9}$$

In (A.8) and (A.9) $I_{ij}^{(n)}$ denotes the iteration parameter at the ith and jth node point and is defined by Pinder & Bredehoeft (1970) as

$$I_{ij}^{(n)} = I_{ij}^{(10)} \exp\left[l_n \frac{2X_m}{\pi} \Big/ (\lambda - 1)\right],$$

where λ is the number of iteration parameters desired. X_m is the larger of the total number of rows and columns in the grid and

$$I^{(i)} = \frac{\pi^2}{2X_m^2} \cdot \frac{1}{1 + \dfrac{(\Delta x)^2}{(\Delta y)^2}} \left[T_{|i-\frac{1}{2}j|} + T_{|i+\frac{1}{2}j|} + T_{|ij-\frac{1}{2}|} + T_{|ij+\frac{1}{2}|}\right],$$

where Δx is maximum grid spacing and Δy is minimum grid spacing given by Trescott (1973).

Known values are on the right side of (A.8) and (A.9). For the imposed grid, (A.8) and (A.9) form two systems of linear equations. The first set represents the row values with column values held fixed and the second set represents the column values with row values held fixed. The values of $h_{ijk-1}^{(n)}$ and $h_{ijk}^{(n+1)}$ are compared for all i's and j's. If the absolute value of their difference is less than some convergence factor ε the time-increment counter k is advanced to $k+1$; if not, the iterative parameter index n is advanced and k remains fixed, until convergence is achieved. The time duration Δt may be large with iterative procedure. The program has two options on the time either to simulate a given number of time steps or to simulate a given pumping period.

The transmissivity is computed at each iteration as product of saturated thickness and hydraulic conductivity at each node. The program is set up to terminate computations when a pumping well "goes dry". For nodes that go dry other than pumping nodes a saturated thickness of 0·305 m (on an empirical basis) is maintained so that a saturated layer is maintained at the top and the unsaturated region is not introduced. The program also has the facility of multiple pumping periods.

The program is set up to terminate computations to save computer time when the solution approaches steady state long before the end of the pumping period. Withdrawal from a well node is assumed to occur over the area of influence of the well node. Drawdown at a pumping node, therefore, is considerably less than would be observed in a real well. The real well drawdown can be predicted by plotting drawdown *versus* the log of distance for nodes near the pumping node (excluding those directions in which other wells are within two nodes) and extrapolating to the radius of a real well. Alternatively, these data can be used in the Theim equation to calculate the additional drawdown in a fully penetrating real well.

Two major assumptions are made in treating the leakage from the multiple pumping periods. Dimensionless time for the previous pumping period is assumed to be so large that storage in the confining bed has a negligible effect on the leakage from this period. For a real problem involving pumping periods of months to years in length this is a reasonable assumption. Rainfall infiltration recharge is treated as pumping into the aquifer. A check is provided that the water table does not rise above the top of the aquifer during computation. If very high recharge rate from rainfall is assumed the program will not allow the water-table to rise above the top of the aquifer in such cases. The water level in the source, from which leakage takes place, can be changed over various pumping periods to simulate the real situations over long pumping periods and the effect of leakage is included implicitly.

The grid spacing in the two directions can be different and quite large. However, smaller grid spacing and shorter time periods will give better results.

Study of Bhakra reservoir operation

P S RAO* and S RAMASESHAN†

* Indian Institute of Management, Bannerghatta Road, Bangalore 560076, India

† Civil Engineering Department, Indian Institute of Technology, Kanpur 208016, India.

Abstract. The study outlines the methodology for working out a multiobjective reservoir operation with conjunctive utilization of surface and groundwater. Irrigation and power have been considered the two objectives for operation of the reservoir. The results of this study are compared with those achieved with conventional operation in the past and show that there is an increase in irrigation by 7 to 8% due to conjunctive use of surface and groundwater. The trade-off between irrigation and power has been developed and discussed. The transformation surface between three objectives *viz.*, power, irrigation and carry-over storage has been developed and the merits of carry-over storage have been discussed.

Keywords. Reservoir operation; multiobjective analysis; conjunctive use of water.

1. Introduction

Irrigation and power are two of the most important purposes for which surface and groundwater resources are used. The integrated operation of a complex system is necessary for efficient management of limited resources to meet irrigation and power demands. The importance of the conjunctive utilization of surface and groundwater in an integrated framework has been realised (Irrigation Commission 1972) but has not been put into practice perhaps due to institutional constraints and lack of coordination. However, using a systems analysis procedure it seems possible to study the integrated operation of a multiobjective reservoir system with conjunctive utilization of surface and groundwater. A case study of the Bhakra reservoir, which has been in operation since 1966 is described in this paper. The object of this study is to analyse the past operation of the reservoir within a multiobjective framework to evaluate the trade-offs between irrigation and power demands in the past. The study also demonstrates the methodology and procedures in multiobjective analysis within an integrated framework.

2. System description

2.1 *The Bhakra*

The Bhakra system in Punjab constitutes one of India's biggest projects (figure 1). The Bhakra dam is a 225·55 m high concrete gravity dam built on the river Sutlej. The river, the largest tributary of the river Indus, begins in Tibet and enters the Indo-Gangetic plains near Bhakra. The total catchment area upstream of Bhakra is 56,980 km^2. The rainfall in the catchment varies over the basin with an annual average of around 875 mm. Govindsagar, the reservoir formed by the Bhakra dam, has a gross capacity of

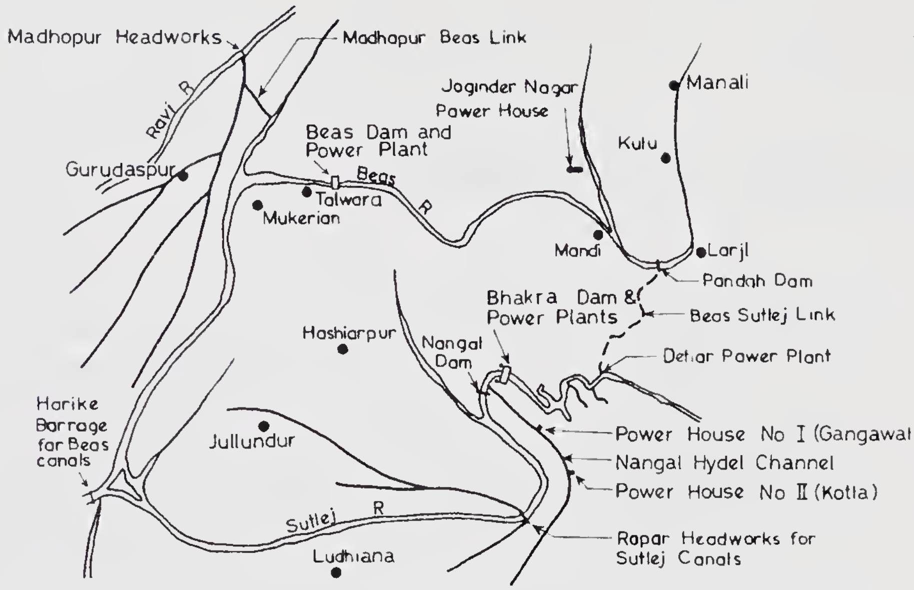


Figure 1. Interconnected system of the rivers Ravi, Beas and Sutlej.

9876 m cu m and a live storage capacity of 7814 m cu m above a dead storage level of 445·62 m. It covers an area of 168·35 km^2 when full. The total run-off at Bhakra for a dependable year works out to 13,723 m cu m and that for a mean year to 16,441 m cu m. A dependable year has been adopted by the planners as a hypothetical year in which the mean discharge of any 10-day period is equalled or exceeded by the corresponding 10-day mean discharges in 67% of the years for which data are considered.

The river flows are high for the four months from June to September due to snowmelt and monsoon rains. Almost 47% of the river flow of a dependable year occurs during these four months. Water from Govindsagar (Bhakra reservoir) can be passed through the turbines of two power houses, one on the right bank and the other on the left bank at the foot of the Bhakra dam. Both the power houses have 5 turbines each. Each of the generators in the right-bank power house has a maximum capacity of 120 MW when the head is 116 m or more, whereas each of the left-bank generators has a maximum capacity of 90 MW when the head is 110 m or more. These capacities fall respectively to 70 MW and 53 MW when the head falls to about 80 m. Thus the power-generating capacity varies from a maximum of 1050 MW to a minimum of 615 MW.

About 11 km downstream of the Bhakra dam is the Nangal reservoir formed by the 28·95 m high Nangal dam. It serves as a head regulator for control of irrigation releases. Part of the water from Nangal is released to the Nangal hydel channel which is 64·48 km long and has a carrying capacity of 353·75 cumecs. The remaining water is released to the Sutlej. The Nangal hydel channel supplies water to two power houses in its path at Ganguwal and Kotla with a total installed capacity of 154 MW. Water from the Nangal hydel channel is then divided between the Bhakra main canal and the Sirhind canal. The Bhakra main canal serves some of the canals of the old western Jamuna canal system which were merged with the Bhakra system and so receives some supplies from the western Jamuna canal.

Downstream of Nangal, there are headworks at two places on the river Sutlej at Ropar and Harike. At Ropar, water is diverted to the Bist Doab and Sirhind canals. The Beas river joins the Sutlej at Harike. Water is diverted at Harike to the Rajasthan feeder and the Ferozepur feeder for the Eastern and Bikaner canals and the Sirhind feeder. Water from all these canals is distributed through the network of the branch canals of the irrigation distribution system. The details of the system are given in figure 1.

Punjab possesses large resources of groundwater which are generally suitable for irrigation. Due to the presence of alluvium, a large-scale programme to install tubewells has been undertaken. The State in 1974 had about 126,000 tubewells and another 75,000 were proposed under the fifth plan (1973–1978). An area of 0·6 to 0·8 m ha suffers from waterlogging. The installation of tubewells would also solve the waterlogging problem to some extent.

2.2 *Irrigation demands*

Bhakra was primarily designed to improve irrigation over an area of 1·42 mha and irrigate an additional 2·43 million hectares. The area served consists of parts of Punjab, Haryana and Rajasthan. The main crops grown in this region are bajra, cotton, maize, rice, jowar, sugarcane, oilseeds, pulses and fodder during the monsoon (kharif) season; and wheat, gram, oilseeds, barley, potatoes and fodder during the winter (rabi) season. Irrigation requirements given in table 1 were assessed when the project was planned

Table 1. Irrigation requirements of the Bhakra system

Month	Period	No. of days	Daily irrigation requirements (in cumec days)	Total irrigation requirements (in cumec days)
	Filling period (from 1st of June to 20th of September)			
June	1–30	30	715·71	21471
July	1–31	31	561·13	17395
August	1–31	31	561·13	17395
September	1–20	20	711·63	14233
				70494 or 6100 m cu m
	Depletion period (from 21st September to 31st of May)			
September	21–30	10	711.63	7116
October	1–15	15	727·71	10916
	16–31	16	654·63	10474
November	1–30	30	654·64	19639
December	1–10	10	611·76	6118
	11–15	5	363·67	1818
	16–31	16	345·80	5533
January	1–15	15	345·80	5187
	16–31	16	363·67	5819
February	1–10	10	390·46	3905
	11–28	18	545·52	9819
March	1–31	31	545·52	16911
April	1–15	15	345·80	5187
	16–30	15	418·89	6283
May	1–31	31	703·50	21809
				136534 or 11800 m cu m
Total 6100 + 11800 = 17900 m cu m				

(Mehndiratta & Hoon 1973)

and were modified only slightly since, although the irrigation demands have changed due to the introduction of high-yielding varieties of crops which require more water. The need to reassess irrigation requirements and revise the demands has been well recognised.

Irrigation requirements are high from September to November owing to the water required for the maturing of the kharif crops and the preparation and sowing of the rabi crops. The requirements are low from December to April, except in the latter half of February and in March when water is required for the maturing of the rabi crops. The rabi crop requirements are smaller than the kharif crop requirements. In May and June, the requirements are again high due to the preparation and sowing of the kharif crops. During the monsoon season also the requirements are quite high as the areas where such water is to be utilized have low rainfall.

2.3 *Power demands*

The releases from the reservoir were originally planned mainly for irrigation. Only 987 mcum (revised upwards to 1360 m cu m recently) was earmarked for releases for power generation. These releases were in addition to those made for irrigation. It was assessed that the releases for power made would yield a firm power of 282 MW from the Bhakra power houses during an empirically-defined dry year.

2.4 *Current operating policy*

Each year the Bhakra Management Board (BMB) conducts operational planning studies, referred to as water power studies, of the system as part of the planning to regulate the supplies from the Bhakra reservoir. The water year from 1 June to 31 May is divided into two periods. June 1 to 20 September is the 'filling period' when supplies are generally available due to snowmelt and the monsoons and the reservoir fills up. September 21 to 31 May is the 'depletion period' when water is released from reservoir storage to meet the demands of irrigation and power.

During the filling period, irrigation demands are met in full subject to the constraint that the reservoir is not allowed to deplete. This means that demands are not fully met if they exceed inflows. This could happen because of the delayed arrival of monsoon, during breaks in monsoon and also in relatively dry years.

Water power studies are conducted for the depletion period using the available utilizable stored volume of water in the reservoir and dependable year or dry year inflows for the depletion period. Although on the basis of 10-day inflows any particular inflow figure of a river in a dependable year would have a probable availability of 67 %, the total yearly inflow of a river at any particular site, corresponding to the dependable year has a probable availability of about 85 %. A dry year is taken as the driest year on record. It is not possible to meet the full irrigation requirements of the depletion period every year. The ratio of deliveries to demands is called the reservoir factor (RF) defined as

RF = (Total storage available in reservoir + expected inflow during depletion period ± gains or losses upto the point of offtake of canals.)/(Total canal requirements during the depletion period.)

The water power studies of BMB indicate that the firm power level is not a constant throughout the depletion period. The firm power level is 15–30 % higher from 21

September to 10 December than from 10 December to 31 May. These studies include the possibility of carryover storage from a good year to the subsequent year. Based on water power studies a decision is taken on 21 September regarding regulation of supplies from the reservoir during the depletion period. The decision implies choice of (i) RF (ii) firm power level, and (iii) minimum reservoir drawndown level to be reached on 31 May (this determines the carryover storage, if any).

3. Review of earlier studies

The Bhakra system has been studied and reported by economists (Raj 1960; Ansari 1968; Minhas *et al* 1972; Reidinger 1974) and by engineers (Singh 1964; Mehndiratta & Hoon 1973). Raj concerned himself with some economic aspects of the Bhakra Nangal project and a preliminary analysis of selected investment criteria. Ansari studied the economics of irrigation rates and examined the basic arguments for incurring financial deficits on irrigation supplies. Reidinger studied the institutional rationing of canal water in an area in Hissar district which is served by one of the Bhakra canals.

Minhas *et al* (1972) made extensive simulation studies of the operations of the Bhakra system (i) to determine for the depletion period the efficient combinations of firm power with certainty and irrigation supplied with a given confidence level, (ii) to evaluate the increase in availability of both irrigation and firm power due to conjunctive utilization of surface and groundwater and to compare the economics of this scheme with that of a thermal back-up. They observed that "in the absence of a satisfactory economic measure of the relative worth of irrigation and power, one cannot determine an ideal operating policy". But the important question of devising such a satisfactory economic measure has been left unanswered in the study. As such the trade-off possibilities delineated in a probabilistic sense cannot be used by decision-makers in choosing the point of operation of the reservoir at the end of the filling period.

Singh (1964) put forward the idea of using seasonally available secondary power for lifting groundwater by tubewells in the general framework of conjunctive utilization of surface and ground waters. Minhas *et al* (1972) noted that the tubewells, when operated solely to augment irrigation supplies, can utilize power which would otherwise go waste and which therefore is 'free' in the economic sense of the term (since the economic value of goods is based on their alternative uses). Operated solely to increase the level of firm power output, tubewells can convert useless secondary power to valuable firm power. Singh also pointed out the role of groundwater development as an antiwaterlogging measure.

Mehndiratta & Hoon (1973) report the methodology adopted by BMB to regulate supplies from the Bhakra reservoir from 1966 to 1972. This report greatly helped in understanding the system and serves as the source material for the present study. Water power studies of BMB, given in tables 2 and 3, reveal that according to the planning studies for the operation of the reservoir in 1969–70 and 1970–71, considerable secondary or dump power was generated during the early part of the depletion period.

From the studies reviewed, it is clear that (i) the sudden peak in the irrigation demands during the rabi sowing season, which is the early part of the depletion period of the reservoir, necessitates the release of water with high potential for power generation for irrigation; (ii) consumers of power who get used to the higher level of firm power supplied during this period find it difficult to reduce their consumption of

Table 2. Water power study for the year 1969–70

Month	Period	Inflows in river Sutlej (cumecs)	Gains or losses between Bhakra & Ropar (cumecs)	Contributions from Sirhind feeder (cumecs)	Total requirements of canals to be fed from Bhakra (cumecs)	Actual release (cumecs)	Actual RF (%)	Reservoir elevations (m)	Available average power (MW)
1	2	3	4	5	6	7	8	9	10
September	23–30	318·10	..	84·95	711·62	519·92	85	512·36	631
October	1–10	275·75	..	79·29	727·72	539·27	85	510·85	650
	11–15	231·18	..	70·79	727·72	539·27	85	509·93	655
	16–20	231·18	..	70·79	654·64	485·65	85	509·32	579
	21–31	191·19	..	56·63	654·64	499·79	85	507·49	590
November	1–10	170·89	..	56·63	654·64	499·79	85	505.36	582
	11–20	152·12	..	42·48	654·64	513·96	85	503.22	590
	21–30	137·65	..	28·32	654·64	528·12	85	501·09	597
December	1–10	130·06	+2·83	21·24	611·75	498·75	85	498·65	552
	11–15	111·25	+2·83	21·24	363·67	396·55	116	497·73	438
	16–20	111·25	+2·83	21·24	345·81	399·15	122	496·82	438
	21–31	114·09	+2·83	21·24	345·81	403·66	124	494·69	438

January	1–10	112·90	+5·66	42·48	345·81	410·06	133	492·55	438
	11–15	114·66	+5·66	42·88	345·81	415·04	134	491·64	438
	16–20	114·66	+5·66	42·88	363·67	418·52	129	490·42	438
	21–31	106·98	+5·66	42·48	363·67	424·53	130	487·98	438
February	1–10	105·37	+11·33	16·99	390·46	433·16	118	485·24	438
	11–20	105·90	+11·33	16·99	545·52	442·14	86	482·49	438
	21–28/29	109·21	+11·33	14·16	545·52	451·00	87	480·36	438
March	1–10	118·76	+5·66	14·16	545·52	461·03	88	477·31	438
	11–20	116·19	+5·66	14·16	545·52	473·29	90	473·96	438
	21–31	133·74	+5·66	14·16	545·52	488·13	93	470·30	438
April	1–10	150·56	−8·50	60·88	345·81	505·43	161	466·65	438
	11–15	149·12	−8·50	60·88	345·81	509·85	163	464·52	438
	16–20	149·12	−8·50	60·88	362·25	528·93	160	462·38	438
	21–30	186·79	−8·50	60·88	362·25	545·27	165	458·11	438
May	1–10	243·67	−16·99	109·02	703·50	568·01	94	454·15	438
	11–20	274·56	−16·99	109·02	703·50	621·08	98	449·88	438
	21–31	400·26	−16·99	109·02	703·50	620·42	101	446·53	438

(Mehndiratta & Hoon 1973)

Table 3. Water power study for the year 1970–71

Month	Period	Inflows in river Sutlej at Bhakra (cumecs)	Gains or losses between Bhakra & Ropar (cumecs)	Contributions from Sirhind feeder (cumecs)	Total requirement of canal to be fed from Bhakra (cumecs)	Actual releases (cumecs)	Actual RF (%)	Reservoir elevation (m)	Available average power (MW)
1	2	3	4	5	6	7	8	9	10
October 1970	21–31	191·19	. .	96·45	654·64	410·60	77·5	492·86	439·00
November	1–10	170·89	. .	65·07	654·64	420·75	74·9	491·34	447·8
	11–20	152·12	. .	58·96	654·64	420·75	74·0	489·20	441·5
	21–30	137·65	. .	55·87	654·64	420·75	73·5	487·07	434·5
December	1–10	130·06	+2·83	53·58	611·75	396·44	74·0	484·94	399·9
	11–15	111·25	+2·83	55·64	363·67	311·96	101·8	484·02	311·9
	16–20	111·25	+2·83	47·68	345·81	313·88	105·3	483·41	311·9
	21–31	114·09	+2·83	47·68	345·81	317·17	106·3	481·58	311·9
January 1971	1–10	112·90	+5·66	29·08	345·81	322·00	103·1	479·76	311·9
	11–15	114·66	+5·66	41·40	345·81	325·70	107·8	478·84	311·9
	16–20	114·66	+5·66	39·04	363·67	328·27	102·5	477·92	311·9
	21–31	106·98	+5·66	53·32	363·67	332·72	107·7	475·79	311·8
February	1–10	105·37	+11·33	63·94	390·46	339·17	106·1	473·35	311·8
	11–20	105·90	+11·33	48·99	545·52	345·92	74·4	474·22	311·9
	21–28/29	109·21	+11·33	70·79	545·52	352·45	79·6	468·09	311·9
March	1–10	118·76	+5·66	84·95	545·52	359·54	82·5	466·65	311·9
	11–20	116·19	+5·66	84·95	545·52	368·20	84·1	463·91	311·9
	21–31	133·74	+5·66	84·95	545·52	378·25	85·9	460·55	311·9
April	1–10	150·56	−8·50	53·83	345·81	389·11	125·6	458·11	311·9
	11–15	149·12	−8·50	63·17	345·81	307·67	131·6	456·59	311·9
	16–20	149·12	−8·50	63·17	418·89	404·18	110·2	455·07	311·8
	21–30	186·79	−8·50	72·21	418·89	414·44	114·1	452·02	311·9
May	1–10	243·67	−16·99	96·45	703·50	427·18	72·0	449·58	311·9
	11–20	274·56	−16·99	87·75	703·50	438·34	72·3	447·14	311·8
	21–31	400·26	−16·99	108·82	703·50	446·30	76·4	446·23	311·9

(Mehndiratta & Hoon 1973).

power subsequently; (iii) it has not been possible for BMB to satisfactorily coordinate the releases for irrigation and power; and (iv) conjunctive utilization of surface and groundwaters may lead to increased firm power level and reliability of irrigation.

4. Conjunctive utilization

4.1 *Conjunctive-use concept*

The Bhakra surface water system has been described in §2.1. There has also been intensive development of groundwater by the public and private sectors. Such combined use of surface and groundwaters as is now practised was not preplanned but has come into being out of necessity. Though the concept of conjunctive utilization of surface and groundwaters has been put forward and widely advocated, it has not been applied systematically. The Irrigation Commission (1972) recognized this fact and recommended that schemes for conjunctive use of surface and groundwaters in existing irrigation schemes should be accorded high priority and that a systematic study should be made by each State to identify areas where conjunctive use is feasible. It appears that conjunctive utilization is considered as the planned development of surface and ground waters for irrigation. It has not been sufficiently realised, despite the good work of Singh (1964) and Minhas *et al* (1972) that conjunctive utilization enables the operating authorities to cope with the differences in time distribution of irrigation and power demands in an optimal way and that it is a means of converting secondary power to valuable firm power. The model described below and applied to the water power studies of BMB for 1969–70 and 1970–71 seeks to emphasize the conjunctive utilization concept and demonstrate the benefits of its application.

4.2 *Conjunctive-use model*

A linear programming model which is an adaptation of a model proposed by Thomas & Revelle (1966) for the Aswan High dam on the Nile river has been developed. Figure 2 is a schematic representation of the model.

The objective is to minimize the discharge from the reservoir during the period 23 September to 30 November. The model is based on the fact that if secondary or dump power generated could be used to lift groundwater and supply part of the irrigation demand, then it is possible to reduce the discharges from the reservoir during this period.

$$\text{Objective function: Minimize } \sum_{i=1}^{N} x_i, \tag{1}$$

where i = index for the subperiod i; subscript i denotes the value of the variable in subperiod i, N = number of subperiods, and X = release from the reservoir in cumec days.

4.3 *Constraints*

4.3a *Power constraint*: The reservoir release in each subperiod should generate the firm power supplied in that subperiod.

$$X_i \geqslant P_i/K_i \quad \text{(for all } i\text{)}, \tag{2}$$

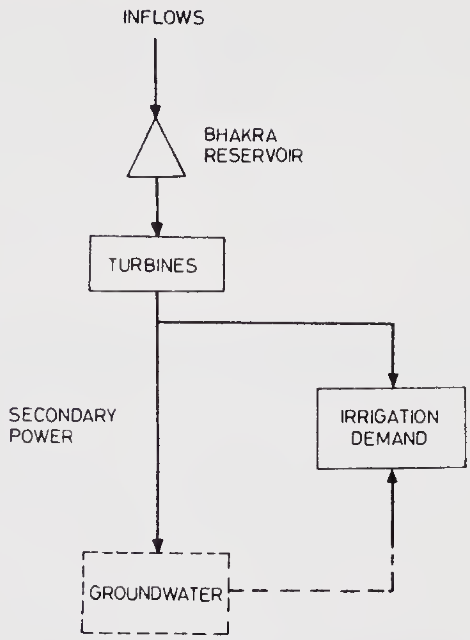


Figure 2. Conjunctive use model for the Bhakra reservoir.

where P = firm power demand, and K = power conversion factor (energy rate function) *i.e.*, power generated by unit volume of water in MW per cumec.

4.3b *Irrigation constraint*: The irrigation demand will be met from two sources: (i) releases from the reservoir and (ii) groundwater lifted by the excess, if any, of power generated over firm power level. The amount of dump power generated should be sufficient to lift the groundwater component of the irrigation demand. This is the modification introduced in the model of Thomas & Revelle (1966) to adapt it to the present problem. Whereas surplus surface water is stored in the aquifers for later use in their model, surplus power is used to lift existing groundwater in this model,

$$X_i \geqslant A_i - m_i(K_i X_i - P_i), \tag{3}$$

where A = irrigation demand, and m = volume of groundwater lifted by unit power (cumecs/MW). When the irrigation demand is overwhelming, this constraint is binding and hence holds as an equality.

4.3c *Continuity constraint*: The continuity constraint specifies that releases upto any time cannot exceed the sum of storage and inflows upto that time. As the reservoir is nearly full during the early depletion period considered in this problem this constraint will not be binding.

$$\sum_{i=1}^{s} X_i \leqslant V + \sum_{i=1}^{s} I_i \text{ for all } s \text{ with } s = 1, 2, \ldots, N, \tag{4}$$

where V = reservoir storage volume at the beginning of the depletion period, and I = inflow into the reservoir.

4.4 *Data and assumptions*

The model is used to study the regulation of the Bhakra reservoir during the depletion period for 1969–70 and 1970–71. Data from the water power studies of BMB (tables 2 and 3) are used in the study.

Turbine efficiencies of the order of 0·85 and pump efficiencies of 0·7 are common. The product of the turbine and pump efficiencies is assumed to be 0·6. Tail race elevation (357 m) is taken from Singh (1965). The power conversion factors K_i are computed from the data in tables 2 and 3. They are assumed constant during the subperiods. As the length of the subperiod is short (8 to 10 days), the variation in the reservoir elevation is small and the head is high, the effect of this approximation is negligible.

The depth to groundwater is assumed to be 15 m in October and 17 m in November. Minhas *et al* (1972) mentioned that in Haryana and Punjab groundwater level rises to 15 to 25 m (50 to 80 ft) below ground surface even for deep tubewells. In many areas groundwater is available much nearer the surface at depths of 3 to 4 m especially after the rainy season in October and November. The assumption of 15 to 17 m depth to groundwater is conservative.

The firm power level and reservoir factor adopted by BMB for the early depletion period up to November 30 are respectively 552 MW and 0·85 in 1969–70 and 400 MW and 0·75 in 1970–71. These values are used in this study.

4.5 *Discussion of results*

The model is applied to study the regulation of the Bhakra reservoir for 1969–70 and 1970–71 during the early depletion period when irrigation alone is constraining. The results given in tables 4 and 5 show that the power used for lifting groundwater is much smaller than the secondary power generated according to BMB studies and that the actual releases of water from the reservoir are reduced by conjunctive use. For example, it is seen from table 4 that during 11–15 October the secondary power generated is 103 MW whereas the model suggests 9·9 MW of power for lifting the groundwater component of the irrigation demand resulting in a saving of 364·35 cumec days of water in the reservoir. It is found that 2800 cumec days (*i.e.* 243 m cu m) of water could be saved in the reservoir during the period 23 September to 30 November (table 4). This is 7·87 % of the total releases made during the same period (table 2). A similar value of 7·28 % is computed for 1970–71 from table 5.

The water so conserved in the reservoir can be used either to expand the irrigated area and help enhance food production under the rabi crop or alternatively it can subsequently help reduce the depletion rate of the reservoir when power demand is constraining and it has a twofold effect. The conserved water increases the storage in the reservoir and also increases the head available for power generation. At the end of the depletion period, the reservoir could end up at a higher elevation. Although 7–8 % of saving of water appears small, it corresponds to 243 m cu m of water and is higher in volume than the evaporation loss of 155·63 m cu m from Bhakra reservoir during 1969–70. Since irrigation is generally not constraining during the remainder of the depletion period a 7 to 8 % increase in irrigation supply during this period can increase the total output of irrigation by a corresponding percentage and this is significant.

5. Multiobjective analysis

5.1 *The concept*

Multiple purposes should be treated as multiple objectives when there is conflict between them as the nature of their consequences is noncommensurable and the linkages between the purposes and the objectives they set out to serve are not known.

Table 4. Early depletion period operation of Bhakra reservoir 1969–70.

Month	Period	Secondary power in BMB Study (MW)	Releases suggested by Model		Available Power (MW)	Power for Groundwater (MW)	Water saved in reservoir	
			cumecs	cumec days			cumecs	cumec days
September	23–30	79	464·25	3714	563·4	11·4	55·67	445·36
October	1–10	98	469·7	4697	565·9	13·9	69·57	695·70
	11–15	103	466·4	2332	561·9	9·9	72·87	364·35
	16–20	27	465·4	2327	556·0	4·0	30·40	101·25
	21–31	38	472·5	5197	557·9	5·9	27·29	300·19
November	1–10	30	479·0	4791	557·0	5·0	20·79	207·90
	11–20	38	485·6	4856	558·2	6·2	28·36	283·60
	21–31	45	488·0	4880	552·0	0	40·12	401·20
			Total:	32793 cumec days			Total:	2799·55 cumec days.

Table 5. Early depletion period operation of Bhakra reservoir 1970–71

Month	Period	Secondary power in BMB study (MW)	Releases suggested by model		Available power (MW)	Power for groundwater (MW)	Water saved in reservoir	
			cumecs	cumec days			cumecs	cumec days
October	21–31	39·0	382	4199·3	406·0	6·0	28·60	314·6
November	1–10	47·8	384	3841·5	408·5	8·5	36·75	367·5
	11–20	41·5	390	3898·6	408·4	8·4	30·75	307·5
	21–30	34·5	395	3946·3	407·2	7·2	25·75	257·5
			Total	15885·7			Total	1247·0

There has been sharp competition for and conflict in the use of the Bhakra reservoir storage for irrigation and power (Mehndiratta & Hoon 1973; Reidinger 1974). In the planning stage Bhakra was considered more of an irrigation project and the power benefits were secondary. A firm power of 282 MW was expected from Bhakra power houses in a dry year. With the rapid increase in power load in the region, the position has completely changed. The power demand overrides other interests of the project during most of the months and it has not been possible to satisfactorily coordinate the releases. It is therefore worthwhile to consider irrigation and power as the two objectives to operate the Bhakra system and to study the complementarity and conflict between the two for the six years for which data are available.

5.2 *The model*

Thomas & Revelle (1966) used a linear programming (LP) model and for a given storage in Aswan High dam derived the transformation curve between irrigation and power by maximizing power for different levels of irrigation demands. A similar approach is used to study the planned and actual depletion period operation of the Bhakra reservoir. The LP model is as follows:

$$\text{Objective function: maximize } P, \qquad (5)$$

where P = firm power level in MW.

5.3 *Constraints*

5.3a *Irrigation constraint*: The reservoir release in each subperiod should meet the irrigation requirements to be supplied from the reservoir,

$$X_i \geqslant A_i, \text{ with } i = 1, 2, \ldots, N, \qquad (6)$$

where N = number of subperiods during the depletion phase of the reservoir, X = reservoir release in cumec days, and A = irrigation requirements to be supplied from the reservoir in cumec days.

5.3b *Power constraint*: The reservoir release should generate the committed firm power in each subperiod.

$$X_i \geqslant \frac{P \cdot \beta_i n_i}{K_i} \quad \text{with} \quad i = 1, 2, \ldots, N, \qquad (7)$$

where β_i = firm power coefficient in subperiod i, n_i = number of days in subperiod i, and K = power conversion factor(MW/cu mec).

5.3c *Continuity constraint*: The total volume of water released from the reservoir during the depletion period should not exceed the total utilizable storage in the reservoir at the beginning of the depletion period and the inflows in the depletion period.

$$\sum_{i=1}^{N} X_i \leqslant V + \sum_{i=1}^{N} I_i, \qquad (8)$$

where V = volume of reservoir storage utilized during depletion period in cumec days, and I = river inflow into the reservoir.

Table 6a. Availability of water in filling period

Year	River inflows (m cu m)	Contribution from Sirhind feeder (m cu m)	Contribution from WJC* (m cu m)	Releases made (m cu m)	Starting reservoir level at the beginning of filling period in meters/ Date of occurrence		Closing reservoir level at end of filling period in meters/ Date of occurrence		Stored supply available at end of filling period up to dead storage reservoir level 445·62 meters (m cu m)
1966–67	11114	913	382	4367	439·83	4-6-66	509·26	14-9-66	6463
1967–68	11397	1172	308	4305	443·80	3-6-67	512·23	21-9-67	6944
1968–69	9819	950	271	4317	454·74	31-5-68	506·76	12-9-68	6056
1969–70	12002	962	74	5230	451·03	27-5-69	513·30	21-9-69	7142
1970–71	7722	1011	247	3256	444·92	25-6-70	495·98	3-10-70	4527
1971–72	11077	999	358	3910	443·23	28-5-71	512·76	16-9-71	7043

(Mehndiratta & Hoon 1973) * West Jamuna canal

Table 6b. Availability of water in depletion period

Year	Reservoir level at beginning of depletion period (in metres)/ Date of occurrence		Reservoir level at end of depletion period (in metres)/ Date of occurrence		Stored supply utilised during depletion period (m cu m)	River inflows (m cu m)	Ravi-Beas contribution (m cu m)	Total supply utilised (m cu m)
1966–67	509·26	14-9-66	443·30	3-6-67	6599	3848	604	11051
1967–68	512·23	21-9-67	454·74	31-5-68	6352	4576	1011	11939
1968–69	506·76	12-9-68	451·03	27-5-69	5711	4317	1493	11521
1969–70	513·30	21-9-69	444·92	25-6-70	7179	5033	1369	13581
1970–71	495·98	3-10-70	443·23	28-5-71	4663	3071	1604	9338
1971–72	512·76	16-9-71	445·54	16-6-72	7043	5205	1850	14098

(Mehndiratta & Hoon 1973)

5.4 *Data and assumptions*

5.4a *Number of subperiods*: The water and power studies of BMB generally divides the depletion period from 23 September to 31 May into 29 periods (table 2). An LP package on the time-sharing computer terminal at the Harvard University Centre for Population Studies limits the total number of constraints to 50. To facilitate its use, the depletion period is divided into 24 subperiods by aggregating some of the subperiods in the waterpower studies.

5.4b *Irrigation requirements*: The irrigation requirements in cumecs are given in table 1. During the depletion period, the irrigation requirements may be satisfied only partly as defined by the reservoir factor (RF). They are computed for values of RF ranging from 0·6 to 1 at increments of 0·05.

The expected inflow during depletion period has two components: (i) the inflow into the reservoir and (ii) the inflows of the Ravi and Beas rivers that contribute through the Sirhind feeder and supply part of the irrigation requirements of the Bhakra command. The Sirhind feeder (Ravi-Beas) contributions vary from year to year and the data are shown in table 6. While the break-up of these contributions period-wise is available for 1969–70 and 1970–71 from tables 2 and 3, an assumption is needed for the other four years. The proportion of the total flow in each subperiod for these years is assumed to be the average of such proportions for 1969–70 and 1970–71. Gains or losses upto the point of offtake of canals are available for each of the subperiods from tables 2 and 3.

5.4c *Firm power level*: The BMB chose for operation the results of water study no. VI for 1969–70 (table 7), study no. 1 for 1970–71 (table 8) and study no. VIII for 1971–72

Table 7. Summary of water power studies for 1969–70

Study No.	Starting reservoir level in meters	Pattern of inflow	Minimum reservoir level in meters	Reservoir factor %	Power
I	513·28	Dry year	445·62	75	22-9-69 to 31-12-69 550 MW 1-1-70 to 20-5-70 450 MW 21-5-70 to 31-5-70 289 MW
II	513·28	Dry year	445·62	75	22-9-69 to 31-12-69 512 MW 1-1-70 to 31-5-70 441 MW
III	513·28	Dry year	445·62	97	Minimum power 282 MW was ensured and releases were proposed in the interest of irrigation
IV	513·28	Dependable year	445·62	78	22-9-69 to 31-12-69 500 MW 1-1-70 to 30-4-70 450 MW 1-5-70 to 31-5-70 500 MW
V	513·28	Dependable year	445·62	80	22-9-69 to 10-12-69 524 MW 11-12-69 to 31-5-70 450 MW
VI	513·28	Dependable year	445·62	85	22-9-69 to 10-12-69 552 MW 11-12-69 to 31-5-70 438 MW
VII	513·28	Dependable year	445·62	100	Minimum power of 282 MW was ensured and releases were proposed in the interest of irrigation

(Mehndiratta & Hoon 1973)

Table 8. Summary of water power studies for 1970–71

Study No.	Starting reservoir level in metres	Pattern of inflows	Minimum reservoir level in metres	Reservoir factor %	Power
I	494·76 on 1st October	Dependable year	445.62	75	Up to 10th Dec. 1970—400 MW 11th December 1970 to 31st May 1971—312 MW
II	494.76 on 31st October	Dry year	445·62	75	Up to 10th Dec. 1970—400 MW 11th December 1970 to 31st May 1971—300 MW

(Mehndiratta & Hoon 1973)

(table 9). The β_i values corresponding to the same were used in this study for the respective years. The β_i were found to be respectively 1·26 in 1969–70 and 1·282 in 1970–71. For 1966 to 1969 for which no data are available, a distribution similar to 1969–70 and 1970–71 with a β_i value of 1·27 is used.

5.4d *Power conversion factors*: The power conversion factors K_i for 1969–70 and 1970–71 are deduced from the data in tables 2 and 3 respectively and the relationship between K_i and reservoir elevation is derived. For the other four years, the approximate reservoir elevations for each of the subperiods are estimated from the anticipated and actual depletion curves in figures 3 (a to f) and the power conversion factors corresponding to these elevations are used in this study. These depletion curves generally correspond to RF values in the ranges of 0·75 to 0·85. For other RF values, the depletion curves would be somewhat different and the reservoir elevations and hence the power conversion factors would also be different. However, for simplicity, it is assumed that the conversion factors are independent of the RF value and the same conversion factors as in the water power studies of BMB are used in each of the subperiods. From the solution thus obtained, it is possible to determine the reservoir elevations implied and hence determine a new set of values of K_i and repeat the procedure till convergence is obtained. However, the irrigation requirement is constraining generally only from 23 September to 10 December when the reservoir elevation is very high and the depletion rate is low. Such refinement is not considered here.

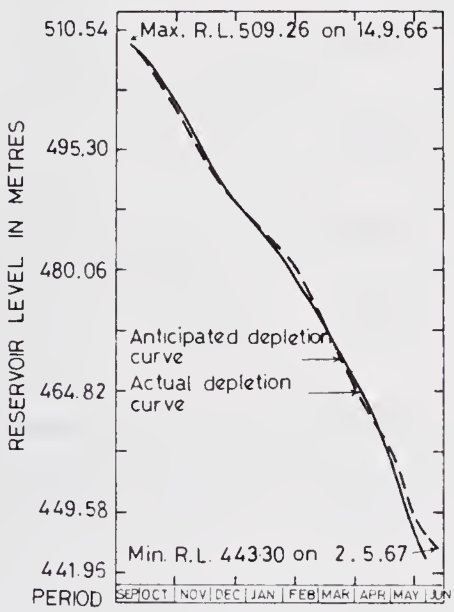
5.4e *Sutlej river inflows*: This study assumes the dependable year inflows for planning as in the case of water power studies of BMB. They are obtained from Mehndiratta & Hoon (1973) and Lamba & Prem (1975) for all years except for 1971–72 for which there is a discrepancy between the two reported values. The dependable year inflow for that year is corrected by interpolation. These are shown in table 10. For actual operation, actual river inflows (table 6b) are used.

Table 9. Summary of water power studies 1971–72

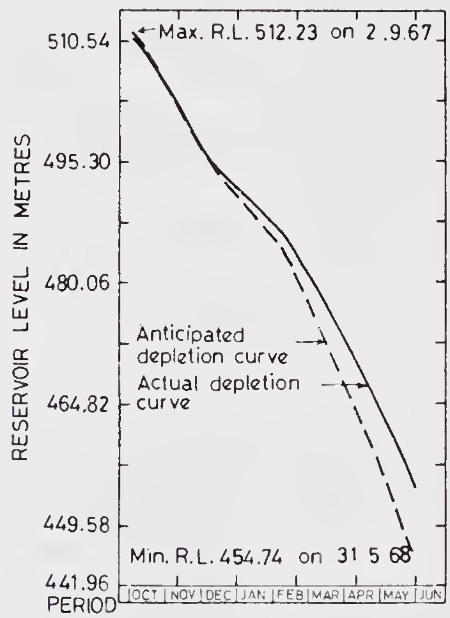
Study No.	Starting reservoir level in metres	Pattern of inflows	Minimum reservoir level in metres	Reservoir factor up to 10th Dec. 71	Power
I	512·06	Dependable year	445·92	85%	512 MW up to 10th December 1971 and 444 MW thereafter up to 31-5-72
II	512·06	Dependable year	451·41	85%	512 MW up to 10-12-71 and 430 MW from 11-12-71 to 31-5-72
III	512·06	Dependable year	456·90	85%	512 MW up to 10-12-71 and 414 MW from 11-12-71 to 31-5-72
IV	512·06	Dry year	445·92	81%	484 MW up to 10-12-71 and 432 MW from 11-12-71 to 31-5-72
V	512·06	Dry year	451·41	81%	484 MW up to 10-12-71 and 419 MW from 11-12-71 to 31-5-72
VI	512·06	Dry year	457·20	81%	484 MW up to 10-12-71 and 402 MW from 11-12-71 to 31-5-72
VII	512·05	Dependable year with month of May as per driest year	446·23	75%	512 MW or more up to 10-12-71 and 425 MW from 11-12-71 to 31-5-72
VIII	512·06	Dependable year	452·32	85%	500 MW up to 31-12-71 and 430 MW for 1/72, 3/72 and 5/72 and 420 MW for 2/72 and 4/72
IX	512·76	Dependable year	·452·32	85%	500 MW upto 31-12-71 and 430 MW for 1/72, 3/72 and 5/72 and 420 MW for 2/72 and 4/72.
X	512·76	-do-	445·62	85%	-do-
XI	512·76	Actual	445·62	85%	-do-

Note:
(1) Study Nos. I to VIII are BMB Water Power Studies for 1971–72 (Mehndiratta & Hoon 1973).
(2) Study No. XI is one of actual operation.

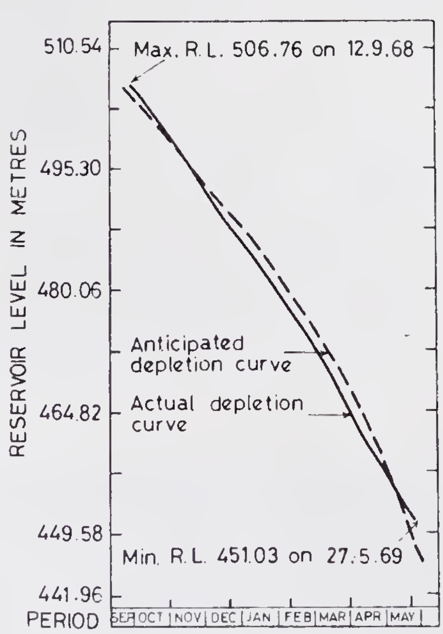
5.4f *Stored volume*: For planning studies, live storage available above dead storage level (DSL) is used in the different studies. In case carryover was planned for, carryover storage was estimated from volume elevation curves and deducted from live storage above DSL to give utilizable storage with carryover. It is presumed that the losses due to evaporation and infiltration from the reservoir are considered by BMB in the specification of demands or in specifying inflows. The total volume of water for utilization during the years is assumed to be the sum of dependable year inflows and the utilizable storage from the reservoir as in the water power studies of BMB. For studies of actual operation the volume of water actually utilized during the depletion period is used. The details of the data are given in table 10.



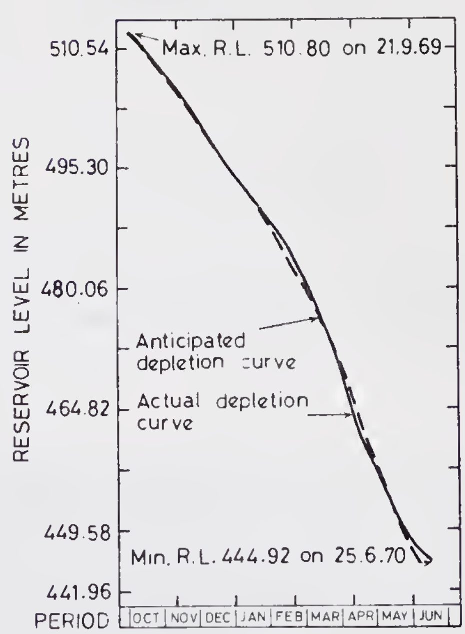
a. 1966 - 67



b. 1967 - 68



c. 1968 - 69



d. 1969 - 70

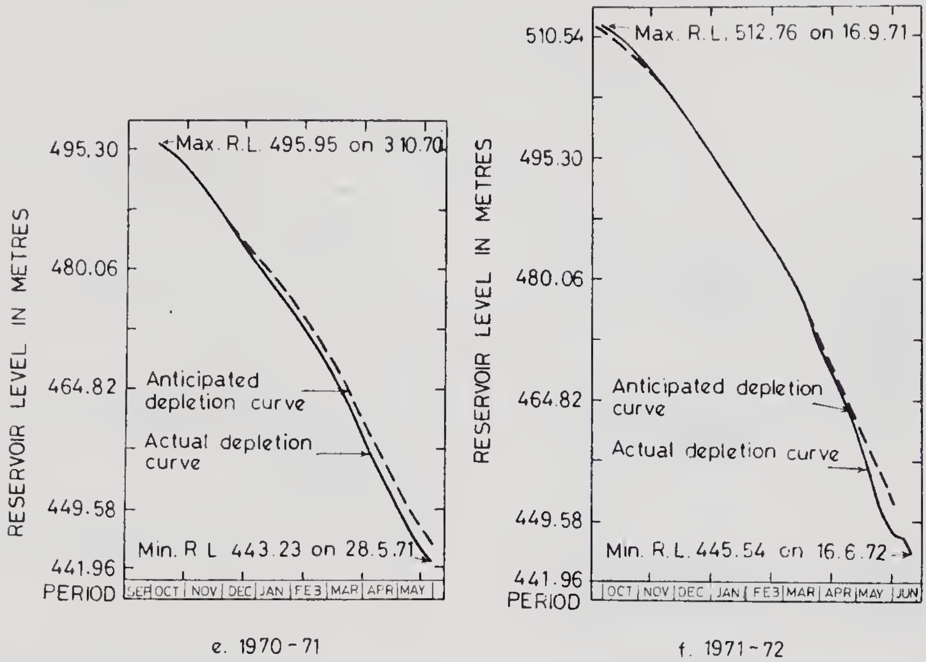


Figure 3. **a, b; c, d; e, f;** Anticipated and actual depletion curves. (Mehndiratta & Hoon 1973)

5.5 *Derivation of irrigation and power transformation curves*

The maximum level of firm power that can be developed for a given RF is determined by solving the LP problem. The values of RF used are 0·6, 0·65, 0·7, 0·75, 0·8, 0·85, 0·9, 0·95 and 1·0. The results of the studies of the planned and actual utilization of the reservoir storage from 1966 to 1972 are given in table 11 and the corresponding transformation curves are plotted in figure 4.

Carryover storage was an additional variable besides irrigation and power in 1971–72. The details and results of the studies with various carryover storages considered in the planning studies in 1971–72 are given in tables 12 and 13. The graphical representation of the concept of transformation surfaces and the resulting transformation surface for Bhakra are plotted in figures 5 and 6. The transformation curves, between irrigation (RF) and carryover storage, and between firm power and carryover storage, are given in figures 7 and 8 and explained later in § 5·7b.

5.6 *Analysis of transformation curves*

The transformation curves for the planned and actual operation of the reservoir for six years are generally similar in shape. The curves for 1966–67 are a little different in shape at higher RF levels and this is presumably due to very low Ravi-Beas contributions in the depletion period of that year (table 6b).

The difference between the curves for planning and operation in each year is due to the difference in the assumed depletion period inflows and actual inflows. The actual inflow is much smaller than the assumed inflow in the dry year 1970–71; slightly smaller

Table 10. Supplies planned for and actually utilized

Year	Stored supply above D.S.L. (m cu m)	Depletion period inflows (dependable year) (m cu m)	Total supply planned for utilization (m cu m)	Total supply planned for utilization (cumec days)	Stored supply utilized (m cu m)	Actual depletion period inflows (m cu m)	Total supply actually utilized (m cu m)	Total supply actually utilized (cumec days)
1966–67	6463	4145	10608	122777	6599	3848	10447	120914
1967–68	6944	3812	10756	124490	6352	4576	10928	126481
1968–69	6056	4231	10287	119062	5711	4317	10028	116064
1969–70	7142	3812	10954	126782	7179	5033	12212	141342
1970–71	4527	3454	7981	92372	4663	3071	7734	89513
1971–72	6463*	4059**	10522	121743	7043	5205	12248	141758

* Minimum reservoir level is 452·32 m; ** Corrected value.

Table 11. Maximum firm power for different reservoir factors.

Reservoir factor	1966–67 Firm power (MW)		1967–68 Firm power (MW)		1968–69 Firm power (MW)		1969–70 Firm power (MW)		1970–71 Firm power (MW)		1971–72 Firm power (MW)	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
0·60	430·8	424·25	445·3	465·0	413·6	401·2	461·9	514·9	320·9	310·1	447·7	521·3
0·65	430·8	424·25	445·3	465·0	413·6	401·2	461·9	514·9	320·9	310·1	447·7	521·3
0·70	430·8	424·0	445·3	465·0	413·6	401·2	461·9	514·9	318·8	305·8	447·7	521·3
0·75	428·1	420·7	445·3	465·0	413·6	401·2	461·9	514·9	308·2	288·4	447·7	521·3
0·80	420·9	411·8	442·5	464·4	412·5	397·8	461·0	514·9	279·4	250·5	446·3	521·3
0·85	404·7	390·3	432·5	459·6	404·0	386·0	454·4	514·9	227·6	N.F.	437·6	521·3
0.90	353·0	339·0	414·5	442·6	383·5	350·8	439·8	512·0	N.F.	N.F.	422·5	520·5
0·95	263·1	N.F.	367·8	397·9	334·2	299·3	409·0	503·7	N.F.	N.F.	402·4	513·7
1.00	N.F.	N.F.	N.F.	339·7	N.F.	N.F.	354·1	488·0	N.F.	N.F.	352·0	499·9

N.F.: Not feasible; Case 1: Study based on stored supply planned for utilisation and dependable year inflows during the depletion period; Case 2: Study based on utilized stored supply and the actual inflows during the depletion period.

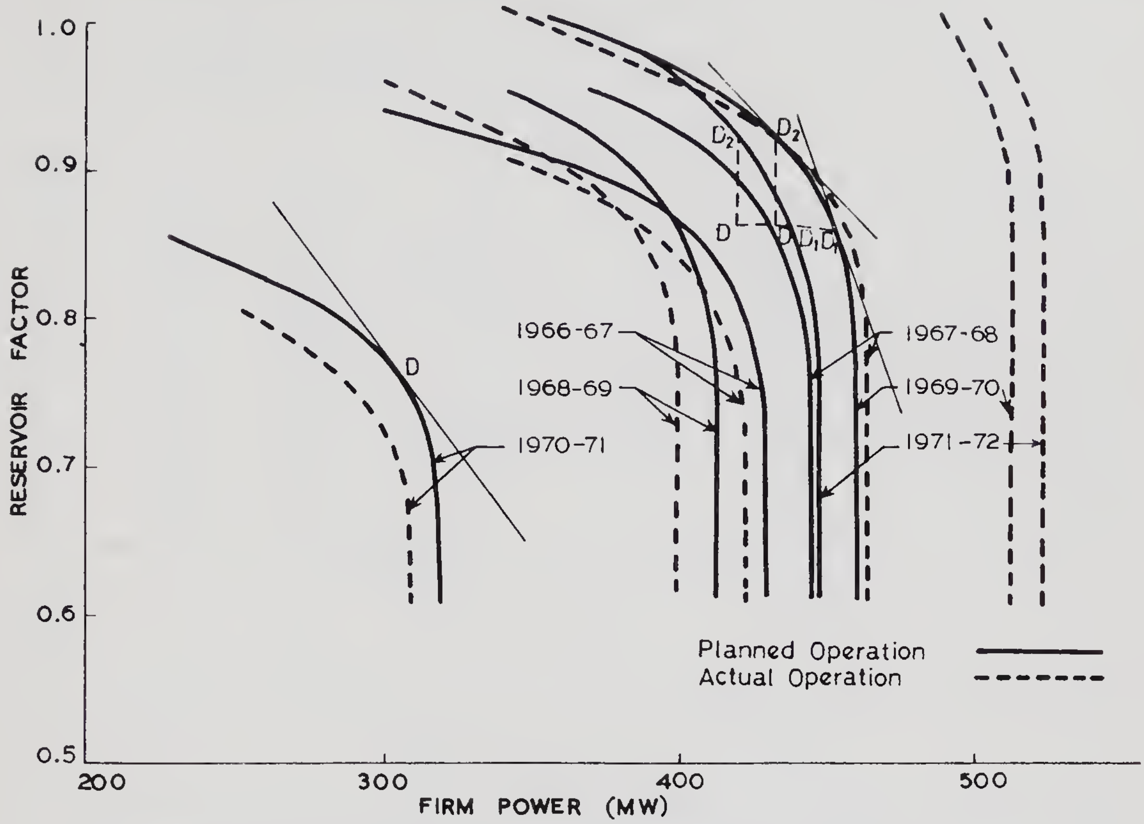


Figure 4. Transformation curves for the Bhakra reservoir (1966–72)

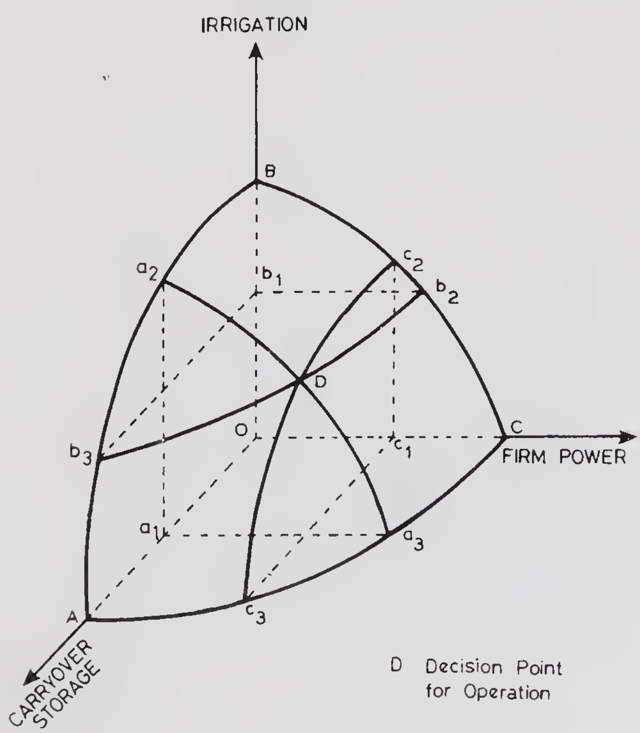


Figure 5. Graphical representation of transformation surface.

Table 12. Details of water power studies for 1970–71

	Study I	Study II	Study III	Study VIII	Study IX	Study X	Study XI
Reservoir level at the beginning of depletion period (m)	512·06	512·06	512·06	512·06	512·76	512·76	512·76
Reservoir level at the end of depletion period (m)	445·92	451·41	456·90	452·32	452·32	445·62	445·62
Stored supply utilized during depletion period (m cu m)	6,871·61	6,521·69	6,162·52	6,462·68	6,634	7,043	7,043
Dependable year inflows (m cu m)	4,059	4,059	4,059	4,059	4,059	4,059	5,205*
Total supply utilized (cumec days)	10,931	10,581	10,222	10,522	10,693	11,102	12,248
Total supply utilizable (m cu m)	126,475	122,476	118,270	121,743	123,726	128,458	141,758**
Carryover storage (m cu m)	19·43	349·92	709·08	409·93	408·93	0	0
Carryover storage as percent of total storage of 6871·61 m cu m	0·3	4·94	10·32	5·95	5·95	0	0

* Actual inflows; ** Total supplies utilized

Table 13. Maximum firm power for different reservoir factors and carryover storages (water power studies for 1971–72)

Reservoir factor	Firm power (MW)						
	Study 1	Study 2	Study 3	Study 8	Study 9	Study 10	Study 11*
0·60	465·1	450·2	434·9	447·7	455·0	472·4	521·3
0·65	465·1	450·2	434·9	447·7	455·0	472·4	521·3
0·70	465·1	450·2	434·9	447·7	455·0	472·4	521·3
0·75	465·1	450·2	434·6	447·7	455·0	472·4	521·3
0·80	464·7	449·1	431·9	446·3	454·2	472·3	521·3
0·85	461·3	441·2	419·3	437·6	447·9	469·8	521·3
0·90	448·2	426·3	403·2	422·5	433·5	458·6	520·5
0·95	432·2	407·7	369·2	402·4	416·4	443·2	513·7
1·00	400·9	359·0	314·1	352·0	372·5	420·5	500·0
Carryover storage (m cu m)	19·4	349·9	709·1	408·9	408·9	0	0

* Actual operation

in the below average years 1966–67 and 1968–69; slightly larger in the above average year 1967–68 and very much larger in the wet years 1969–70 and 1971–72. It shows that using dependable year inflows for planning every year irrespective of how wet the year has been and how high the reservoir has filled up led to very conservative planning in wet years and the opposite of it in a dry year. It is not sound practice. It seems possible to delineate an average year with a transformation curve between the above average and

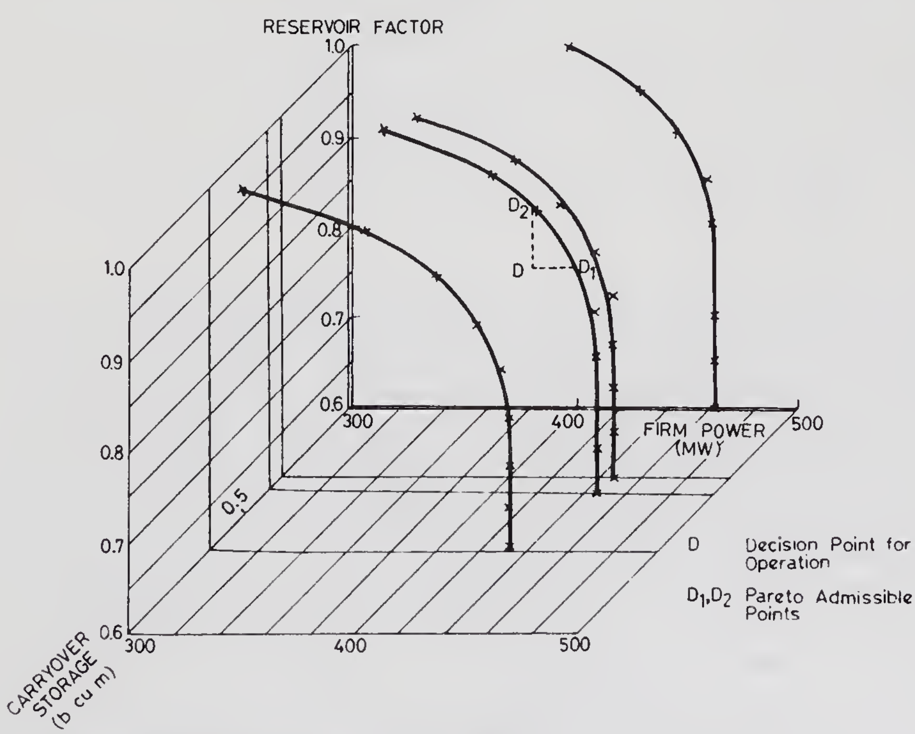


Figure 6. Transformation surface for the Bhakra reservoir.

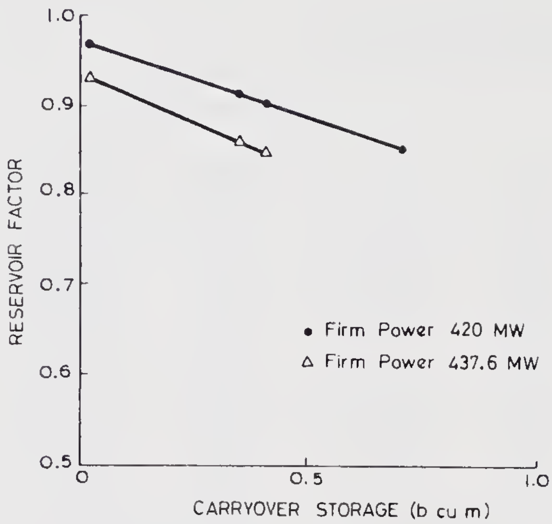


Figure 7. Transformation curve at constant firm power (1971–72).

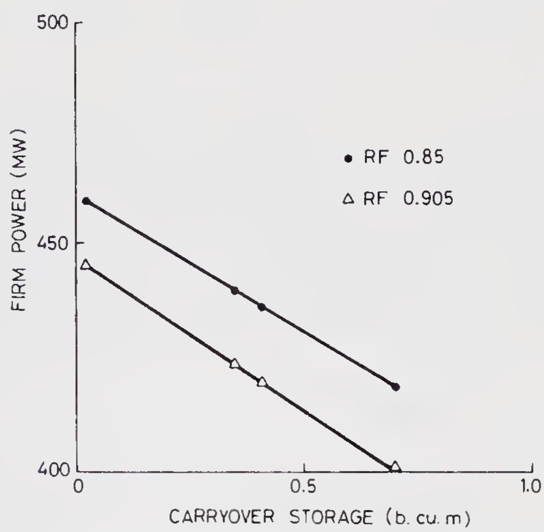


Figure 8. Transformation curve at constant reservoir factor (1971–72).

below average years for which the assumption of dependable year inflows in depletion period would be correct. Forecasting models for the stochastic inflows (Krishnasami 1976) are required to predict depletion period inflows for use in planning.

The points of operation D chosen in the planning studies in 1969–70 and 1971–72 (figure 4) lie inside the respective transformation curves indicating that the planned operation is inferior and nonoptimal. The point D could be moved on to the curve at D_1 or D_2 and the operation would be Pareto-superior to that at D. A higher firm power level would be attained for the same RF of 0·85 at D_1 while a higher RF would be obtained for the same firm power level at D_2. RF planned was never higher than 0·85 and so it seems reasonable to suppose that the points D_1 would be the decision points of BMB for operation in 1969–70 and 1971–72.

The RF planned for was 0·75 in the dry year 1970–71. The decision point chosen in planning is not feasible with respect to the actual transformation curve. The firm power level planned for was stuck to and the adverse impact of the shortage must have been borne by irrigation only. So the actual RF provided would have been lower than 0·75.

Irrigation supplies at RF of 1 were feasible in 3 out of 6 years and at RF of 0·9 to 0·95 in 2 out of 6 years. In the dry year an RF of only 0·8 was feasible.

Firm power levels planned for varied from 312 MW in a dry year to 438 MW in a wet year. In actual operation it seemed that 510 to 520 MW of power was generated in the wet years of 1969–70 and 1971–72 and 280 to 300 MW in the dry year of 1970–71. The high order of fluctuations in firm power from year to year can be reduced by carryover storage from wet to dry years. For example, a carryover of about 1500m cu m storage from 1969–70 to 1970–71 would have facilitated operation in both years around the level of an average year (1968–69) with firm power of about 400 to 420 MW. The recommendation of Minhas *et al* (1972) that a high dead storage level should be maintained for high levels of firm power (which are possible in years of good inflows) implies, in a way, the concept of carryover storage. Carryover storage was planned for in 1971–72 possibly because of the experience of the previous two years, but in actual operation this sound policy was not carried out.

Irrigation and power are almost wholly complementary up to an RF level of about 0·9 in years of good inflows but the complementarity could not be exploited because of the uncertainty of depletion period inflows. This again points to using appropriate streamflow forecasting models for planning reservoir operation.

5.7 *"Top-down" and "bottom-up" planning*

The transformation curves provide the frontier on which an optimal decision point for operation should lie. If the social welfare function or the preference function of the decision makers is available, the optimal point is obtained as the point of tangency between the transformation curve and the welfare function or preference curve respectively and the slope of the tangent gives the trade-off between the objectives. The slope of the tangent to the transformation curve gives the marginal rate of technical transformation between the objectives at that level of attainment of the objectives. The slope of the tangent to the preference curve provides a measure of the relative marginal economic worth of the two objectives (ratio of the shadow prices) at that level of attainment of the objectives. At the decision point they are equal and the converse is also true.

Well-defined preference functions do not exist. Shadow prices of the objectives vary from time to time and depend on the levels of attainment of the objectives. They need to be derived from an overall economic framework by a central planning organisation and given to the project operators for use in decision-making. This is "top-down" planning. If the ratio of shadow prices of the objectives are so defined exogenously (along the transformation curve) the point on the transformation curve where the slope equals this ratio defines the decision point. If it is not available from decision makers it is possible to arrive at a decision point by interaction with the decision makers using techniques like SWT method or Paretian analysis. In the absence of these, a "bottom-up" planning procedure seems possible.

5.7a *Analysis and discussion of implied trade-offs*: The results presented in § 5.4 are analysed and discussed in the framework of "bottom-up" methodology to elicit the trade-offs implied in the choice of the decision points in the planned and actual operation of the reservoir during six years.

The trade-offs between irrigation and firm power in the planned and actual operation for the six years are given in table 14. The trade-offs implied in planned operation vary from 200 MW/RF in average years to 360 MW/RF in a dry year. Since the results indicate a higher trade-off for irrigation in a dry year, the value system adopted in planning is consistent.

In 1969–70 (figure 4), the trade-offs of 200 MW/RF at D_1 and 500 MW/RF at D_2 provide the bounds for the marginal rates of transformation implied in the choice of decision point D for operation. The BMB has used a maximum RF of 0·85 for operation (tables 7, 8 and 9). Assuming, therefore, an RF of 0·85 corresponding to D_1 the trade-off implied is 200 MW/RF. The trade-off on the transformation curve of actual operation at the level of D_1 corresponding to RF of 0·85 is 0·0 MW/RF. This implies that, in actual operation, there is complete complementarity between irrigation and firm power up to RF of 0·85 and that the irrigation supply could have been increased upto RF levels of 0·9 or even upto 1 with a small loss of firm power. Even at an RF of 1·0, 50 MW more of firm power than that planned for would have been produced (table 11).

In the dry year 1970–71 (figure 4) the trade-off between irrigation and power implied by the decision is 360 MW/RF. The planned operation at point D is not feasible for actual inflows. If an RF level of 0·75 was maintained, a firm power level of 288·4 MW would have been reached on the transformation curve for actual operation and it would have meant a trade-off of 490 MW/RF at that point. This is larger than the trade-off in an average year. During the early part of the depletion period from 3 October 1970 to about 15 December 1970 the operation was as per the plan, *i.e.* at point D with RF of 0·75 and firm power level of 400 MW (figure 3e). The adverse effect of the shortage seems to have been borne by the latter part of the depletion period from 15 December 1970 to 31 May 1971. The average power generation for the year 1970–71 was 335 MW. It can be deduced from these that the RF level achieved was certainly less than 0·75 and must have been somewhere between 0·65 and 0·7 with a trade-off of 160 MW/RF or less. This, in turn, implies a higher value for power than irrigation compared to an average year. This indicates not only a contradiction between planning and operation but also an inconsistency in economic evaluation. If, as pointed out earlier, the reservoir was not depleted as it was in 1969–70 but some storage was carried over to 1970–71, it would have greatly cushioned the adverse impact due to poor inflows in 1970–71 and enabled the achievement of a higher RF for irrigation.

Table 14. Trade-off between firm power and irrigation

Year	Irrigation level (RF)	Trade-off (MW/RF) Planned operation	Actual operation
1966–67*	0·85	450	600
1867–68	0·85	260	210
1968–69	0·85	240	360
1969–70	0·85	200	0
1970–71	0·75	360	490
1971–72	0·85	230	0

* Ravi-Beas contribution is low as compared to other years.

5.7b *Transformation surface for* 1971–72: The concept of the transformation surface among the three objectives has been illustrated in figure 5. ABC constitutes the surface bounded by the three coordinate planes. D is the decision point for operation. If it is on the surface, it is Pareto-optimal. Curves a_2a_3, b_2b_3 and c_2c_3 pass through the decision point and lie respectively in planes $a_1a_2a_3$ parallel to the coordinate plane BOC, $b_1b_2b_3$ parallel to OAC and $c_1c_2c_3$ parallel to OAB. The trade-off implied by decision point D between any two of the objectives can be derived as the negative of the slope of the curve in the plane parallel to the coordinate plane defined by the same objectives.

For 1971–72, water power studies for planning the reservoir operation were conducted by BMB assuming different levels of irrigation and firm power supplies and different carryover storages. They are listed in table 9. Four of the studies, *viz*., I, II, III and VIII assumed an irrigation level at RF 0·85 and dependable year inflows during depletion period but they differ in that they assume different carryover storages. Details of these studies are given in table 12.

The maximum firm power levels for different reservoir factors and carryover storages are given in table 13. The transformation surface among the three objectives, irrigation, firm power and carryover storage for the four planning studies is shown in figure 6. The BMB decided to operate the reservoir according to study No. VIII with a carryover storage of 408·93 m cu m, a firm power level of 420 MW and RF of 0·85. A firm power level of 437·6 MW was possible for an RF of 0·85 and carryover storage of 408·93 m cu m (table 13, figure 4). Hence the decision point D (figure 4) is inside the transformation curve and though feasible is not Pareto-optimal. For the same carryover storage, any operation between D_1 (RF of 0·85 and firm power of 437·6 MW) and D_2 (RF of 0·905 and firm power of 420 MW) will be better than the point D chosen and will be Pareto-superior. The trade-offs implied by choice of D_1 or D_2 as decision points can be obtained from the transformation curves in figures 4, 7 and 8 and are respectively 230 to 350 MW/RF between irrigation and power, 4824 to 5976 m cu m/RF between carryover storage and irrigation, and 60·6 to 67·6 MW/b cu m (billion cubic metres) between firm power and carryover storage. As the RF level of 0·85 was always adhered to as an upper limit, it appears that D_1 would have been the choice. Hence the trade-offs implied by D_1 are relevant indicators of decision makers' values.

The planning studies of BMB (table 9) assumed that the reservoir would reach an elevation of 512·06 m on 16 September 1971. But the reservoir actually filled to an elevation of 512·76 m on that date with 171 m cu m more storage than planned for in these studies. Study Nos. IX and X (table 9) are revisions to account for this increase. Study No. IX assumes carryover storage of 408·9 m cu m as in study No. VI and corresponds to planned operation. Study No. X assumes no carryover storage as in Study No. XI and corresponds to actual operation. They are reported in tables 12 and 13. The transformation curve for actual operation (figure 4) indicates that irrigation could have been supplied at an RF of 0·9 instead of 0·85 without any loss of firm power and this too at a power level of 521·30 MW as against 420 MW planned for. An increase in RF to 1 would have resulted in a loss of only about 20 MW.

If the reservoir was operated according to the decision on 16 September, 1971 the carryover storage would have been much more than what was planned for because the excess of actual inflows over the assumed dependable year inflows, would have been stored, and carried over to the subsequent year. The reservoir elevation at the end of the depletion period would have been about 8 m higher than the planned elevation of 452·32 m. In actual operation the reservoir was drawn down to about the dead storage elevation of 445·62 m. Thus 1746 m cu m of water consisting of excess storage and excess inflows was used over and above the planned volume of 10,522 m cu m and all the excess was used in the interest of power alone and the trade-off implied is 0·0 MW/RF which considered irrigation above RF of 0·85 to be completely worthless. Such a value judgement needs justification. Thus, carryover storage, though planned for, was not realized in practice. This was particularly striking after the dismal experience of the previous year.

6. Summary of results

The analysis of the results of the study of the Bhakra reservoir operation from 1966 to 1972 indicates that (i) the depletion period inflows are correlated to the filling period inflows and planning should be based on appropriate estimates of depletion period inflows; (ii) an RF of 0·85 or above can be attained in an average year and an RF of 1 can be obtained at a loss of firm power of about 80 MW in an average year; (iii) planning and operation should be based on consistent estimates of economic parameters; and (iv) carryover storage will serve to reduce year to year fluctuations in firm power and irrigation levels.

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Integrated operation of the Beas-Sutlej system

P S RAO* and S RAMASESHAN†

*Indian Institute of Management, Bannerghatta Road, Bangalore 560076, India
†Civil Engineering Department, Indian Institute of Technology, Kanpur 208016, India

Abstract. The study deals with the integrated operation of the Beas and Sutlej link, a complex system. It utilizes the methodology developed in an earlier paper for reservoir operation. The results show the definite advantages of conjunctive use and carry over storage. The results also show that it is advantageous to divert as much water from the Beas to the Sutlej as possible.

Keywords. Integrated reservoir operation; conjunctive use.

1. Introduction

To study the conventional operation of a reservoir system in a multiobjective framework in order to evaluate the trade-offs between irrigation and power implied by past decisions, a case study of the Bhakra reservoir was undertaken. This study demonstrates the methodology and procedures of multi-objective analysis in an integrated framework.

2. System description

2.1 *The Beas-Sutlej system*

The Beas river originates in the lower ranges of the Shiwaliks. The catchment area of the river upstream of Pong, where a storage dam has just been completed is 12,561 km^2. The average rainfall in the catchment is 1,778 mm. For a mean year the discharge at the Mandi plain varies from 152 cumecs in the dry season to 1,830 cumecs during the monsoon, with an annual average run-off of 16,763 m cu m. For a dependable year, the run-off is 12,835 m cu m. The Beas joins the Sutlej river at Harike.

The Beas project was undertaken to harness the water and power resources of the Beas river by storage and diversion works. It consists of (i) the Beas-Sutlej link, which comprises a diversion dam at Pandoh across the Beas in the Kulu Valley to transfer 4727 m cu m of water to the Bhakra reservoir through tunnels and open conduits capable of passing a maximum discharge of 255 cumecs; and (ii) the Pong dam which provides for a storage dam at Pong with a maximum height of 132·6 m, a gross storage of 8141 m cu m. and a live storage capacity of 6,767 m cu m. The power plant will have 4 units with an installed capacity of 60 MW each with provision for two additional units in the future. The water released from the Pong dam and utilized for generation of power will be used for irrigation through the canal system from the Harike headworks. Water from the Ravi is transferred by a diversion at the Madhopur headworks through the Madhopur-Beas link (maximum capacity: 283 cumecs) to the Beas river. This can be diverted at Harike to irrigate the Beas command. The Bhakra component of this system has been described in Rao & Ramaseshan (1985) and the interconnected system of the Beas, the Sutlej and the Ravi is shown in figure 1 of that paper. The inflows of the three rivers for a dependable year are summarized in table 1 and those for a mean year are shown in figure 1.

2.2 *Irrigation and power demands*

A salient feature of the irrigation system is that the releases from the Bhakra reservoir can supply the Sutlej and Beas canal command areas and the releases from the Pong reservoir can be used only in the Beas canal command areas. Gross irrigation requirements for the Sutlej and Beas canals adopted by the Beas Designs Organization (BDO) are given in table 2. A comparison of the irrigation requirements of the Sutlej canal command with those of table 1, Rao & Ramaseshan (1985) reveals that there has been a slight upward revision of the requirements perhaps due to the increased crop water requirements of the high-yielding varieties.

Constant firm power throughout the year for the Bhakra system was assumed by Minhas *et al* (1972). Table 3 indicates that planned levels of power generation vary widely between 766 MW from December through April to 1,697 MW in September. It seems that considerable secondary power is generated during the filling season when irrigation requirements are met fully by surface water at a reservoir factor (RF) of 1. From the available data, three types of firm power distribution over the years are abstracted and used in this study. They are shown in figure 2. The firm power level from December to April is denoted by P, and β_i is the ratio of the firm power level in any

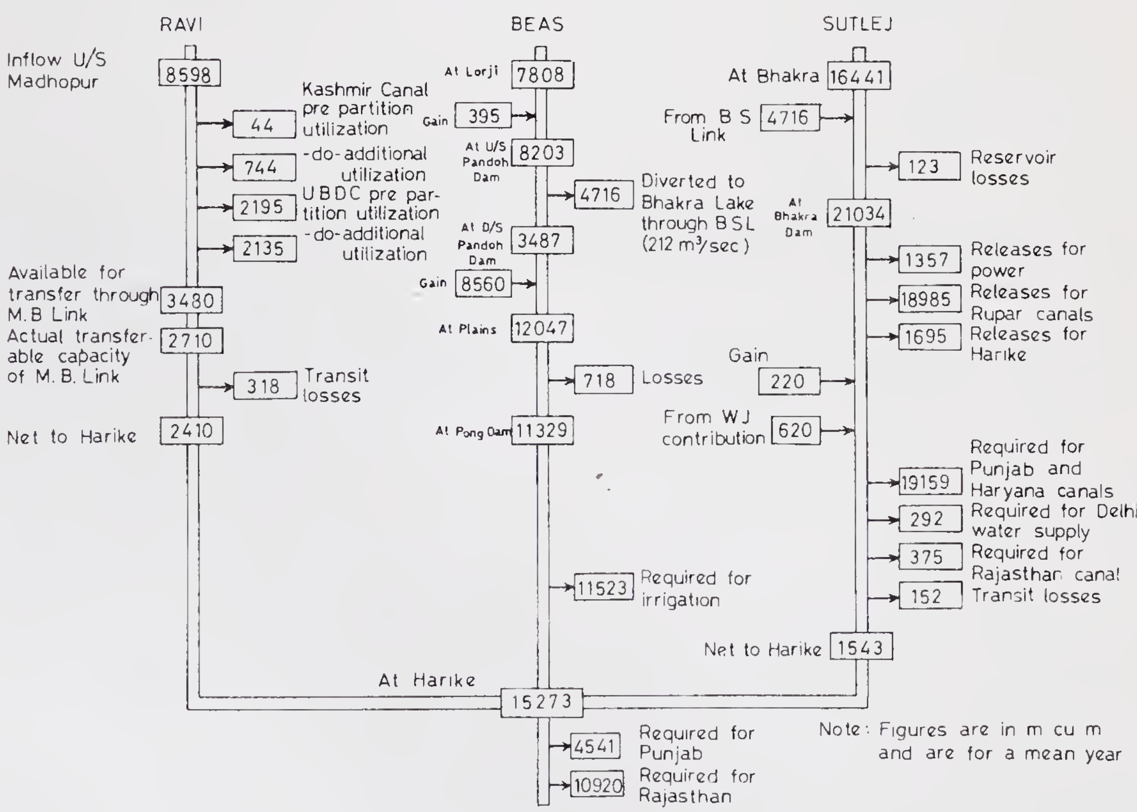

Figure 1. Surface water budget for Punjab water resources system (Lamba & Prem 1975)

Table 1. Inflow of rivers Sutlej, Beas and Ravi in cumecs for a dependable year

Month	River Sutlej at Bhakra	River Beas at Mandi Plain	River Ravi at Madhopur	Total inflow
June 11–20	707·5	360·5	312·3	1380·3
21–30	857·9	420·8	327·1	1605·8
July	1233·4	918·7	513·8	2665·9
August	1293·9	1464·6	530·6	3289·1
Sept 1–10	821·1	944·1	317·7	2082·9
11–20	582·2	649·9	221·0	1453·1
21–30	366·1	436·8	151·7	954·6
October	233·8	256·4	95·7	585·9
November	153·8	148·5	62·9	365·2
December	122·9	130·5	53·0	306·4
January	109·4	125·7	55·6	290·7
February	108·7	131·2	76·8	316·7
March	124·2	157·6	128·4	410·2
April	162·6	193·6	195·2	551·4
May	314·3	249·9	257·4	821·6
June 1–10	524·3	272·5	295·1	1086·9
Total inflow in million hectare metres	1·3723	1·2835	0·6713	3·3271

(Bhalla & Bansal 1975).

Table 2. Irrigation requirements for Sutlej and Beas canal systems in cumecs

Month	Sutlej canal system at Ropar	Beas canal system at Harike	Total of Sutlej and Beas canal systems
1	2	3	4
April	388·3	262·5	650·8
May	760·9	406·1	1167·0
June 1–10	773·2	620·6	1393·8
11–30	773·2	628·3	1401·5
July	658·0	570·5	1228·5
August	658·0	570·5	1228·5
Sept. 1–10	770·8	623·2	1394·0
11–20	770·8	683·3	1454·1
21–30	770·8	803·5	1574·3
Oct. 1–15	776·7	713·6	1490·3
16–31	776·7	602·9	1379·6
November	703·6	492·2	1195·8
December 1–10	675·8	381·5	1057·3
11–31	392·3	328·6	715·9
Jan. 1–15	388·9	317·6	706·5
16–31	395·6	317·6	713·2
Feb. 1–10	409·8	338·6	748·4
11–28	582·8	374·8	957·6
March	589·0	519·9	1108·9

(Bhalla & Bansal 1975)

Table 3. Beas-Sutlej system water power study for a dependable year

Month	Releases in cumecs			Power in MW			
	Bhakra	Pong	Total releases at Bhakra & Pong	Bhakra	Pong	Dehar	Total
June 11–20	915·6	155·2	1070·8	620	64	530	1214
21–30	1066·1	215·6	1281·7	724	87	530	1341
July	571·2	273·2	844·4	471	123	530	1124
August	527·9	273·2	801·1	574	153	530	1257
Sept. 1–10	725·1	512·3	1237·4	851	316	530	1697
11–20	545·9	409·7	955·6	647	251	529	1427
21–30	545·9	486·9	1032·8	644	297	527	1468
October	550·2	402·0	952·2	651	234	366	1251
November	498·6	310·5	809·1	571	173	197	941
December	480·0	135·0	615·0	534	75	157	766
January	526·7	135·9	662·6	550	74	142	766
February	580·5	135·9	716·4	548	73	145	766
March	514·8	240·7	755·5	427	123	216	766
April	499·8	32·1	531·9	372	16	378	766
May	556·1	274·6	830·7	388	124	530	1042
June 1–10	738·9	212·4	951·3	509	86	530	1125

(Bhalla & Bansal 1975)

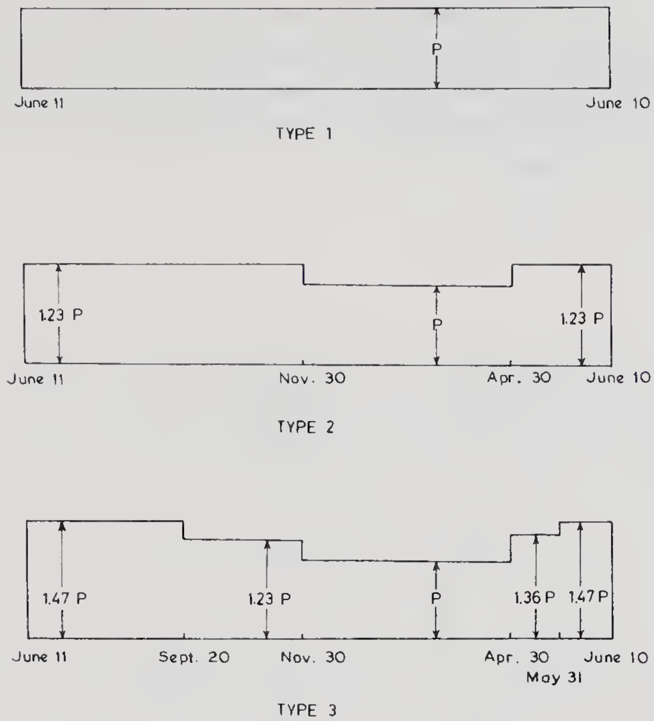

Figure 2. Firm power distributions

month i to P. A uniform firm power level, *i.e.* $\beta_i = 1$ for all i, is assumed in type 1, while in type 2, $\beta_i = 1$ from December to April and $\beta_i = 1.23$ for other months. Similarly in type 3, values of i vary in different months from 1 to 1·47.

2.3 *Planned operating policies*

The planned operation of the reservoirs of the interconnected Beas-Sutlej system is described by Bhalla & Bansal (1975) and Lamba & Prem (1975). The operating policy of the system of reservoirs is the same as that of the Bhakra reservoir (§2.4, Rao & Ramaseshan 1985). In the original Beas project report, the Bhakra and Pong reservoirs were assumed to be depleted almost simultaneously to their dead pond levels, the firm power being 766 MW. Releases from the two reservoirs and power generation during different months of the year are given in tables 2 and 3. Bhalla & Bansal suggested staggering the time of depletion of the Bhakra and Pong reservoirs to their respective dead pond levels and thus increasing the firm power from 766 to 799 MW. Planning by BDO is confined to the management of the surface waters. Conjunctive utilization of surface and ground waters has not been considered by them.

3. Conjunctive utilization

3.1 *System model*

Conjunctive utilization models are developed for integrated management of surface and ground waters. They are necessarily simplified representations of a more complex reality, as in the planning studies of BDO, and are limited to the use of published information. The aim is essentially to focus on the methodology and demonstrate the utility of model building and systems studies for improvement.

The system is shown in figure 3. A linear programming model of the system is developed and used in these studies. The model maximizes the level of firm power P. Irrigation demands are to be satisfied in each of the subperiods. The power required to lift groundwater is over and above the firm power that is to be supplied. The mathematical formulation of the model is as follows:

$$\text{Objective function: Maximize } P \tag{1}$$

3.2 *Constraints*

3.2a *Power constraint*: The power generated in the system in any period should be equal to or greater than the firm power demand plus the power required to lift groundwater in the Bhakra and Beas irrigation commands. The model assumes that dump power has no value and is indifferent to whether this constraint is defined as an equality or inequality. In this study, power constraints are equality constraints.

$$K_{1i}T_{1i} + K_{2i}T_{2i} + K_3 DI_i - n_i\beta_i P - P_{1i} - P_{2i} \geqslant 0, \tag{2}$$

$$\text{with} \qquad i = 1, 2, \ldots, 16.$$

where the first subscripts 1, 2 & 3 refer to the Bhakra, Pong and Dehar plants respectively; the second subscript i indicates the variable in a subperiod i; coefficients K_{1i}, K_{2i} and K_3 are the power conversion factors (or energy rate functions) for power plants and represent power generated by a unit volume of water in megawatts per cumec and K_3 is a constant for all the subperiods; T_{1i}, T_{2i} are the flows through the turbines at the power plants; DI is the inflow diverted through the Beas-Sutlej link and passing through the Dehar power plant in cumec days; n_i is the number of days; and P_{1i} and P_{2i} are power in megawatt days used for lifting groundwater in the Bhakra and Beas command areas respectively.

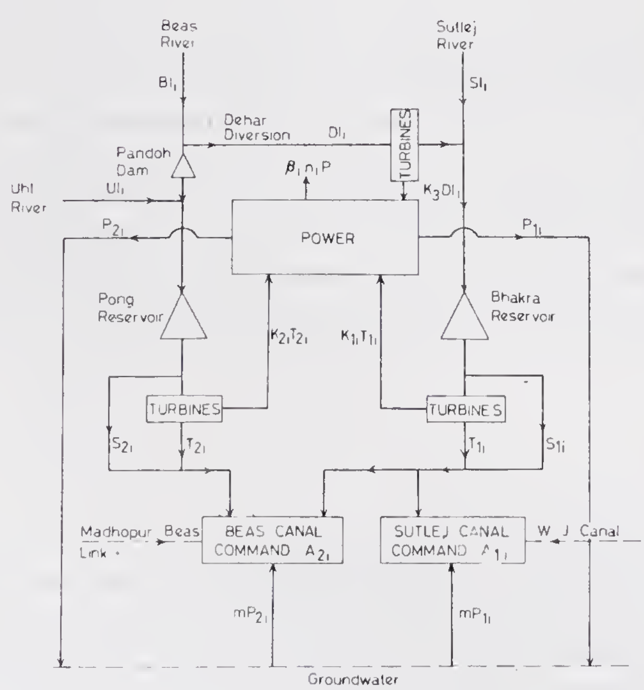

Figure 3. The Beas-Sutlej system model

3.2b *Turbine capacity—inflow constraints*: Flows through turbines are limited by the maximum turbine flow capacities in any of the periods. Diversion through Dehar is, in addition, limited by the upstream Beas flows. Hence, the flow through turbines at the Dehar plant is the minimum of the available flow for diversion and the turbine flow capacity.

$$T_{1i} \leqslant TC_{1i}, \tag{3}$$

$$T_{2i} \leqslant TC_{2i}, \tag{4}$$

$$DI_i \leqslant \mathrm{Min}(\mathrm{BI}_i, \mathrm{DTI}_i), \tag{5}$$

where TC_{1i}, TC_{2i}, and DTI_i are the maximum turbine flow capacities; BI_i is the inflow in the Beas river above Pandoh and i varies from 1 to 16. The flow unit used in this study is cumec day.

3.2c *Irrigation constraints for the Beas and Sutlej canal systems*: The total irrigation requirements of the Beas and Sutlej canal systems should be met by (i) releases at the Bhakra reservoir through the turbines and/or outside the turbines; (ii) releases at the Pong reservoir through the turbines and/or outside the turbines; and (iii) groundwater which may be used in either the Beas or the Sutlej command areas or in both.

$$(T_{1i} + S_{1i}) + (T_{2i} + S_{2i}) + m(P_{1i} + P_{2i}) \geqslant A_{1i} + A_{2i} \tag{6}$$

with $\quad i = 1, 2, \ldots, 16,$

where S_{1i} and S_{2i} are flows released through irrigation sluices or over the spillway and not through turbines; m is the volume of groundwater lifted by unit power (cumecs/MW) and A_{1i} and A_{2i} are the irrigation requirements of the Sutlej canal system at Ropar and of the Beas canal system at Harike respectively.

The irrigation requirements of the Sutlej canal system should be met by (i) releases at the Bhakra reservoir through the turbines and/or outside the turbines; and (ii) groundwater lifted in the Bhakra command area

$$(T_{1i} + S_{1i}) + m \cdot P_{1i} \geqslant A_{1i} \tag{7}$$

with $i = 1, 2, \ldots, 16.$

3.2d *Continuity and capacity constraints*: The continuity equation relates the volume of storage at the end of any period to the initial volume, inflows and releases. The capacity constraint equations limit the volume of storage to the reservoir capacities and these are used for the filling periods. In the depletion period, a simpler relationship, *viz* the sum of the releases during the total depletion period, limited to the total utilizable storage in the reservoir at the end of the filling period plus the inflows during the depletion period, is used.

Bhakra reservoir:

(i) Filling period

$$T_{1i} + S_{1i} - DI_i + V_{1,i} - V_{1,i-1} = SI_i, \tag{8}$$

and $\quad V_{1,i} \leqslant C_1 \quad$ with $\quad i = 1, 2, \ldots, 6. \qquad (9)$

(ii) Depletion period

$$\sum_{i=7}^{16} (T_{1i} + S_{1i} - DI_i) - V_{1,6} + V_{1,0} = \sum_{i=7}^{16} SI_i. \tag{10}$$

Pong reservoir:

(i) Filling period

$$T_{2i} + S_{2i} + DI_i + V_{2,i} - V_{2,i-1} = BI_i + UI_i \tag{11}$$

$$\text{and } V_{2,i} \leqslant C_2 \quad \text{with} \quad i = 1, 2, \ldots, 6. \tag{12}$$

(ii) Depletion period

$$\sum_{i=7}^{16} (T_{2i} + S_{2i} + DI_i) - V_{2,6} + V_{2,0} = \sum_{i=7}^{16} (BI_i + UI_i), \tag{13}$$

where V_1, V_2 are the volumes of storage; C_1 and C_2 are the reservoir capacities; and SI and UI are the inflows in the Sutlej river and in the Uhl river which joins the Beas river at Mandi; the unit is cumec day for all variables.

3.3 *Data and assumptions*

3.3a *Number of subperiods*: As in the BDO studies, the year is divided into sixteen subperiods, six in the filling period and ten in the depletion period.

3.3b *Power conversion factors*: The power conversion factors (K_{1i}, K_{2i}, and K_3) are calculated for each reservoir for each subperiod from the BDO data in table 3 and are shown in table 4. As in the study on the Bhakra reservoir (Rao & Ramaseshan 1985) their variation as a function of the actual reservoir level in each subperiod is ignored. Dehar is a constant head power plant and the power conversion factor is computed as 2.616 MW/cumec from the total power generated and the total flow through the plant in a year.

3.3c *Irrigation requirements*: The irrigation requirement of the Sutlej canal system to be supplied from the Bhakra reservoir in any subperiod is taken as the minimum of the Sutlej canal requirement (table 2) and the Bhakra reservoir release (table 3). The total irrigation requirements for the system are available from the BDO study. Both are shown in table 4. With contributions from other sources, namely, the Western Jamuna canal and the Madhopur-Beas link, accounted for, they correspond to a filling period RF of about 1 and a depletion period RF of about 0·85.

3.3d *Turbine capacities*: Assuming a standby unit of 120 MW and a maximum power plant capacity of 930 MW at Bhakra, and a standby of 60 MW and a maximum power plant capacity of 300 MW at Pong and using the power conversion factors, the maximum turbine flow capacities are calculated (table 4). The Beas river flow available for diversion at Pandoh is calculated from the Beas river flow at Mandi in proportion to the ratio of the respective catchment areas.

3.3e *Volume of storage in reservoirs*: A summary of river inflows and reservoir releases in the filling and depletion periods for a dependable year is shown in figure 4. The storage capacities of Bhakra and Pong reservoirs are respectively 9,320 and 6,767 m cu m. The storage capacities in the BDO study in a dependable year are

Table 4. Data for Beas-Sutlej system.

Month	Power conversion factors (MW/cumec)		Turbine flow capacities (cumec days)		Net irrigation requirements (cumec days)	
	Bhakra reservoir	Pong reservoir	Bhakra power plants	Pong power plants	Sutlej canal system	Beas-Sutlej system
June 11–20	0·6771	0·4124	11656	7275	7732	10708
21–30	0·6791	0·4035	11656	7435	7732	12817
July	0·8246	0·4502	34968	20656	17707	26176
August	1·0873	0·5600	26536	16606	16365	24834
Sept. 1–10	1·1736	0·6168	7920	4864	7251	12374
11–20	1·1853	0·6126	7850	4897	5459	9556
21–30	1·1797	0·6100	7880	4918	5459	10328
October	1·1832	0·5821	24366	15977	17056	29518
November	1·1465	0·5572	24330	16153	14958	24273
December	1·1125	0·5556	25916	16740	14880	19065
January	1·0443	0·5445	27621	17080	12164	20541
February	0·9435	0·5372	27608	15637	14588	21492
March	0·8295	0·5110	34751	18199	15959	23421
April	0·7443	0·4984	18057	11649	11649	15957
May	0·6977	0·4516	20595	23587	17239	25752
June 1–10	0·6888	0·4049	7409	7732	7389	9513

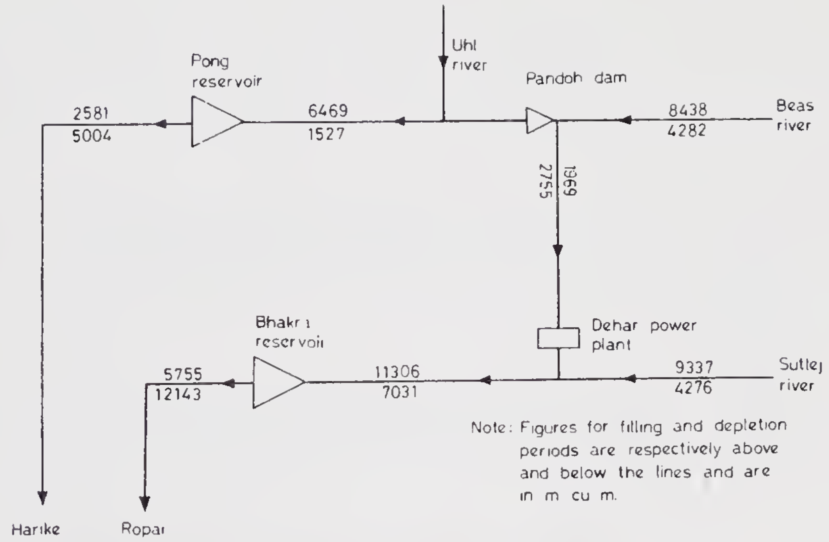

Figure 4. Water balance of the Beas–Sutlej system

respectively 5,112 and 3,477 m cu m corresponding to final volumes of storage at the end of the depletion period, 4,208 and 3,290 m cu m respectively. These are assumed to be the levels of storage at the beginning of the filling period (case 1) and are referred to as initial volumes in this study. In case 6 the initial volumes of storage are 2,426 m cu m in Bhakra corresponding to a dead storage level of 445·62 m, and zero in Pong. Cases 2 to 5 correspond to intermediate values and details are given in table 5.

3.3f *Power for groundwater*: It is assumed that 1 MW of power can lift 2.832 cumecs of groundwater. This corresponds to a lift of 25 m and for Punjab this is a conservative assumption (Minhas *et al* 1972).

3.3g *Dehar diversion flows*: The system is studied with two different assumptions regarding the Beas-Sutlej diversion flows.

Model 1: For comparability of results, Dehar inflows are calculated from the seasonal distribution of power generation and total diversion as specified by the BDO study (Mehndiratta & Hoon 1973; Bhalla & Bansal 1975). It is assumed in this model that they are prespecified and are not subject to control. Model 1 has 109 variables and 106 constraints.

Model 2: It is assumed that the Beas-Sutlej diversions can be changed, if necessary, subject to the availability of flows in the Beas above Pandoh for diversion and limited by the turbine flow capacity at Dehar. Additional diversion of water through Dehar generates power at Dehar and Bhakra at heads higher than at Pong and can also meet irrigation demands in the Bhakra or Beas canal systems. This flexibility can and does increase the firm power level. Model 2 has 125 variables and 122 constraints.

4. Discussion of results

The firm power level is maximized for each case defining initial reservoir volumes for each type of firm power distribution and for specified (model 1) and variable (model 2) Dehar diversions. MPSX (Mathematical Programming System Extended) available in the Harvard-MIT Computer system was used and each solution required about 45 to 50 seconds for computation and execution. The maximum firm power levels for all the cases are shown in table 5.

Table 5. Maximum firm power in Beas-Sutlej system

Case No.	Initial reservoir volume				Firm power in megawatts					
	Bhakra		Pong		Type 1		Type 2		Type 3	
	mcum	cumec days	mcum	cumec days	Specified Dehar diversion	Variable Dehar diversion	Specified Dehar diversion	Variable Dehar diversion	Specified Dehar diversion	Variable Dehar diversion
1	4208	48689	3290	38067	891	962	824	884	797	851
2	3769	43609	2879	33307	923	994	853	913	825	880
3	3330	38529	2467	28547	955	1025	882	942	835	905
4	2891	33449	2056	23787	987	1055	901	970	835	905
5	2452	28369	1644	19027	1008	1085	902	977	835	905
6	2426	28066	0	0	1006	1092	900	976	834	904

For any level of initial storage, the firm power level for type 1 distribution is higher than that for type 2, which in turn is higher than that for type 3. This implies that higher values of variable β_i reduce the firm power level.

Even in case 1 with wasteful spillage of the order of 10% of total storage, the firm power is 797, 824 and 891 MW respectively for firm power distribution types 3, 2 and 1. With no spillage, the firm power increases respectively to 835, 902 and 1008 MW. Thus conjunctive utilization can increase firm power at least by 36 MW above that of improved operation and 69 MW above the original planned operation of BDO. In case firm power distribution can be represented by type 1 or type 2, the firm power levels increase further by 173 MW and 67 MW above those of type 3. The small differences between case 5 and case 6 seem to be due to numerical errors.

Since in this study the power conversion factors are considered to be independent of the variations of the actual reservoir level in any period, the variation between case 1 and case 6 corresponds to various levels of spillages. Variable Dehar diversion (model 2) increases firm power levels over specified Dehar diversion (model 1) by 54 MW to 86 MW or 7 to 8%.

The details of power generation and of groundwater utilization are not reported in the study but are summarised below:

(i) Generally, in June and July, the Pong reservoir is filling up and no releases are made; and for a continuous period of two to three months between November and February also, no releases are made from Pong.

(ii) Whenever possible, water is diverted through Dehar as the power generation at Dehar and Bhakra is much larger than that at Pong.

(iii) The current practice is to release surface water liberally in the filling period to meet the irrigation demand and use groundwater essentially in the depletion period. However, the results of this study are contrary to the current practice and they indicate groundwater use generally between May and November and not from December to April. Groundwater utilization peaks in September, is significant for parts of July, August and October, and is somewhat smaller in May, June and November. The quantities vary from solution to solution. For example, the groundwater used for case 1, type 1 of model 1 varies as follows: 36, 298 and 438 cumecs in the three subperiods of June: 236 cumecs in July; 226 cumecs in August; 500, 286 and 110 cumecs in the three subperiods of September; and 193 cumecs in November. A maximum pumping capacity of 500 cumecs is indicated and in case the pumps operate only for part of the day and not fully, the installed capacity should be proportionately higher. By staggering the cropping pattern, the peak groundwater use may be reduced resulting in a higher utilization of the installed pumping capacity.

In the Kharif season, irrigation demands are high and constraining and a large amount of secondary or dump power is currently generated. By lifting groundwater in this period, it is possible to conserve surface water for future use and to eliminate any secondary power generation except when unavoidable. The surface water so conserved is generally adequate to meet the full irrigation demands in the Rabi season except perhaps for very limited groundwater use in one or two periods. In addition to this, the firm power level is also raised significantly *i.e.*, part of the seasonal excess power of low value is converted to firm power of high value. This is similar to the concept of using a pumped storage scheme. But rather than looking for a smaller reservoir at a higher elevation, the larger and lower ground-water reservoir is used advantageously. It may still be possible to generate dump power using the wasteful spills provided both reservoirs can be full at the end of the filling period.

5. Trade-off analysis

The operation of the Beas-Sutlej system with a specified irrigation demand was considered in the study discussed above. The advantages of conjunctive utilization with variable Dehar diversion flows (model 2) have also been demonstrated. Model 2 is used here to study the trade-off between irrigation and power in the integrated operation of the surface and groundwater system. The three types of firm power distributions considered earlier are also used here. Initial volumes of storage in the reservoirs are assumed at dead storage levels and these correspond to case 6 of table 5. In order to study the implication of dry year flows on systems operation, the study is repeated for type 2 firm power distribution only with dry year flows.

5.1 *Data and assumptions*

The data used in this study are the same as in the study discussed in § 3. For any RF the irrigation demands for the Bhakra and Bhakra-Beas commands are calculated from the canal requirements in table 2. Subtracting the contributions from other sources (the Madhopur-Beas link and the Western Jamuna canal), the corresponding net irrigation releases required for the RF are determined. 1965–66 is the driest year on record (as of 1969) for inflows to the Bhakra reservoir. Beas river inflows at Dehar and estimates of inflows to the Pong reservoir were derived for the same year and used for the study with dry year flows.

5.2 *Discussion of results*

The maximum firm power was determined for RF levels of 0·6, 0·75, 0·85, 0·9, 0·95 and 1. All the three types of firm power distributions (figure 2) were considered for dependable year inflows and only type 2 distribution for the dry years. The results are presented in table 6 and figure 5. The original and improved planned operations of BDO are also indicated in the same figure. For any RF, the firm power for type 1 distribution is larger than that for type 2 distribution, which in turn is larger than that for type 3 distribution. This is similar to the results for planned operation with an RF of 1 in the filling period and 0·85 in the depletion period (table 5).

Table 6. Maximum firm power for different reservoir factors

Reservoir factor	Firm power in megawatts.			
	Type 1	Type 2		Type 3
	Dependable year	Dependable year	Dry year	Dependable year
0·60	1129	1000	815	923
0·75	1121	995	803	918
0·85	1107	987	789	912
0·90	1098	980	780	906
0·95	1089	972	770	900
1·00	1079	962	758	890

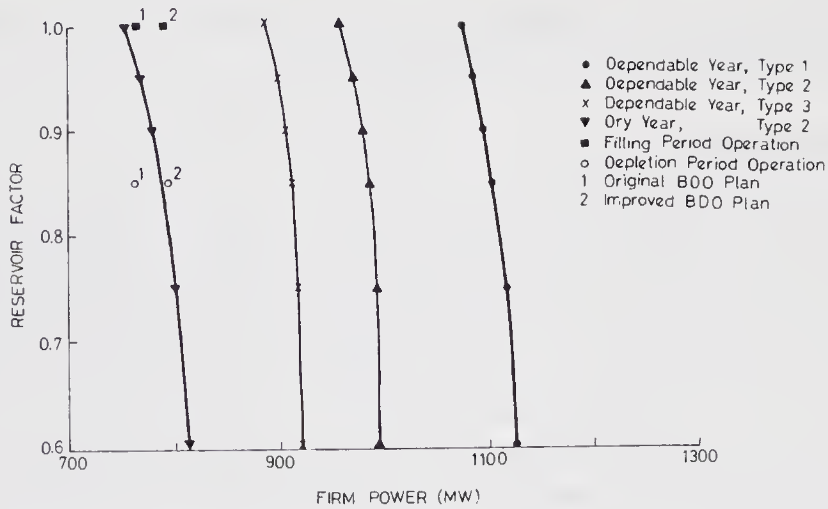

Figure 5. Transformation curves for the Beas-Sutlej system

For a dependable year, the points of operation according to the original and improved plans of the BDO lie very much within the transformation curves. Conjunctive utilization, integrated operation and optimization increase the firm power level of the improved BDO operation (799 MW) by at least 91, 163 and 280 MW respectively for type 3, type 2 and type 1 distributions. Even in a dry year the original planned levels of power and irrigation can be met by adopting conjunctive utilization in an integrated framework.

The trade-off between irrigation and power ranges between 140 and 200 MW/RF. The trade-off between irrigation and power implied in the planned operation of the Bhakra reservoir in an average year is between 240 and 260 MW/RF (table 14, Rao & Ramaseshan, 1985). At higher firm power levels, the relative value of power may decrease indicating a higher trade-off. As the operation at RF of 1 implies a trade-off of utmost 200 MW/RF, operation at RF of at least 1 is indicated. An increase in RF level from 0·85 to 1 can be achieved at a loss in firm power of 22 to 28 MW in a dependable year, and 31 MW in a dry year. This corresponds to a loss of 2·5 % to 4 % of firm power for a gain in irrigation of 17·5 %. Hence it is necessary and possible to meet the irrigation requirements fully, *viz* at RF of 1 throughout the year.

The firm power level reached in a dry year is 200 MW (*i.e.* 20 %) less than that reached in a dependable year. It shows that wide fluctuations in firm power levels are inherent in the system due to hydrologic uncertainty and they remain wide even with conjunctive utilization. This emphasizes the need for over-the-year carryover from wet years to dry years.

6. Conclusions

The following conclusions are derived from this study.

(i) System modelling and optimization of conjunctive utilization of surface and ground waters in an integrated framework leads to a better understanding of the interactions between the irrigation and firm power objectives;
(ii) It is advantageous to divert as much water as possible from the Beas to the Sutlej through the Dehar power plant. This generates much more power at Dehar and Bhakra than at Pong;

(iii) Contrary to current practice groundwater should be used from May to November and surface water conserved in reservoirs during the period. This raises the firm power level significantly;
(iv) The levels of irrigation and power planned for a dependable year from the reservoirs of the Beas-Sutlej system can be attained even in a dry year by conjunctive utilization of surface and groundwaters;
(v) It is desirable and certainly possible to meet the full irrigation requirements of the system throughout the year; and
(vi) Over-the-year carryover storage from wet years to dry years is essential to reduce the wide fluctuations in the levels of objectives attained in different years.

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Optimal irrigation planning in river basin development: The case of the Upper Cauvery river basin

S VEDULA

Ford India Project, Department of City and Regional Planning, Harvard University, Cambridge, Massachusetts, USA

Present address: Department of Civil Engineering, Indian Institute of Science, Bangalore 560012.

Abstract. The study deals with the irrigation planning of the Cauvery river basin in peninsular India which is extensively developed in the downstream reaches and has a high potential for development in the upper reaches. A four-reservoir system is modelled on a monthly basis by using a mathematical programming (LP) formulation to find optimum cropping patterns, subject to land, water and downstream release constraints, and applied to the Cauvery basin. Two objectives, maximizing net economic benefits and maximizing irrigated cropped area, considered in the model are analysed in the context of multiobjective planning and the trade-offs discussed.

Key words. Irrigation planning, multiobjective planning; Cauvery basin; four-reservoir system; Karnataka master plan.

1. Introduction

There is an increasing awareness in recent times of a need to evolve comprehensive basin plans for river basin development to meet the national or regional objectives as best as possible. Irrigation has been one of the most important aspects of this planning. Development plans call for improved strategies to conserve water by adopting better and more efficient water management techniques in existing areas and an optimum irrigation planning in those areas proposed to be brought under new irrigation. Linear programming models of various kinds have been used in the past as planning models in river basin development.

The present study concerns the case of the interstate Cauvery river basin in South India. The lower reaches of the basin have excellent irrigation facilities and extensive irrigation has been in practice in these areas since the beginning of the century. Irrigation development in the upper reaches of the basin has been rather slow and restricted by bilateral agreements between the basin states *viz*. Karnataka, Kerala and Tamil Nadu.

Thus there is a need to extend irrigation facilities to the areas of the upper reaches of the basin subject to providing adequate water supplies to all the areas presently under irrigation in the basin. The present study is based on this hypothesis. An irrigation planning model is formulated for the upper basin (basin above Mettur) to optimize

1. Parts of this paper have been reprinted with permission from the American Geophysical Union: Vedula S and Rogers P P *Water Resources Res.* 17: 1304–1311, 1981 ©AGU.
2. A list of symbols is given at the end of the paper.

crop patterns in the proposed area of development, while meeting the irrigation requirements of the lower basin according to the existing cropping pattern. A linear programming technique was used to find solutions for different objectives. Keeping the proposals made by the Karnataka Master Plan in view, a multi-objective analysis is also made and the implicit trade-off relationships between the different objectives used in planning are determined.

2. The Cauvery basin

2.1 *Basin description*

The Cauvery is one of the major interstate rivers of South India. The river rises in the Coorg district of Karnataka, flows in a general south-east direction across the plateau of Karnataka, and after traversing a distance of 400 km runs along the boundary between Karnataka and Tamil Nadu for 60 km before entering Tamil Nadu upstream of the Mettur Reservoir (built in 1934). The river then flows through Tamil Nadu for 230 km before reaching the Grand Anicut, the head of the Delta, and thereafter it divides into a number of branches and finally joins the Bay of Bengal in Tamil Nadu. The total length of the river from its origin to the sea is 800 km. Figure 1 gives a plan of the basin.

The salient features of the basin are given in detail in the Karnataka State Master Plan (1976). The Cauvery has 21 principal tributaries (drainage area of each of which is greater than 250 km^2). Of these, 9 are located wholly or largely in Karnataka and 12 in Tamil Nadu. The basin has a total drainage area of 81,155 km^2 of which 34,273 km^2

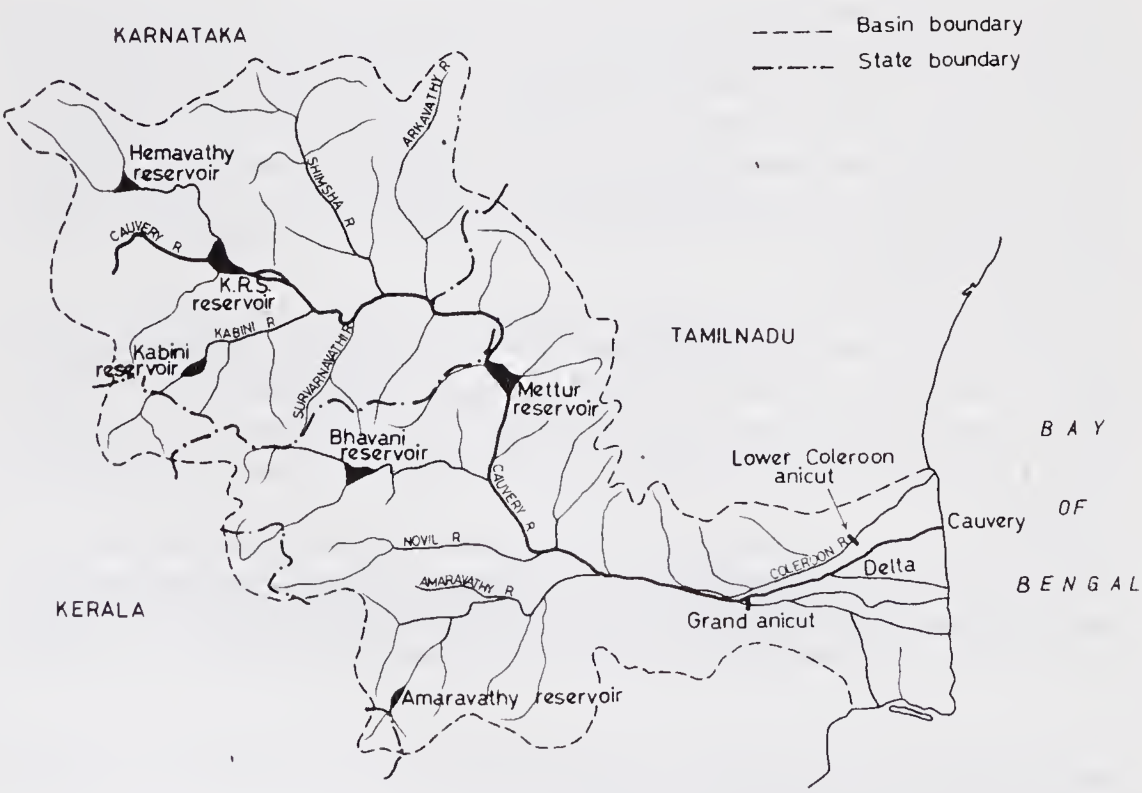

Figure 1. Cauvery basin plan (not to scale).

(42.2 %) lies in Karnataka, 2866 km^2 (3.5 %) in Kerala and 44,016 km^2 (54.3 %) in Tamil Nadu.

2.2 *Rainfall*

The basin is under the influence of both the south-west (June to September) and the north-east (October to December) monsoons. The annual rainfall in the basin varies from less than 60 cm over the north-western part of the Amaravathi sub-basin to more than 600 cm near the source of the Cauvery River in the extreme west of the basin. The high rainfall however diminishes rapidly eastward. The basin in the east (Lower Coleroon sub-basin and the Delta) has an average annual normal rainfall of about 120 cm. Elsewhere in the basin the annual rainfall is lower than 80–85 cm.

2.3 *Surface water resources*

There are 24 discharge sites on the Cauvery River and its tributaries, of which 8 are on the main river. Fifteen discharge sites are in Karnataka, while 9 are in Tamil Nadu.

The mean annual flows in the Cauvery River at different locations along its course are as follows, the flows indicated being exclusive of consumptive use by upstream irrigation: at Chunchanakatte, 48 km upstream of the Krishnaraja Sagara (KRS) dam, 2908 m cu m; at the KRS dam, 5904 m cu m; at Dhanagere Ane, upstream of its confluence with the Shimsha, 8874 m cu m; and at Mettur, 9628 m cu m.

The net gain (average annual gain) in the river flow in each of the three important reaches is as follows: KRS-Mettur, 2973 m cu m; Mettur-Grand Anicut, 2690 m cu m; and Grand Anicut-Lower Coleroon Anicut, 827 m cu m.

2.4 *Groundwater resources*

No estimates of groundwater potential are available for the Cauvery basin in Karnataka. However, Karnataka estimated the quantum of deep percolation in its part of the basin as 3936 m cu m (Master Plan, Part I, page 52) of which a substantial part is supposed to be flowing down to the lower reaches of the basin (in Tamil Nadu). The groundwater development to date has been estimated to be 538 m cu m only. The reason for this low rate of groundwater development is that the area in Karnataka is largely rocky comprising mainly of igneous and metamorphic rocks. However, the geological settings are believed to be quite favourable for groundwater development in the delta region with the thickness of sedimentary formations extending to great depths. The total quantity of replenishable groundwater that can eventually be extracted in the delta, according to UNDP investigations, amounts to about 3650 m cu m per year (Master Plan, Part I, 1976). This is apparently unused at the present time. The total recharge in the non deltaic area in Tamil Nadu is estimated to be 2718 m cu m, whereas the groundwater utilization is to the extent of 1954 m cu m.

2.5 *Development of irrigation*

Irrigation has been practised in the Cauvery Basin from ancient times, by inundation from delta channels and by tanks and river/anicut channels in the entire basin above the delta.

At the beginning of the 20th century, the aggregate ayacut developed for irrigation was about 700,000 ha out of which nearly 430,000 ha was in the delta. Two major reservoirs were constructed in the early thirties on the main river: the KRS reservoir in Karnataka with a live storage of 1269 m cu m and the Mettur reservoir in Tamil Nadu with a live storage of 2648 m cu m. The third major irrigation project on the river is the delta canal irrigation, the canals taking off from the Grand Anicut in Tamil Nadu. Thus by 1971 this aggregate ayacut progressively increased to 840,000 ha. The position in 1971 indicates that Karnataka had irrigation facilities available to 11 % of its culturable area in the basin as against 30 % in Tamil Nadu (table 1). The irrigated cropped area in the basin in 1971 was 1·57 million ha, of which 1·26 million ha was in Tamil Nadu (table 2). Thus irrigation facilities are not evenly distributed over the whole basin.

2.6 *The problem*

One fourth of the people of Karnataka, about 7·14 million, live in the Cauvery Basin, the second largest river basin in the State, covering 18 % of its total area. Almost 2/3 of the basin area in Karnataka State has been identified by the Irrigation Commission (1972) as drought-affected. Thus large areas of the basin with scanty rainfall are starved of irrigation waters in Karnataka, whereas lower downstream the methods of irrigation are old, with the result that a large amount of water is being wasted by going into the sea unutilized. An examination of the withdrawal rates of water for canal irrigation indicates that the withdrawals are far greater than the irrigation requirements

Table 1. Area irrigated in Cauvery basin (ayacuts)

	Karnataka	Kerala	Tamil Nadu	Total
		(in lakh hectares*)		
1. Culturable area in basin	24·8	1·5	28·9	55·2
Area developed as in 1971				
2. *Ayacut*				
(*a*) Under tanks or minor works	1·0	0·2	1·2	2·4
(*b*) Under river/anicut channels	0·8	· ·	0·9	1·7
(*c*) In delta, old	· ·	· ·	4·3	4·3
(*d*) Under major and medium schemes of twentieth century	0·9	· ·	2·3**	3·2
(*e*) Total	2·7	0·2	8·7	11·6
3. Percentage of total ayacut to culturable area	(11)	(13)	(30)	(21)
Developments as per Master plan				
4. New ayacut				
(*a*) Under minor schemes	0·5	0·1	0·1	0·7
(*b*) Under major and medium projects	5·6	0·7	1·1***	7·4
(*c*) Total	6·1	0·8	1·2	8·1
5. Aggregate ayacut $2e+4c$	8·8	1·0	9·9	19·7
6. Percentage of aggregate ayacut to culturable area	(36)	(67)	(34)	(36)

Source: Karnataka Master Plan (1976)

* except figures in brackets which are percentages, correct to the nearest whole number.
** including 43,700 ha outside the basin developed by Cauvery waters.
*** including 72,500 ha developed by waters imported from outside the basin.

Table 2. Irrigated cropped areas in Cauvery basin

	Karnataka	Kerala	Tamil Nadu	Total
		(in lakh hectares)		
1. Culturable area in basin	24·8	1·5	28·9	55·2
Developments as in 1971				
2. Irrigated cropped area (ICA)				
(*a*) Under tanks or minor works	1·0 (100)	0·3 (150)	1·2 (100)	2·5
(*b*) Under river/anicut channels	0·8 (100)	..	1·5 (167)	2·3
(*c*) In delta, old	..	..	7·1 (165)	7·1
(*d*) Under major and medium schemes of twentieth century	1·0 (111)	..	2·8 (122)	3·8
(*e*) Total	2·8 (104)	0·3 (150)	12·6 (145)	15·7
Developments as per Master plan	(as in a dependable year)			
3. Increased cropped area on 2(b), (c) and (d) above	2·8 (155)	..	14·6 (195)	17·4
4. New cropped area				
(*a*) Under minor schemes	0·5 (100)	0·1 (150)	0·1 (100)	0·7
(*b*) Under major and medium projects	7·9 (141)	1·4 (200)	1·4 (127)	10·7
5. Aggregate cropped area	12·2 (139)	1·8 (180)	17·3 (175)	31·3

(Figures in brackets represent intensity of irrigation over ayacut in per cent)
Source: Karnataka Master Plan (1976)

and that a substantial amount of water is just flowing into the sea. Severe waterlogging and drainage problems have been reported in the downstream reaches and in the delta (Master Plan, Part I, 1976). Development of irrigation in Karnataka had been severely restricted after the construction of the KRS and Mettur reservoirs by a 50 year bilateral agreement between the states of Karnataka and Tamil Nadu, commonly known as the 1924 agreement (which expired in 1974). There has been considerable development in the basin in recent times and consequently the upstream states are demanding a better share of the river waters.

Karnataka took a critical view of the position as it existed in 1971 and proposed a number of developments and new projects in the Master Pian (1976) and also recommended cropping patterns in the whole basin, based on an analysis of rainfall distribution. Tamil Nadu, on the other hand, essentially proposed a modernization of the entire delta system. This is meant to put the waters presently available to more efficient use, alleviate the drainage problems in the delta and bring about better management of the irrigation system as a whole. Negotiations are presently underway for an amicable solution regarding sharing of waters among basin states.

2.7 *The Karnataka Master Plan*

The Karnataka Master Plan divides the entire Cauvery Basin into 16 sub-basins for its analysis. The improvement of irrigation envisaged in the plan is shown in tables 1 and 2. The plan was developed on the premise that only one crop of paddy will be grown in the entire basin (including those areas in Tamil Nadu where extensive double cropping of paddy has been in vogue traditionally for many years). The Master Plan recommends construction of three new reservoirs across the Cauvery river, two in Karnataka and one in the river reach common to Karnataka and Tamil Nadu to gain better control of the waters for irrigation development and to substantially increase the power production. The plan suggests that the cost be shared by the two states appropriately. The details of the plan are contained in the three part publication of the Master Plan (1976).

2.8 *Assumptions in the present study*

There are already a few major storage structures under construction in the upper basin and there is great need for planning the optimum use of the diversions from these reservoirs. It may not be easy to radically change the cropping patterns in areas below Mettur to a single paddy cropping as suggested in the Master Plan. Earlier experience in the Lower Bhavani (Planning Commission 1965) clearly shows the difficulty of adopting the planned cropping patterns in practice. Radical changes in existing cropping patterns which have been in existence for a long time could be expected to be even more difficult to accomplish. This forms one of the working assumptions for the present study. Secondly, the present withdrawals into the canals and the diversions seem to be far greater than the actual requirements in certain areas. Also there is great potential for developing the groundwater resources available in the delta to augment the surface supplies.

3. The Upper Cauvery Basin Study

3.1 *Object of the study*

This study aims at bringing out an optimum plan of cropping in the upper basin ensuring adequate supplies for irrigation according to the existing cropping pattern in the lower basin. For the present investigation, the reservoir site at Mettur forms the boundary between the upper basin and the lower basin. This is considered appropriate because (i) most of the proposed new irrigation developments are upstream of Mettur and (ii) Mettur reservoir primarily regulates the flow for downstream irrigation needs along the main river and in the delta.

All major irrigation projects in the upper basin are considered in the study. The activity points for study in the upper basin are the diversions at the four reservoirs: Hemavathy, KRS, Kabini and Mettur (table 3). The water diversion requirements for existing irrigation considered are for those areas presently being irrigated by diversions from the main river. These areas comprise of (i) the delta including the ayacut of the Grand Anicut canal and (ii) the non delta. The non delta area comprises the ayacuts of the Mettur canal, Salem Trichy channels, Kattalai channels, New Kattalai high level canal and Pullambadi canal. It is assumed that the requirements of the Lower Coleroon sub-basin would be met by the river gains between the Grand Anicut-Lower Coleroon Anicut reach and from the groundwater available in the sub-basin.

Table 3. Reservoir capacities and areas planned for irrigation

Status	Reservoir	Capacity m cu m	Land area proposed for irrigation (ha)
Under construction	Hemavathy	962·77	248,900
Existing	KRS	1268·59	77,900*
Under construction	Kabini	453·07	87,800
Existing	Mettur	2647·60	—

* This is in addition to the existing irrigation at KRS reservoir.

3.2 *Features of the study*

Optimum crop patterns in the upper basin are arrived at by an optimization process using a linear programming model for the upper basin. Two systems are formulated: a four-reservoir system consisting of the Hemavathy, KRS, Kabini and Mettur reservoirs and a three-reservoir system consisting of the Hemavathy, KRS and Kabini reservoirs. In the three-reservoir system, the storage at Mettur is not considered and the release from the three-reservoir system is controlled in such a way that the inflows at Mettur are adequate to meet the requirements of the lower basin. For each of the two systems studied, two cases are examined, with and without considering the 'upstream developments'. The 'upstream developments' considered provide for the water requirements of all projects under construction and proposed (in the Master Plan) upstream of KRS reservoir. These include irrigation by storages at (i) Harangi (under construction), and (ii) Votehole, Yagachi, Cauvery reservoir project, Chicklihole and Lakshmanathirtha (proposed). For each of the cases considered above, three objectives *viz* maximizing (i) the net benefit from agriculture, (ii) the total irrigated cropped area and (iii) the total reservoir diversions are studied. The trade-off relationships between the first two objectives are also discussed.

In all cases, it is ensured that the water available at Mettur is adequate to meet the irrigation requirements of the lower basin as defined earlier on a monthly basis according to the existing cropping pattern. Out of the four major reservoirs in the upper basin, two exist and two are under construction. The Hemavathy and Kabini reservoirs are presently under construction with ayacuts of 248,900 ha and 87,800 ha respectively. The ayacut of the existing KRS reservoir which is presently at 716,600 ha is proposed to be extended by an additional 77,900 ha. The Mettur reservoir supplies water to the Mettur canal which has an ayacut of 18,200 ha.

3.3 *The model*

A twelve season (monthly) linear programming model is formulated for the reservoir system in the upper basin. The input for the deterministic model consists of the mean monthly inflows into the reservoirs, mean monthly evaporation and mean monthly water diversion requirements at existing areas (if any) irrigated by reservoir diversions (KRS and Mettur reservoirs). Two models are formulated, one for the four-reservoir system and another for the three-reservoir system. In the formulation of the model, the reservoirs are represented as A, B, C, and D (explained in figure 2). The models have a lot in common. Departures occur in the formulation of constraints which will be mentioned where necessary. The objectives are common for both the models.

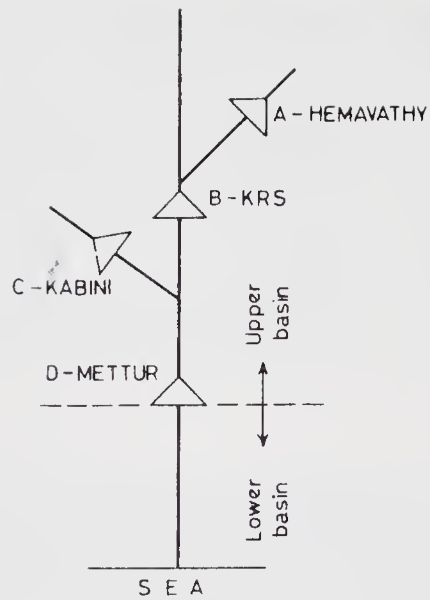

Figure 2. The four-reservoir system of the river basin under study.

3.3a *Objective function*: Three objective functions are studied.

Objective (1): To maximize the net benefit from all crops

$$\max \sum_{i=1}^{M_a} \alpha_i (IA)_i + \sum_{j=1}^{M_b} \beta_j (IB)_j + \sum_{k=1}^{M_c} \gamma_k (IC)_k$$
$$+ \sum_{u=1}^{N_a} \alpha'_u (UA)_u + \sum_{v=1}^{N_b} \beta'_v (UB)_v + \sum_{w=1}^{N_c} \gamma'_w (UC)_w. \tag{1}$$

The model with this objective function considers the options of irrigating or not irrigating any or all of the area available under the command of each reservoir.

Objective (2): Maximize total irrigated cropped area:

$$\max \sum_{i=1}^{M_a} (IA)_i + \sum_{j=1}^{M_b} (IB)_j + \sum_{k=1}^{M_c} (IC)_k. \tag{2}$$

Objective (3): Maximize total annual reservoir diversions:

$$\max \sum_{i=1}^{M_a} p_i (IA)_i + \sum_{j=1}^{M_b} q_j (IB)_j + \sum_{k=1}^{M_c} r_k (IC)_k. \tag{3}$$

3.3b *Constraints*: The constraints are discussed below.

(i) Storage-continuity equations: There are 12 equations for each reservoir, one for each month. Each of the equations states that {storage at the beginning of a month + total inflow during the month (unregulated inflow plus release from an upstream reservoir, if applicable) – total amount of water diverted to irrigated crops during the month as per their requirement – downstream release during the month – evaporation during the month} = {storage at the beginning of the next month}. Thus the storage continuity equations for the four reservoirs A, B, C and D for the month m read (after rearrangement) as,

$$(SA)_m - (SA)_{m+1} - \sum_{i=1}^{M_a} p_{m,i}(IA)_{m,i} - (RA)_m = (EA)_m - (FA)_m. \tag{4}$$

$$(SB)_m - (SB)_{m+1} + (RA)_m - \sum_{j=1}^{M_b} q_{m,j}(IB)_{m,j} - (RB)_m$$
$$= (EB)_m - (FB)_m + (WB)_m, \tag{5}$$

$$(SC)_m - (SC)_{m+1} - \sum_{k=1}^{M_c} r_{m,k}(IC)_{m,k} - (RC)_m = (EC)_m - (FC)_m, \tag{6}$$

$$(SD)_m - (SD)_{m+1} + (RB)_m + (RC)_m - (RD)_m$$
$$= (ED)_m - (FD)_m + (WD)_m, \; m = 1, 2, \ldots 12. \tag{7}$$

The three-reservoir system model will not involve (7) given above.

(ii) Land area constraints: The total cropped area (irrigated and unirrigated) in each month is limited to the land that is in command of each of the reservoirs. There can be a maximum of 12 such constraints for each reservoir. The actual number of constraints depends on the cropping pattern. The constraint for reservoir A in a typical month m is expressed in the form

$$\sum_{i=1}^{M_a} (IA)_{m,i} + \sum_{u=1}^{N_a} (UA)_{m,u} \leqslant (LA), \quad m = 1, 2, \ldots, 12. \tag{8}$$

Similarly, the constraints for month m in the case of reservoirs B and C are expressed as

$$\sum_{j=1}^{M_b} (IB)_{m,j} + \sum_{j=1}^{N_b} (UB)_{mj} \leqslant (LB), \quad m = 1, 2, \ldots, 12, \tag{9}$$

and

$$\sum_{k=1}^{M_c} (IC)_{m,k} + \sum_{k=1}^{N_c} (UC)_{m,k} \leqslant (LC), \quad m = 1, 2, \ldots, 12, \text{ respectively.} \tag{10}$$

In a month where one crop ends and another begins, the area of ending crop is not included in the constraint to permit the possible use of the land for both the crops during different times in that month. No such constraints are needed for reservoir D as there is no new irrigation proposed. The requirements of existing irrigation are accounted for in the storage continuity equations (7) and the only decision variable at reservoir D is the downstream release.

(iii) Downstream release constraints: For a three-reservoir system, the sum of the releases from the reservoirs B and C (KRS and Kabini reservoirs respectively) in each month should not be less than a specified value for that month, *i.e.*

$$(RB)_m + (RC)_m \geqslant (DM)_m, \quad m = 1, 2, \ldots, 12. \tag{11}$$

The values $(DM)_m$ for $m = 1, 2, \ldots, 12$ were computed such that if the river flows are maintained at these values, they ensure adequate water supply for existing irrigation in the delta and the non delta areas below Mettur as defined earlier.

For the four-reservoir system, the storage at reservoir D is also taken into account and the downstream release, $(DD)_m$ in each month m, is specified as the minimum release to ensure adequate water supply for existing irrigation in the delta and the non delta areas below Mettur as defined. In this case however, the area irrigated by the Mettur canals is not included in the 'non delta' area as their water requirements were accounted for by the term $(WD)_m$ in (7). Thus for reservoir D, the release constraints are

$$(RT)_m \geqslant (DD)_m, \quad m = 1, 2, \ldots, 12. \tag{12}$$

The values of $(DM)_m$ in (11) and $(DD)_m$ in (12) were computed from the data as described later.

(iv) Storage capacity constraints: The storage in any month is limited to the capacity (live storage capacity) of the reservoir. For a given month m ($m = 1, 2, 3, \ldots 12$),

$$(SA)_m \leqslant (SA)_{\max}, \tag{13}$$

$$(SB)_m \leqslant (SB)_{\max}, \tag{14}$$

$$(SC)_m \leqslant (SC)_{\max}, \tag{15}$$

$$(SD)_m \leqslant (SD)_{\max}, \tag{16}$$

where $(SA)_{\max}$, $(SB)_{\max}$, $(SC)_{\max}$ and $(SD)_{\max}$ represent the live storage capacities of reservoirs A, B, C and D respectively.

The decision variables in the model are the cropped areas (irrigated and unirrigated) in the areas commanded by each of the reservoirs A, B and C, beginning-of-the month storage and the monthly downstream releases at each of the reservoirs. As the reservoirs are assumed to be operated for irrigation only, the fluctuations of the reservoir level are not considered to pose any problems.

3.4 *Data input to the model*

Most of the data used in this study were either taken directly or computed from the information provided in the Karnataka Master Plan (1976).

3.4a *Inflow*: The mean monthly unregulated inflows into the four reservoirs (Hemavathy, KRS, Kabini and Mettur) in the upper basin are given in table 4. These inflows are exclusive of the existing consumptive use upstream of the reservoir sites. The river gain in the KRS-Mettur reach is taken as the unregulated inflow into reservoir D (for modelling) and is given in table 4. Table 5 gives the estimated mean monthly evaporation at the four reservoirs. The monthly distribution of the total annual evaporation at each reservoir is obtained by proportioning it according to the observed monthly evaporation in the area (Master Plan, appendix V, p. 30, statement I).

3.4b *Cropping and crop water requirements*: There are 12 principal crops proposed (in the Master Plan) to be grown in the areas commanded by reservoir A (Hemavathy Reservoir), 10 crops by reservoir B (KRS Reservoir extension) and 14 by reservoir C (Kabini). The model exercises the option of irrigating or not irrigating any or all of these crops depending on the objective used. Table 6 lists the crops considered for irrigation from reservoir A, table 8 shows those from reservoir B and table 10 from reservoir C. Tables 7, 9 and 11 list the unirrigated crops considered for cropping by reservoirs A, B and C respectively, with the growing months for each indicated by the symbol $\times$. These are the same crops as the irrigated crops listed earlier in tables 6, 8 and 10 where the

Table 4. Mean monthly inflows (unregulated) into the reservoirs (in m cu m)

Month m (1)	Reservoir A $(FA)_m$ (2)	B $(FB)_m$ (3)	C $(FC)_m$ (4)	D $(FD)_m$ (5)
June	109·13	254·49	256·2	−1·7
July	716·10	1552·56	997·7	77·3
August	566·79	1121·51	714·0	360·3
September	238·41	407·29	303·0	495·2
October	255·85	325·31	257·1	884·6
November	98·81	101·13	131·6	471·9
December	44·18	53·81	64·6	282·6
January	25·61	35·09	35·8	109·2
February	15·92	26·39	27·0	25·8
March	12·25	15·00	21·8	17·9
April	11·99	23·25	28·2	47·2
May	28·20	49·27	59·9	194·1
	2124·23	3965·10	2896·9	2964·4

(2): Average of 38 years; (3): Average of 35 years at reservoir B – value at (2); (4): Average of 38 years; (5): Net river gain above reservoir D and below reservoirs B and C (Average of 38 years)

Table 5. Estimated monthly reservoir evaporation losses (in m cu m)

Month m	Reservoir A $(EA)_m$	B $(EB)_m$	C $(EC)_m$	D $(ED)_m$
June	8·2	12·9	8·0	15·4
July	7·0	11·1	6·9	13·9
August	6·9	10·8	6·6	13·3
September	6·2	9·7	6·0	13·7
October	6·6	10·3	6·4	11·3
November	6·2	9·7	6·0	9·1
December	7·2	11·4	7·0	9·0
January	8·5	13·4	8·3	10·7
February	9·6	15·1	9·3	11·9
March	12·6	19·6	12·2	14·7
April	11·3	17·8	11·0	13·2
May	8·8	13·9	8·6	13·8
	99·1	155·7	96·3	150·0

monthly water diversion requirements for irrigation are given during the growing months for each crop.

Monthly crop water requirements were computed based on the guidelines given by the Water Technology Division of the Indian Council of Agricultural Research (1971). (Minor modifications were introduced to facilitate computations on a computer in

Table 6. Water diversion requirements of irrigated crops at reservoir A (as depth in metres)

Crop	Number	1 June	2 July	3 August	4 September	5 October	6 November	7 December	8 January	9 February	10 March	11 April	12 May
Rice	1	0·102	0·127	0·200	0·173	0·086	0·014						
Ragi/jowar	2	0	0·044	0·155	0·077	0							
Maize	3	0	0·044	0·155	0·079	0							
Groundnut	4	0	0·044	0·155	0·079	0							
Maize	5					0	0·099	0·277	0·302	0·128			
Poato	6							0·104	0·311	0·373	0·058		
Wheat	7					0	0·037	0·176	0·305	0·038			
Ragi/jowar	8							0·104	0·311	0·373	0·335		
Pulses/ vegetables	9							0·053	0·187	0·225	0·091		
Ragi/jowar	10			0	0·036	0·043	0·117	0·089					
Maize	11			0	0·036	0·043	0·117	0·089					
Soybeans	12						0·020	0·249	0·331	0·220			

respect of averaging the water requirements during a month). Net irrigation requirements of all crops proposed to be grown in all projects (under construction and proposed) in the upper basin were computed taking into account the crop consumptive use and the effective rainfall in the area. In the case of the KRS reservoir, irrigation requirements of existing and proposed (extension) ayacuts were computed as required by the data input to the model, Farm losses are assumed to be 30% and a conveyance efficiency of 70% is assumed. Thus the water diversion requirements (WDR) at the reservoir is twice the net irrigation requirement (NIR) at the farm. The actual crops and the crop periods are chosen according to the proposals of the Karnataka Master Plan at each of the ayacuts. The computed crop water diversion requirements at the Hemavathy, KRS and Kabini reservoirs are given in tables 6, 8 and 10 respectively. The water diversion requirements for existing irrigation at the KRS and Mettur reservoirs are given in table 12.

3.4c *Crop water requirements for areas below Mettur* An estimate is made of the monthly water diversion requirements for existing irrigated areas in the delta and the non-delta areas downstream of Mettur. Only those areas that are irrigated by diversions from the main river are considered. The non-delta areas comprise those areas irrigated by (i) Salem-Trichy channels (ii) Kattalai channels (iii) New Kattalai high level canal (iv) Pullambadi canal and (v) Mettur canal. The delta area is taken to include the ayacut of the Grand Anicut canal.

The total annual water diversion requirements for existing irrigation in the Lower Coleroon sub-basin were estimated at 483·6 m cu m, whereas the average river gain in the reach between the Grand Anicut and the Lower Coleroon Anicut is 827 m cu m. The Master Plan (appendix V, p. 105) estimates that the groundwater potential in the sub-basin is 651 m cu m. For these reasons, it is assumed in the present study that the Lower Coleroon sub-basin does not require any releases from the upstream areas other than the unregulated river flow into the sub-basin.

The minimum downstream release requirements at Mettur reservoir for the four-reservoir system were obtained by summing up the total water diversion requirements for the lower basin (delta and non-delta excluding the Mettur canal area) and deducting the river gain in the Mettur-Grand Anicut reach. The requirement is set at zero in those months when the river gain is greater than the diversion requirement. The monthly releases computed thus, $(DD)_m$, are shown in table 13.

In the case of the three-reservoir system, the minimum sum of the releases from the KRS and Kabini reservoirs has to be specified for each month. To work it out, first the water diversion requirements of the delta and non-delta areas are summed up. The river gain between the Mettur-Grand Anicut reach is deducted from this, rounding off the negative values to zeros. This then gives the inflow requirement at Mettur. The average river gain between KRS and Mettur is deducted from this next, again rounding the negative values to zeros. The monthly releases computed thus, $(DM)_m$, are also shown in table 13.

3.4d *Effect of 'upstream developments' on river inflows* A modification of the inflows given in table 4 is necessary when the proposed 'upstream developments' are taken into account. The computations of water diversion requirements at the projects Yagachi, Harangi, Votehole, Lakshmanathirtha, Chicklihole, and the Cauvery reservoir project, revealed that the annual inflow into the KRS reservoir and into the Hemavathy reservoir would be reduced by 19·7% and 5·7% respectively. The monthly inflows into the KRS

Table 7. Unirrigated crops at reservoir *A*

Crop	Number	1 June	2 July	3 August	4 September	5 October	6 November	7 December	8 January	9 February	10 March	11 April	12 May
Rice	1	×	×	×	×	×	×						
Ragi/Jowar	2	×	×	×	×	×							
Maize	3	×	×	×	×	×							
Groundnut	4	×	×	×	×	×							
Maize	5					×	×	×	×	×			
Potato	6							×	×	×	×		
Wheat	7					×	×	×	×	×			
Ragi/Jowar	8							×	×	×	×		
Pulses/ Vegetables	9							×	×	×	×		
Ragi/jowar	10			×	×	×	×	×					
Maize	11			×	×	×	×	×					
Soybeans	12						×	×	×	×			

Note: × in each row indicates the months in which the crop is grown.

Table 8. Water diversion requirements of irrigated crops at reservoir *B* (as depth in metres)

Crop	Number	1 June	2 July	3 August	4 September	5 October	6 November	7 December	8 January	9 February	10 March	11 April	12 May
Mulberry	1	0·114	0·102	0·095	0·071	0·019	0·083	0·104	0·028	0·059	0·108	0·088	0·016
Rice	2	0·115	0·209	0·206	0·159	0·092	0·014						
Ragi/ jowar	3	0·017	0·142	0·149	0·065	0							
Ground-nut	4	0·017	0·142	0·149	0·065	0							
Ragi/ jowar	5								0·137	0·351	0·479	0·229	
Ground-nut	6						0·018	0·249	0·331	0·264	0		
Pulses/ vegetables	7						0	0·142	0·200	0·075			
Maize	8						0·018	0·249	0·331	0·264	0		
Soybean	9						0·010	0·249	0·331	0·176			
Safflower	10						0	0·142	0·200	0·075			

Table 9. Unirrigated crops at reservoir *B*

Crop	Number	1 June	2 July	3 August	4 September	5 October	6 November	7 December	8 January	9 February	10 March	11 April	12 May
Mulberry	1	×	×	×	×	×	×	×	×	×	×	×	×
Rice	2	×	×	×	×	×	×						
Ragi/jowar	3	×	×	×	×	×							
Ground-nut	4	×	×	×	×	×							
Ragi/jowar	5								×	×	×	×	
Ground-nut	6						×	×	×	×	×		
Pulses/vegetables	7						×	×	×	×			
Maize	8						×	×	×	×	×		
Soybean	9						×	×	×	×			
Safflower	10						×	×	×	×			

Note: × in each row indicates the months in which the crop is grown.

Table 10. Water diversion requirements of irrigated crops at reservoir C (as depth in metres)

Crop	Number	1 June	2 July	3 August	4 September	5 October	6 November	7 December	8 January	9 February	10 March	11 April	12 May
Rice	1	0·117	0·213	0·210	0·167	0·090	0·011						
Ragi/jowar	2	0	0·119	0·141	0·081	0·046							
Jowar	3	0	0·119	0·141	0·081	0·046							
Maize	4	0	0·119	0·141	0·081	0·046							
Groundnut	5	0	0·119	0·141	0·081	0·046							
Potato	6	0·016	0·167	0·153	0·008								
Wheat	7						0	0·091	0·225	0·343	0.047		
Maize	8						0·006	0·247	0·331	0·263			
Jowar	9						0·006	0·247	0·331	0·263			
Groundnut	10						0	0·225	0·345	0·40	0·268		
Potato	11						0	0·153	0·205	0·109			
Soybeans	12							0·104	0·311	0·373	0·280		
Vegetables	13						0	0·142	0·200	0·112	0		
Ragi/jowar	14								0·139	0·350	0·475	0·209	

Table 11 Unirrigated crops at reservoir *C*

Crop	Number	1 June	2 July	3 August	4 September	5 October	6 November	7 December	8 January	9 February	10 March	11 April	12 May
Rice	1	×	×	×	×	×	×						
Ragi/jowar	2	×	×	×	×	×							
Jowar	3	×	×	×	×	×							
Maize	4	×	×	×	×	×							
Groundnut	5	×	×	×	×	×							
Potato	6	×	×	×	×								
Wheat	7						×	×	×	×	×		
Maize	8						×	×	×	×			
Jowar	9						×	×	×	×			
Groundnut	10						×	×	×	×	×		
Potato	11						×	×	×	×			
Soybeans	12							×	×	×	×		
Vegetables	13						×	×	×	×			
Ragi/jowar	14								×	×	×	×	

Note: × in each row indicates the months in which the crop is grown.

Table 12 Water diversion requirements at existing reservoirs in m cu m.

Month	Reservoir *B*	Reservoir *D**	Month	Reservoir *B*	Reservoir *D**
June	82·4	0	December	32·2	4·4
July	149·0	31·2	January	50·2	0
August	134·6	50·0	February	58·8	0
September	95·6	56·0	March	59·2	0
October	52·8	30·4	April	18·2	0
November	24·2	26·0	May	5·2	0

* Mettur canal paddy sowing in mid-July

Table 13 Minimum monthly downstream releases (computed in m cu m)

Month	Four-reservoir system*	Three-reservoir system**	Month	Four-reservoir system*	Three-reservoir system**
June	570·0	610·47	December	0	0
July	1668·5	1719·22	January	329·2	220·04
August	1360·8	1061·47	February	569·5	543·73
September	775·9	308·30	March	708·6	690·73
October	0	0	April	140·0	64·95
November	0	0	May	0	0

* release from Mettur reservoir

** total release from the KRS and Kabini reservoirs, Mettur canal paddy sowing in mid-June and Hemavathy reservoirs given in table 4 were thus reduced by 19·7% and 5·7% respectively and the modified inflows were then used as the input to the model in those studies which included the effect of upstream development.

3.4e *Net benefits from crops* Estimates of net benefit per unit area of irrigated and unirrigated crops are given in table 14. The gross income was computed at the wholesale price of the crop produce and from representative values of crop yield per hectare for the region under study. The only cost of inputs deducted to estimate net benefits is of fertilizers. The dosage of fertilizers is assumed at the optimum value to give maximum yield (Parikh & Srinivasan 1974). All other costs such as labour, pesticides, insecticides and cost of water were not deducted. Thus net benefit, as used in this study, is the gross income less the cost of fertilizer only.

3.5 *Cases studied and their solutions*

The computer solutions were obtained using a MPSX linear programming package on the IBM 370/168 system at Harvard University, Cambridge, Massachusetts. In all runs, the value of $(IB)_1$, the irrigated area for crop 1 (mulberry) at the KRS reservoir, was fixed at 20,700 hectares as proposed in the Karnataka Master Plan. This was done because of the growing demand for the mulberry leaves for sericulture in Karnataka which produces 82% of the total mulberry silk in the country (Report of the National Commission on Agriculture, 1976). The net benefits arrived at in all the solutions exclude those associated with the fixed mulberry cropping.

The following are the various cases considered for detailed analysis, and the table numbers are also given in brackets for reference to their detailed solution: 4*YN* (15); 4*YI* (16); 4*YD* (17); 4*NN* (18); 4*NI* (19); 4*ND* (20); 3*YN* (21); 3*YI* (22); 3*YD* (23); 3*NN* (24); 3*NI* (25); 3*ND* (26); where 3 and 4 in the first place indicate a three-and a four-reservoir system, respectively; *Y* and *N* in the second place indicate that "upstream developments" were considered and not considered, respectively; *N*, *I* and *D* in the third place maximize total net benefits, total irrigated cropped area and total reservoir diversions, respectively.

4. Results and discussion

The results of all cases analysed in respect of the four-reservoir system are summarised below.

Case	*Net benefits* (10^6 Rs)	*Irrigated cropped area* (100 ha)	*Total diversion* (m cu m)
4*YN*	2084.709	527,570	3463.88
4*YI*	1659.623	755,600	3540.15
4*YD*	1738.194	666,061	3994.09
4*NN*	2124.313	621,860	4365.90
4*NI*	1809.500	756,680	4516.80
4*ND*	2008.316	688,090	4767.30

It may be noted that the maximum net benefits for the four-reservoir system increase by only 2% when the upstream developments are not considered. This is because the inflows into the KRS reservoir are not affected significantly by considering upstream developments, as a large portion of the inflow consists of unregulated flow above the reservoir. There is practically no change in the maximum irrigated cropped area between the two cases $4YI$ and $4NI$ indicating that the optimal plan for the water use for the four-reservoir system is practically independent of the existing and proposed upstream developments. The locations of these developments are so far ahead of the major reservoirs in the upper basin that their consideration has little effect on the optimum values of the objectives attained. The optimum total diversion, however, changes by nearly 20 % between the cases $4YD$ and $4ND$.

The optimum cropping patterns for different cases considered in the four-reservoir system are presented in tables 15 through 20. Tables 15 to 17 contain results of the runs with 'upstream developments' and tables 18 to 20 without these. The results of the run $4YN$ (table 15) give the solution for maximizing net benefits in the case in which it is assumed that there is no change in the existing cropping pattern in the upper or the lower basin. All projects existing, under construction and proposed are taken into

Table 14 Estimated net benefits of crops

Crop	Net benefits* (Rs/ha) Irrigated	Unirrigated	Crop	Net benefits (Rs/ha) Irrigated	Unirrigated
Rice	2950	1525	Potato	2500	2380
Ragi/jowar	2450**	1450	Wheat	1900	825
Maize	2300	1300	Soybeans	2800	1300
Groundnut	2400	1100	Pulses/vegetables	600	360

* Net benefits are obtained by deducting the estimated cost of fertilizer from the produce value at wholesale prices (at 1970–72 levels) ** Rs 3200 used for runs with the three-reservoir system.

Table 15. Solution for maximum net benefits*—case $4YN$
Maximum net benefits = Rs $2\cdot1 \times 10^3$ million; Total diversion = 3463·88 m cu m; Total irrigated cropped area = 527,570 ha.

Crop	Season	I/U	Cropped area (100 ha)	
Diversion from Hemavathy reservoir				
Rice	June–November	I	1244·5	
Ragi/jowar	June–October	I	1244·5	
Soybeans	November–February	I	557·7	$CI = 2.0$
Potato	December–March	U	1931·3	$II = 1{\cdot}22$
Diversion from KRS reservoir				
Mulberry	Perennial	I	207·0	
Rice	June–November	I	572·0	$CI = 1{\cdot}73$
Soybeans	November–February	I	572·0	$II = 1{\cdot}73$
Diversion from Kabini reservoir				
Rice	June–November	I	878·0	$CI = 2{\cdot}0$
Potato	November–February	U	878·0	$II = 1{\cdot}0$

* Exclusive of mulberry cropping fixed at 20,700 ha; I = irrigated, U = unirrigated: CI = cropping intensity; II = irrigation intensity.

Table 16. Solution for maximum irrigated cropped area—case 4*YI*
Maximum irrigated cropped area = 755,600 ha; Total diversion = 3540·151 m cu m; Total net benefits (excluding mulberry) = Rs $1{\cdot}7 \times 10^3$ million.

Crop	Season	*I/U*	Cropped area (100 ha)	
Diversion from Hemavathy reservoir				
Rice	June–November	*I*	264·5	
Maize	June–October	*I*	492·1	
Groundnut	June–October	*I*	1732·4	
Wheat	October–February	*I*	1960·0	*CI* = 2·0
Potato	December–March	*U*	529·0	*II* = 1·79
Diversion from KRS reservoir				
Mulberry	Perennial	*I*	207·0*	
Groundnut	June–October	*I*	572·0	
Pulses/Vegetables	November–February	*I*	108·7	*CI* = 1·73
Soybeans	November–February	*I*	463·3	*II* = 1·73
Diversion from Kabini reservoir				
Rice	June–November	*I*	260·6	
Ragi/jowar	June–October	*I*	617·4	*CI* = 2·0
Vegetables and minor crops	November–March	*I*	878·0	*II* = 2·0

I = irrigated, *U* = unirrigated; *CI* = cropping intensity; *II* = irrigation intensity; * fixed value

Table 17. Solution for maximum total diversion—case 4*YD*
Maximum reservoir diversion = 3994·092 m cu m; Total irrigated cropped area = 666,061 ha; Total net benefits (excluding mulberry) = Rs $1{\cdot}7 \times 10^3$ million

Crop	Season	*I/U*	Cropped area (100 ha)	
Diversion from Hemavathy reservoir				
Maize	June–October	*I*	2489·0	
Maize	October–February	*I*	297·5	
Wheat	October–February	*I*	1554·7	*CI* = 2·0
Potato	December–March	*U*	636·8	*II* = 1·74
Diversion from KRS reservoir				
Mulberry	Perennial	*I*	207·0*	
Groundnut	June–October	*I*	214·8	
Ragi/jowar	January–April	*I*	572·0	*CI* = 1·73
Rice	June–November	*U*	357·2	*II* = 1·28
Diversion from Kabini reservoir				
Rice	June–November	*I*	878·0	
Ragi/jowar	January–April	*I*	447·6	*CI* = 2·0
Wheat	November–March	*U*	430·4	*II* = 1·51

I = irrigated, *U* = unirrigated; *CI* = cropping intensity; *II* = irrigation intensity; * Fixed value

Table 18. Solution for maximum net benefits*—case 4*NN*
Maximum net benefits = Rs $2{\cdot}1 \times 10^3$ million; Total diversion = 4365·9 m cu m; Total irrigated cropped area = 621, 860 ha.

Crop	Season	*I/U*	Cropped area (100 ha)	
Diversion from reservoir A				
Rice	June–November	*I*	1244·5	
Ragi/jowar	June–October	*I*	1244·5	*CI* = 2·0
Soybeans	November–February	*I*	981·1	*II* = 1·39
Potato	December–March	*U*	1507·9	
Diversion from reservoir B				
Mulberry	Perennial	*I*	207·0	
Rice	June–November	*I*	572·0	*CI* = 1·73
Soybeans	November–February	*I*	572·0	*II* = 1·73
Diversion from reservoir C				
Rice	June–November	*I*	878·0	
Soybeans	December–March	*I*	519·5	*CI* = 2·00
Potato	November–February	*U*	358·5	*II* = 1·59

* Exclusive of mulberry cropping fixed at 20,700 ha, *I* = irrigated, *U* = unirrigated; *CI* = cropping intensity; *II* = irrigation intensity.

Table 19. Solution for maximum irrigated cropped area—case 4NI
Maximum irrigated cropped area = 756,680 ha; Total diversions = 4,516.8 m cu m; Total net benefits = Rs $1{\cdot}8 \times 10^3$ million.

Crop	Season	*I/U*	Cropped area (100 ha)	
Diversion from reservoir A				
Rice	June–November	*I*	259·1	
Ragi/jowar	June–October	*I*	1478·6	*CI* = 2·0
Maize	June–October	*I*	751·3	*II* = 1·79
Wheat	October–February	*I*	1970·8	
Potato	December–March	*U*	518·2	
Diversion from reservoir B				
Mulberry	Perennial	*I*	207·0*	
Rice	June–November	*I*	572·0	*CI* = 1·73
Ragi/jowar	January–April	*I*	572·0	*II* = 1·73
Diversion from reservoir C				
Rice	June–November	*I*	878·0	
Wheat	November–March	*I*	495·6	*CI* = 2·0
Vegetables/pulses	November–March	*I*	300·1	*II* = 2·0
Ragi/jowar	January–April	*I*	82·3	

I = irrigated, *U* = unirrigated; *CI* = cropping intensity, *II* = irrigation intensity; *Value fixed in model.

Table 20. Solution for maximum total diversion—case 4*ND*
Maximum reservoir diversions = 4767·3 m cu m; Total irrigated cropped area = 688,900 ha; Total net benefits = Rs 2·0 × 10^3 million.

Crop	Season	*I*/*U*	Cropped area (100 ha)	
Diversion from reservoir A				
Rice	June–November	*I*	811·7	
Maize	June–October	*I*	1677·3	
Maize	October–February	*I*	608·7	*CI* = 2·0
Wheat	October–February	*I*	256·9	*II* = 1·58
Soybeans	November–February	*I*	573·9	
Potato	December–March	*U*	1049·5	
Diversion from reservoir B				
Mulberry	Perennial	*I*	207·0*	
Rice	June–November	*I*	572·0	*CI* = 1·73
Ragi/jowar	January–April	*I*	572·0	*II* = 1·73
Diversion from reservoir C				
Rice	June–November	*I*	878·0	
Potato	November–February	*I*	376·4	*CI* = 2·0
Ragi/jowar	January–April	*I*	346·9	*II* = 1·82
Potato	November–February	*U*	154·7	

I = irrigated, *U* = unirrigated; *CI* = cropping intensity; *II* = irrigation intensity; *Value fixed in model.

Table 21. Solution for maximum net benefits*—case 3*YN*.
Maximum net benefits = Rs 2·2 × 10^3 million; Total irrigated cropped area = 447,722 ha; Total diversion = 1826·5 m cu m.

Crop	Season	*I*/*U*	Cropped area (100 ha)	
Diversion from reservoir A				
Ragi/jowar	June–October	*I*	2489·0	*CI* = 2·0
Potato	December–May	*U*	2489·0	*II* = 1·0
Diversion from reservoir B				
Mulberry	Perennial	*I*	207·0	
Ragi/jowar	June–October	*I*	572·0	*CI* = 1·73
Ragi/jowar	January–April	*I*	331·2	*II* = 1·43
Ragi/jowar	January–April	*U*	240·8	
Diversion from reservoir C				
Jowar	June–October	*I*	878·0	*CI* = 2·0
Potato	November–February	*U*	878·0	*II* = 1·0

* Exclusive of mulberry cropping fixed at 20,700 ha; *I* = irrigated, *U* = unirrigated; *CI* = cropping intensity; *II* = irrigation intensity.

Table 22. Solution for maximum irrigated cropped area—case *3YI*. Maximum irrigated cropped area = 578,910 ha; Total deversion = 2136·5 m cu m; Total net benefits = Rs 1·6 × 10^3 million

Crop	Season	*I/U*	Cropped area (100 ha)	
Diversion from reservoir A				
Maize	June–October	*I*	2489·0	
Pulses/vegetables	August–December	*I*	193·1	*CI* = 2·0
Potato	December–March	*U*	2295·9	*II* = 1·08
Diversion from reservoir B				
Mulberry	Perennial	*I*	207·0*	*CI* = 1·73
Ragi/jowar	June–October	*I*	572·0	*II* = 1·73
Pulses/vegetables	November–Febraury	*I*	572·0	
Diversion from reservoir C				
Potato	June–September	*I*	878·0	*CI* = 2·0
Vegetables	November–March	*I*	878·0	*II* = 2·0

* Fixed, excluded in computing net benefits; *I* = irrigated, *U* = unirrigated; *CI* = cropping intensity; *II* = irrigation intensity.

Table 23. Solution for maximum diversion—case *3YD*. Maximum diversion = 2277·1 m cu m; Total irrigated cropped area = 444,012 ha; Total net benefits = Rs 1·8 × 10^3 million.

Crop	Season	*I/U*	Cropped area (100 ha)	
Diversion from reservoir A				
Maize	June–October	*I*	2489·0	*CI* = 2·0
Potato	December–March	*U*	2489·0	*II* = 1·0
Diversion from reservoir B				
Mulberry	Perennial	*I*	207·0*	*CI* = 1·73
Ragi/jowar	January–April	*I*	572·0	*II* = 1·00
Ragi/jowar	June–October	*U*	572·0	
Diversion from reservoir C				
Maize	June–October	*I*	851·5	*CI* = 2·0
Ragi/jowar	June–October	*I*	320·6	*II* = 1·33
Rice	June–November	*U*	26·5	
Wheat	November–March	*U*	557·4	

* Fixed, excluded in computing net benefits; *I* = irrigated, *U* = unirrigated; *CI* = cropping intensity; *II* = irrigation intensity.

account above the KRS reservoir including those on the tributaries. In other words, this solution gives the optimum cropping patterns at each of the reservoirs *A*, *B* and *C*, which maximizes the total net benefits. The maximum net benefit from table 15 is Rs 2·1 × 10^3 million and the corresponding irrigated cropped area is 527,570 ha, while the maximum irrigated cropped area possible is 755,600 ha (table 16), which reduces the net benefit to Rs 1·7 × 10^3 million. Table 17 gives the results of the same case but for the

Table 24. Solution for maximum net benefits—case 3*NN*.
Maximum net benefits = Rs $2{\cdot}3 \times 10^3$ million; Total irrigated cropped area = 537,896 ha; Total diversion = 2636·9 m cu m.

Crop	Season	*I/U*	Cropped area (100 ha)	
Diversion from reservoir A				
Ragi/jowar	June–October	*I*	2448·5	*CI* = 2·0
Ragi/jowar	August–December	*I*	40·5	*II* = 1·0
Potato	December–March	*U*	2489·0	
Diversion from reservoir B				
Mulberry	Perennial	*I*	207·0*	*CI* = 1·73
Ragi/jowar	June–October	*I*	572·0	*II* = 1·73
Ragi/jowar	January–April	*I*	483·4	
Soybeans	November–February	*I*	88·6	
Diversion from reservoir C				
Ragi/jowar	June–October	*I*	878·0	*CI* = 2·0
Jowar	November–February	*I*	661·0	*II* = 1·75
Potato	November–February	*U*	217·0	

* Fixed, excluded in computing net benefits; *I* = irrigated, *U* = unirrigated; *CI* = cropping intensity; *II* = irrigation intensity.

Table 25. Solution for maximum irrigated cropped area—case 3*NI*.
Maximum irrigated cropped area = 647,795 ha; Total diversion = 2557·2 m cu m; Total net benefits = Rs $1{\cdot}9 \times 10^3$ million.

Crop	Season	*I/U*	Cropped area (100 ha)	
Diversion from reservoir A				
Ragi/jowar	June–October	*I*	2376·9	*CI* = 1·65
Maize	June–October	*I*	112·1	*II* = 1·65
Wheat	October–February	*I*	1607·0	
Diversion from reservoir B				
Mulberry	Perennial	*I*	207·0*	*CI* = 1·73
Ragi/jowar	June–October	*I*	572·0	*II* = 1·73
Pulses/vegetables	November–February	*I*	572·0	
Diversion from reservoir C				
Ragi/jowar	June–October	*I*	878·0	*CI* = 2·0
Vegetables	November–March	*I*	878·0	*II* = 2·0

* Fixed, excluded in computing net benefits; *I* = irrigated, *U* = unirrigated; *CI* = cropping intensity; *II* = irrigation intensity.

objective of maximizing the total diversions. The maximum diversions are 3994·1 m cu m which yield net benefits of Rs $1{\cdot}7 \times 10^3$ million (all these benefits are at 1970–72 levels). As far as the net benefits are concerned, the results of the case 4*YD* are somewhat midway between the cases 4*YN* and 4*YI*.

There is a definite trade-off between the objectives of maximizing net benefits and maximizing the irrigated cropped area. The latter objective brings a larger number of

Table 26. Solution for maximum diversions—case 3*ND*. Maximum diversion = 3158·5 m cu m; Total irrigated cropped area = 537,561 ha; Total net benefits = Rs $1{\cdot}9 \times 10^3$ million.

Crop	Season	I/U	Cropped area (100 ha)	
Diversion from reservoir A				
Rice	June–November	I	71·0	
Maize	June–October	I	2418·0	CI = 2·0
Maize	October–February	I	281·1	II = 1·11
Potato	December–March	U	2207·9	
Diversion from reservoir B				
Mulberry	Perennial	I	207·0*	CI = 1·73
Rice	June–November	I	572·0	II = 1·73
Ragi/jowar	January–April	I	572·0	
Diversion from reservoir C				
Rice	June–November	I	878·0	CI = 2·0
Soybeans	December–March	I	376·5	II = 1·43
Wheat	November–March	U	501·5	

* Fixed, excluded in computing net benefits; *I* = irrigated, *U* = unirrigated; *CI* = cropping intensity; *II* = irrigation intensity.

less water intensive crops into the solution than the former. In this case, rice and soybeans are reduced or replaced by crops requiring less water like ragi, jowar and wheat, vegetables and pulses. The object of maximizing the irrigated cropped area, has been cited (Report of the Irrigation Commission, 1972, Vol. I, p. 112) as one of the goals set by the Irrigation Commission in irrigation planning. This is meant to primarily increase employment and improve the economic base of the areas proposed for development. In this present case, the maximum irrigated cropped area is 755,600 ha, an increase of 43%, and the corresponding benefits are about Rs $1{\cdot}7 \times 10^3$ million (1970–72 level), a reduction of 20%, compared to the results for the objective of maximizing net benefits. The (total) cropping intensity however remains the same. The net effect of increasing the irrigated cropped area by choosing low water requiring crops on the diversions is that the diversions for maximizing the irrigated cropped area are increased by 2.2% compared with that for net benefits. The aim of maximizing diversions is to some extent complementary to that of maximizing the irrigated cropped area and the results for this are also presented for each case although the objective by itself may not have any practical significance.

The three-reservoir system consisting of the Hemavathy, KRS and Kabini reservoirs is operated such that the releases from the system are adequate to meet the downstream irrigation requirements. In this analysis, the storage at Mettur was not considered. This gives a flexibility of using Mettur storages in lean years. The solutions for this case, again with and without considering upstream developments are given in tables 21, 22, 23 and 24, 25, 26 respectively.

4.1 *Trade-off analysis*

As the sole purpose of diversions is assumed to be irrigation, the objectives of maximizing diversions and irrigated cropped area complement each other. However,

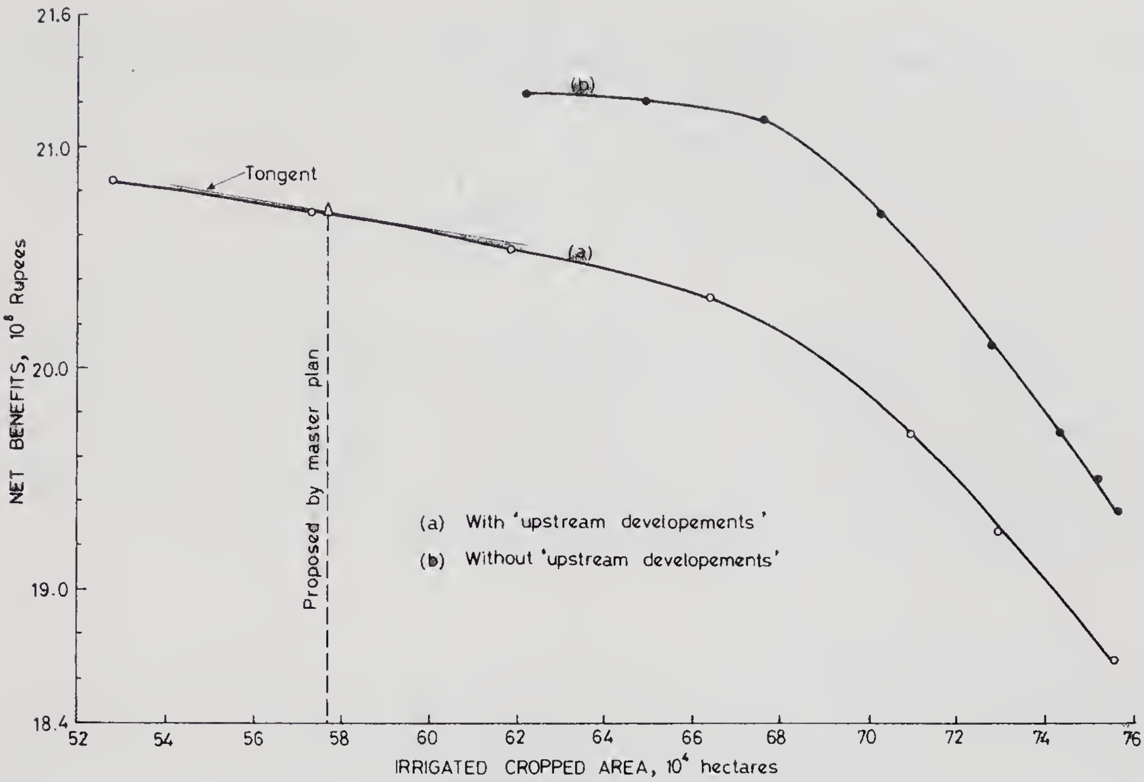

Figure 3. Transformation curves for the four-reservoir system.

the objective of maximizing net benefits is in conflict with either of the other two. Thus, from the point of view of evaluating the trade-offs, it is useful to consider maximizing net income and irrigated cropped area. This is best done by plotting the transformation curve between the irrigated cropped area and the maximum net benefits as in figure 3. Each of the points plotted in the figure is obtained by maximizing the net benefits for a fixed value of the irrigated cropped area and for each of these points, there exists a solution similar to the one given in table 15.

4.1a *Reservoir system with 'upstream developments'—Cases* 4*YN*, 4*YI and* 4*YD*: These cases of the four reservoir system take the upstream developments into account. The solutions for these cases are given in tables 15, 16 and 17. The irrigated cropped area is varied between 527,570 ha and the maximum possible value of 755,600 ha to obtain the corresponding net benefits. The values obtained are given below and their plot is shown in figure 3(a)

Irrigated cropped area fixed at (100 ha)	Maximum net benefits (10^9 Rupees)
5276	2.08
5732	2.07
6188	2.05
6644	2.03
7100	1.97
7300	1.93
7556 (max)	1.87

Any point on the curve defined by these points is then Pareto admissible.

The total irrigated cropped area proposed by the Karnataka Master Plan at reservoirs *A*, *B* and *C* is 576,800 ha after considering the rainfall and local conditions. The model shows that the irrigated cropped area can be increased to any value upto 755,600 ha. It should now be interesting to determine the implied trade-off in the proposed value of 576,800 ha by finding the slope of the tangent to the curve plotted in figure 3(a) at the point corresponding to the irrigated cropped area of 576,800 ha. This was found to be Rs 360 of net benefits per hectare of irrigated cropped area.

4.1b *Four-reservoir system without upstream developments—Cases 4NN, 4NI and 4ND*: These are the cases of the four-reservoir system without the upstream developments, which aim at maximizing net benefits, irrigated cropped area and total diversions, respectively. The solutions for these three cases are given in tables 18, 19 and 20 respectively. The trade-off curve between the net income and the irrigated cropped area is developed for the present case in the same way as in the case with upstream developments. The resulting transformation curve is shown in figure 3(b).

4.2 *Limitations of the study*

The most obvious limitation of the study is that it does not consider the variability of river flows. The model is deterministic with the input consisting of mean monthly values of river flows and evaporation losses. It also does not consider overyear storage. Estimation of crop water requirements is based on general guidelines and assumptions but the actual requirements may vary significantly from place to place depending on the local soil conditions and climatology. Similarly, the farm losses and the conveyance losses to estimate the water diversion requirements from net irrigation requirements may vary from place to place depending on local conditions. In addition, the study carries with it all the limitations of the basic data itself used in various other computations and estimates. Crop yields and net returns for the irrigated and unirrigated crops were estimated based on the data for the whole state, wherever available, and representative values used on consulting available sources of published information (FAO 1975; Government of India 1974).

Another limitation may seem to stem from the argument that the optimum crop patterns obtained from the model may not be acceptable to the farmers. It is emphasized that the present model is a planning model which determines what the optimum or the best cropping pattern should be depending on the objective. Once the possibilities are tested to the limit to see the maximum possible output, the next course of action could be to formulate an operational model to find out how much of this optimum output can actually be realized and in what way.

5. Concluding remarks

The application of the techniques of operations research to the study of the upper Cauvery river basin reveals the extent of irrigation potential at the major projects (existing, under construction and proposed) of the basin. The study is based on mean monthly flows and on a linear programming model. Of all the cases considered, the case of the four-reservoir system comprising the Hemavathy, KRS, Kabini and Mettur reservoirs and which considers the proposed developments upstream of the KRS reservoir is the most interesting. The analysis for the trade-off between the objectives of maximizing net benefits and irrigated cropped area has been carried out, which reveals the implicit trade-off relationships used in the proposals made by the Karnataka Master Plan.

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List of symbols

$(DD)_m$ = minimum release requirement at reservoir D in month m

$(EA)_m$, $(EB)_m$, $(EC)_m$, $(ED)_m$, = evaporation in month m at reservoirs A, B, C and D respectively.

$(FA)_m$, $(FB)_m$, $(FC)_m$, $(FD)_m$ = mean inflows in month m to reservoirs A, B, C and D respectively.

i, j, k = irrigated crop index at reservoir A, B and C respectively.

$(IA)_i$, $(IB)_j$, $(IC)_k$ = irrigated cropped area under crop i at reservoir A, j at B, k at C respectively.

$(IA)_{m,i} = (IA)_i$, the irrigated cropped area for the crop i during the growth month m at reservoir A; (and similar notations for corresponding symbols in (5), (6), and (7), for reservoirs B, C, and D, respectively) = 0, for all other (non-growing) months.

(LA), (LB), (LC) = total land available under the command of reservoirs A, B and C respectively.

p_i, q_j, r_k = total water diversion requirement of crop i at reservoir A, j at B and k at C respectively.

$p_{m,i}$, $q_{m,j}$, $r_{m,k}$ = water diversion requirement for irrigating crop i at reservoir A, j at B, and k at C respectively, during the month m.

$(RA)_m$, $(RB)_m$, $(RC)_m$, $(RD)_m$ = downstream releases from reservoirs A, B, C and D respectively in the month m

$(RT)_m$ = downstream release from reservoir D in month m

$(SA)_m$, $(SB)_m$, $(SC)_m$, $(SD)_m$ = storage at the beginning of month m at reservoirs A, B, C and D respectively.

u, v, w = unirrigated crop index at reservoirs A, B and C respectively

$(UA)_u$, $(UB)_v$, $(UC)_w$ = unirrigated cropped area under crop u at reservoir A, v at B and w at C, respectively.

$(UA)_{m,u} = (UA)_m$, the unirrigated cropped area under crop u during the growing month m (similar notations for corresponding symbols in (9) and (10) for reservoirs B and C respectively) which $= 0$, for all other (non-growing) months.

$(WB)_m$, $(WD)_m$ = water diversion requirements for existing irrigation at reservoirs B and D respectively, during month m

α_i, β_j, γ_k = net benefit per unit area of crops i, j and k respectively.

α'_u, β'_v, γ'_w = net benefit per unit area of crops u, v, and w respectively.

A case study of the Rajasthan canal

RAMESHWAR D VARMA

Department of Civil Engineering, M.R. Engineering College, Jaipur 302017, India

Abstract. The study deals with the policy issues relevant to agriculture development in arid regions where water has a very high economic value. The experience gained in irrigation planning under such conditions in different parts of the world is described. The issues relevant for such a study are the level of technology, the cropping pattern, the area under cultivation and the size of the holdings. For the study of these issues a linear programming model maximizing returns, subject to land and water constraints, has been developed and is applied in the Rajasthan canal command area. The study concludes that agriculture and irrigation technology of a high level should be used to maximize benefits and production, which would also generate more employment.

Keywords. Irrigation planning; arid region; Linear programming model.

1. Introduction

About 36% of the total land area of the world is arid, housing only about 13% of the world's population. With the increasing population of the world the use of arid lands for the settlement of people, food production and other economic activities will increase. Although the experience of some arid lands (*e.g.*, Arizona in the United States and Negev in Israel) has established that economic growth in such areas is possible through agriculture, it is generally believed that because of the acute shortage of water, agriculture may not be a very desirable sector for the economic development of such regions. Whether agriculture should be a primary activity or not, the extent of this activity in desert areas should be determined by formulating a desert development plan for the economic growth of the region, which should take into account the available resources and the expectations of the people. While formulating the plan it should be kept in mind that the delicate environmental balance of the area is easily disturbed and that the unplanned depletion of the productive resources of the region could be dangerous.

The issues involving agricultural development in an arid environment are quite different from those in a humid environment. The important factors for this difference are water shortage, low atmospheric humidity resulting in high rates of evaporation, different soil characteristics, low population density, uneven topography and high cost of regional infrastructure.

The most important input limiting agricultural development in arid lands is water. Water for agriculture is available in the form of precipitation or groundwater or surface water imported from other drainage basins. It can also be made available by treating and purifying waste water or by desalinating seawater; however such waters are usually too expensive to use for agriculture. Water in the form of precipitation is very meagre for sustaining plant life and its availability in quantity as well as in time is highly uncertain. It may become even more uncertain with the unpredictable changes that seem to be taking place in the world climates. Unless good water-harvesting techniques, which are usually capital-intensive, are used rain-fed agriculture will be a risky enterprise and the farmer will be tempted justifiably not to use the essential inputs thereby limiting agricultural production to a very low level. The situation can be improved by developing better predictive methods of rain-water availability and by extending insurance policies to the farmers against crop failures. Policies relating to this dry farming agricultural development involve decisions under risk and uncertainty and have not been considered further in this discussion.

The groundwater resources in arid lands are usually not replenishable. Mining of groundwater for a limited period for agricultural development has been used for some desert areas. However unless definite plans for replenishing these resources are in operation, mining the productive resources of an arid area usually leaves behind an exploited and impoverished resources base. The various issues involved in mining groundwater resources in an arid environment have been discussed by Domenico (1968).

Agricultural development in arid areas is mostly achieved by importing water from other areas. This water has a very high economic value and many policy issues such as the level of technology to be used, cropping pattern, area to be committed for agriculture and size of holdings are involved in its use for the agricultural development and the overall economic growth of the region. Some of these policy issues for the arid lands in India with particular reference to the arid areas commanded by the Rajasthan Canal Project in India are discussed in this paper.

2. Experiences of some other countries

2.1 *USA* (*Arizona*)

Most of Arizona state in the United States is arid. The average precipitation in most parts of the state is less than 50 cm. But with proper planning and water resources management the state has been able to achieve substantial economic growth. The water scarcity was resolved by evolving a set of water-related institutions that would facilitate change in water development and use so that each unit of scarce water used will make its maximum contribution to economic well-being directly through its consumption and indirectly through its use in production (Kelso *et al* 1973). A solution to the problem was found not only in improving water supplies but, more important, in reducing water demands by encouraging change in the structure of the state economy and pattern of water uses.

2.2 *Israel*

Some of the policies followed by Israel in planning its irrigation system were included in the following development criteria (Wiener 1964).

(i) Intensive conservation of available water resources and design of projects to minimize losses.
(ii) A complex resources appraisal methodology.
(iii) Sophisticated management planning of uses of resources.
(iv) Selective use, where feasible, of substandard water for less sensitive uses.
(v) Minimizing (within economic reason) the quantity of water consumed per production unit. In agriculture this requires the proper choice of crops and the

regions where they are to be grown, increasing efficiency in irrigation, artificial reduction of evaporation and evapotranspiration and seed selection.

Table 1 compares the yields at Arizona, Israel and Rajasthan, and also the average for India. The figures indicate the positive effect of proper planning and water resources management in agriculture in the arid regions of Arizona and Israel.

2.3 *USSR*

The New York Times (Anon 1977) reported that the largest canal of its kind in the world, constructed by the Russians, has transformed the economic and social life in Turkmenia, a Soviet Central Asian Republic lying just North of Iran and Afghanistan. More than 80% of Turkmenia is desert. The canal which presently extends 912 km will eventually be 1392 km long with the final section swinging southwest to Turkmenia's subtropical region while a smaller pipeline splits Northwest to carry water for drinking and industrial use. It has been reported that the canal has already paid for itself; Turkemenia's cotton production increased nearly five-fold over the last three decades to 1·12 million tonnes last year with at least half of this growth attributed to the canal. Increases in some other crops like fruit have been nearly as dramatic.

3. Rajasthan canal project

Conceived at the turn of the century to rejuvenate a part of the Indian desert, the Rajasthan Canal Project was formally launched some six decades later in 1958. It contemplates the conveyance of a portion of the Ravi-Beas run-off in Punjab for irrigating 1·15 million hectares of an assorted arid area of Rajasthan State in its districts of Ganganagar, Bikaner and Jaisalmer all bordering Pakistan. Under a treaty between India and Pakistan in 1960, an annual supply of more than 18500 m cu m has been made available to India in which Rajasthan will be entitled to about 9866 m cu m. With the construction of the Pong Dam, assured monthly flows for the year are now available for the Rajasthan canal project (Rao 1975). The Rajasthan canal with a full supply capacity of about 530 cumecs (18700 cusecs) takes off from the Harike Barrage across the Sutlej. The total length of the canal is about 680 km; the main canal and distributaries are to be lined (Irrigation Commission 1972). The conveyance losses in the main canal and distributaries are estimated to be 10%. Water distribution losses in the field (on the farm) are estimated to be 20%. Efforts are being made to reduce these losses by levelling the fields and lining the water courses. The irrigation intensity of the project is expected to be 130%. The project is divided into two stages, the first stage commands an area of about 0·54 million hectares. The construction of the project is an engineering feat achieved by Indian engineers under extremely difficult environmental conditions. A map of Rajasthan showing its soils and the canal is given in figure 1.

Statistics of the arid land of Rajasthan, giving area, population and mean annual rainfall, are given in table 2 districtwise. This shows that the population density in the area commanded by the Rajasthan Canal is low and the project will induce migration of agricultural workers to the area and will provide self employment to the people already there. The existing cropping patterns in the various districts of the desert area of Rajasthan along with the adopted cropping pattern of the project are given in table 3. In this table the cropping pattern in the arid state of Arizona has also been given for

Table 1. Comparative yield in tonnes per hectare of various crops grown in arid regions.

	Yield (1966 to 1975 data)					
Crops	India (average)	Rajasthan (average)	North America	Israel	World maximum	Yield value adopted in the present study
Sugarcane	51·2	13·7	98·5	—	218·2 (Iran)	80·0
Cotton	0·7	0·8	1·6	3·1	3·8 (Botswana)	2·5
Millet (Bajra)	0·5	0·2	3·1	2·5	4·2 (Egypt)	3·6
Pulses	0·5	0·2	1·5	1·4	4·0 (Switzerland)	1·2
Groundnut	0·9	0·4	2·9	3·6	4·3 (Mauritius)	3·0
Paddy (Rice)	1·8	0·7	5·1	—	6·8 (Australia)	5·0
Wheat	1·3	1·0	3·4	3·1	5·7 (Netherlands)	4·0
Mustard	0·5	0·3	—	—	1·8 (Denmark)	1·6
Gram/Peas	0·8	0·6	1·8	5·9	5·9 (Israel)	2·5
Potatoes	10·4	1·5	28·1	29·4	47·6 (Switzerland)	20·0

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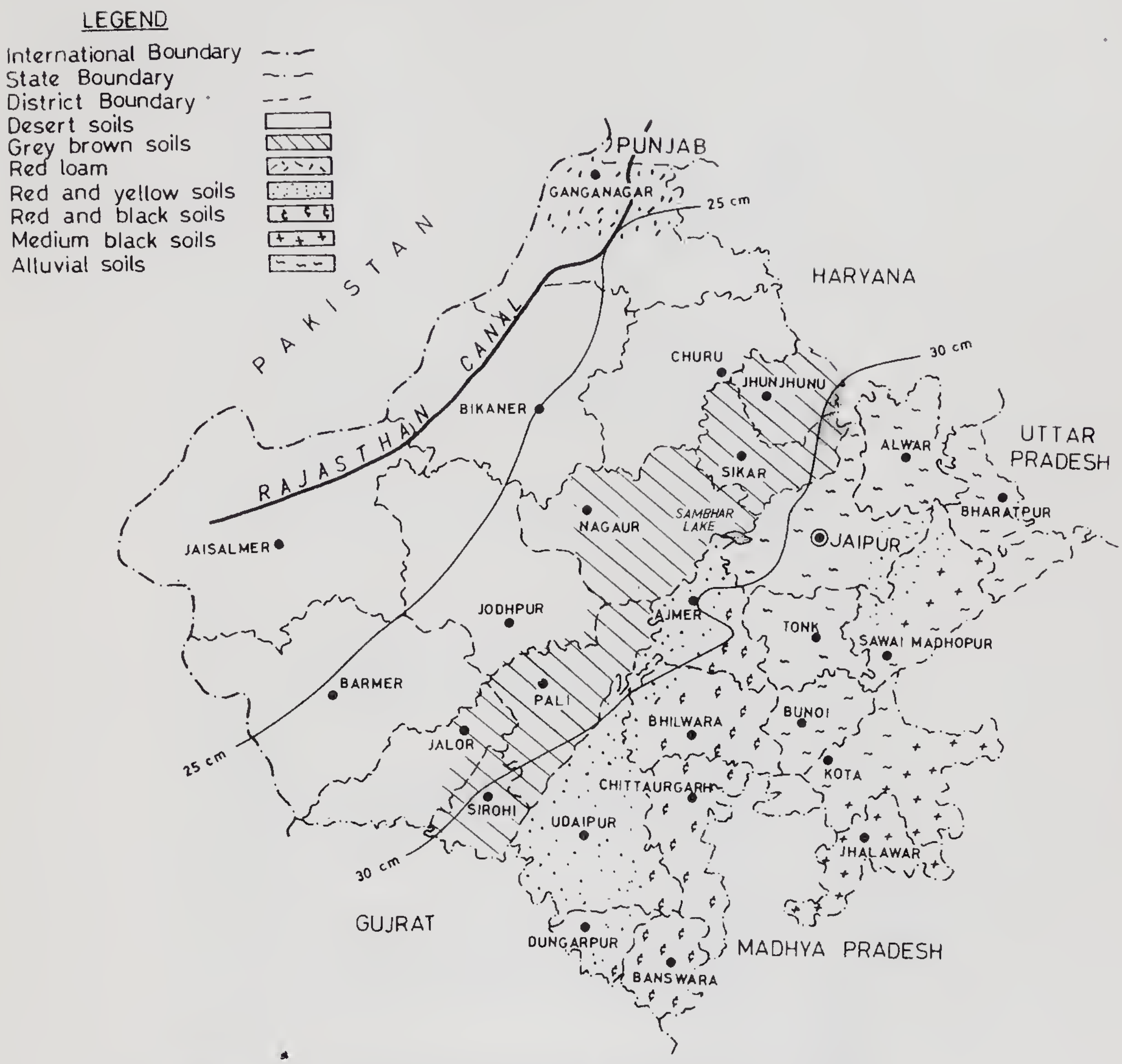

Figure 1. Map of Rajasthan showing soils and the Rajasthan canal.

comparison. Benefits per hectare of farm agriculture have been estimated as given in table 4. In the table, data for citrus fruits and a possible multiple cropping pattern of three short-duration crops have also been included, although these crops presently are not amongst those adopted in the cropping pattern.

The project area is located in an ancient flood plain of the Indus river system. In recent geological times, the alluvial soils have been overlain and mixed with wind-blown sand resulting in a vast expanse of shifting sand dunes. About 20% of the command area of the canal has *tal* (saline/alkaline) soil which is amenable to reclamation through leaching. Most of the paddy, sugarcane and cotton included in the adopted cropping pattern of the project are expected to be grown on the *tal* soil.

4. Policy issues

One very important policy matter for the agricultural development of arid lands pertains to the level of technology (agriculture as well as irrigation) that should be used.

Table 2. Statistics of the arid areas of Rajasthan

District	Area in km²			Population in millions			Population density (persons/km²)		Mean annual rainfall (cm)
	Rural	Urban	Total	Rural	Urban	Total	Rural	Urban	
Ganganagar*	20544	85	20629	1·164	0·230	1·394	57	2697	21·8
Bikaner*	27057	174	27231	0·336	0·237	0·573	12	1360	29·2
Churu	16604	225	16829	0·616	0·259	0·874	37	1151	—
Jhunjhunu	5849	80	5929	0·767	0·162	0·929	131	2031	—
Sikar	7671	61	7732	0·865	0·177	1·043	113	2932	43·1
Jaisalmer*	38051	350	38401	0·142	0·024	0·167	4	70	17·9
Jodhpur	22404	456	22860	0·409	0·197	0·607	35	807	36·1
Nagaur	17478	240	17718	1·107	0·155	1·262	63	647	—
Pali	12198	193	12391	0·862	0·108	0·970	71	562	—
Barmer	28353	34	28387	0·719	0·056	0·775	25	1654	26·3
Jalore	10629	11	10640	0·638	0·030	0·668	60	2810	—
Total	206838	1909	208747	7·625	1·635	9·262	35†	856†	

*Most of the command area of the Rajasthan Canal lies in these districts; †Average

Table 3. Proportion of area under important crops to total cropped area in districts of desert region of Rajasthan (present)

Districts	Proportion of crops									
	Millet (bajra)	Sorghum (jowar)	Maize	Wheat	Barley	Pulses	Gram	Rape and mustard	Sesame	Groundnut
Barmer	81·1	8·2	—	1·3	0·1	1·8	0·1	—	1·0	—
Jalore	65·6	8·3	0·2	7·1	0·5	3·5	0·3	0·7	4·0	—
Jaisalmer	77·6	3·9	—	1·2	—	—	—	—	—	—
Jodhpur	57·4	1·1	—	2·3	0·2	17·3	0·3	—	3·8	—
Bikaner	39·9	0·2	—	—	—	42·1	—	—	—	—
Churu	36·4	—	—	—	—	38·1	3·3	—	0·2	—
Ganganagar	12·2	0·4	0·1	12·3	2·8	8·4	29·3	1·6	—	—
Nagaur	46·1	6·2	0·1	1·6	1·0	23·1	0·7	0·1	5·7	0·3
Pali	27·3	12·2	5·0	9·2	4·7	3·9	1·5	0·2	17·7	0·3

Cropping pattern in Arizona U.S.A.: Alfalfa 17%, citrus fruits 4%, cotton 22%
grains 40%, vegetables 7%, others 10%

Cropping pattern adopted in Rajasthan Canal Project:
Sugarcane (*Tal* soil) 4%, cotton 25%, millet 5%, pulses 16%
fodder 5%
groundnut 5%, paddy 12%, wheat 34%, mustard 12%
gram 24% (*Tal* soil)
fodder 2%, potatoes 2%

Table 4. Benefits per hectare of farm agriculture

Computer names	Crop	Yield in tonnes	Estimated farm gate price per tonne Rs	Cost of production Rs	Estimated cost of input use (excluding labour) Rs	Net Benefit per hectare Rs
CP1	Sugarcane	80	100	8000	1700	6300
CP2	Cotton	2·5	2100	5250	850	4400
CP3	Millet	3·63	800	2904	525	2379
CP4	Pulses	1·24	1200	1488	315	1173
CP5	Fodder	45	90	4050	30	4030
CP6	Groundnut	3·0	1400	4200	535	3665
CP7	Paddy	5·0	900	4500	980	3520
CP8	Wheat	4·0	1940	7800	910	6890
CP9	Mustard	1·6	1750	2800	550	2250
CP10	Gram	2·52	900	2268	370	1898
CP11	Citrus fruits	60,000 No. per year	0·20 Paise per orange	12000	650	11350
MCP1	Wheat (Sonora) (January to April)	3·2	1950	6240	740	5500
MCP2	Maize (June to September)	3·0	1200	3600	1100	2500
MCP3	Potato (October to December)	16·0	600	9600	1800	7800

As will be discussed later, there are divergent views on this issue in literature.

Another important policy question pertains to the use of water. Water in an arid land can be used to meet the full irrigation requirements of the plants in a limited area thereby obtaining maximum crop yield per unit land area (assuming adequate supplies of other inputs) or the water could be used to meet only part of the irrigation requirements of the plants in a greater cropped area. The basic difference on this question between an arid and humid environment is that while in the case of the former, the plant will grow and survive only because of the water supplied from the irrigation system, the soil moisture in a humid environment may always remain above the permanent wilting point and therefore the plant can grow even without the use of irrigation water.

A third policy question deals with the appropriate size of land holdings in areas to be colonized. Should the holding size be large, small or some in-between size?

The fourth important policy area is that of the employment generated by the developments. As will be seen later, these four policy questions cannot be considered as separate issues. Choices in one area make large impacts in other areas.

5. Study model

The objective of this study is to evolve the effect of technology transfer on the total benefits of the project and on the agricultural income of the farmers after full project development has taken place and all the capital expenditure incurred initially has been recovered. Two parameters of the technology transfer were considered. One parameter was the level of technology used in improving the irrigation efficiency of the system. It was assumed that with the furrow or the border strip irrigation system, an irrigation efficiency of 70% could be achieved, while with the use of drip irrigation or sprinklers, an irrigation efficiency of 90 or even 95% may be quite valid. The other parameter considered was biological, that is, the effect of short-duration high-yielding varieties of seed (commonly used in multiple cropping) on the benefits of the project and on the income of the farmer. In addition, the possibility of growing citrus fruits was also considered.

A linear programming (LP) model to maximise the benefits from the cropping pattern in the 12 months with only the available water (and in some cases also the land) as constraints was used. Such models have often been used for determining optimum cropping patterns by Heady & Nicol (1975) and others.

An LP model was used to maximize (i) benefits (ii) cropped area from a given fixed quantity of water in each of the twelve months of the year in the Rajasthan canal. The maximum benefits (or the maximum cropped area) and the optimum cropping patterns in the twelve months were determined with available water in the canal as the only constraints. Three levels of agricultural technology (giving high, medium, and low crop yields) and two levels of irrigation technology (95% irrigation efficiency with sprinklers or drip irrigation and 70% irrigation efficiency with furrow or border strip irrigation) and with two strategies (maximize benefits or maximize cropped area) were used to determine the benefits, cropped area and the cropping pattern with water supplied to the plants equalling their consumptive requirements.

The objective function is

$$\text{Maximize } Z = \sum_{j=1}^{m} p_j y_j, \tag{1}$$

subject to constraints of water and land, where y_j = area of crops ($j = 1, 2, \ldots n$) in hectares and p_j = coefficient of return from a unit of land for each crop.

(i) *Water constraint*

$$\sum_{i=1}^{12} x_{ij} y_j \leqslant X_i; \quad i = 1, 2, \ldots 12 \tag{2}$$

where x_{ij} = quantity of water required by one hectare of crop j during month i and X_i = volume of water available for irrigation in month i.

(ii) *Land constraints*

$$\sum_{j=1}^{n} y_j \leqslant A \tag{3}$$

where A is the total area of land available

$$y_j \geqslant 0 \quad \text{for} \quad j = 1, 2, \ldots n.$$

The consumptive use water requirements for growing per unit crop area were determined by using climatic data and the monthly consumptive use coefficients of various crops given by Christensen (1968), Hargreaves (1956), Ministry of Agriculture (1970) and Ministry of Irrigation and Power (1971). The available water for the consumptive use was determined by allowing 10 % loss in the main canal and its distributaries and 5 % loss in the field water courses. In addition, allowance was made for the irrigation method assuming 95 % irrigation efficiency for drip irrigation or sprinklers and 70 % irrigation efficiency for furrow or border strip irrigation systems. The model also explored the case when the water supplied to the plants was only 60 % of their consumptive requirements for high agricultural technology and for both levels of irrigation technology.

The benefits per unit crop area are given in table 4 and were obtained assuming crop yield with adequate use of fertilizers and assured supply of water. The labour cost was not considered as it was assumed that each unit of the farm can be managed by a farmer and his family. The agricultural labour requirements for each of the above cases for the full command area of the Rajasthan canal project as well as for farms of 4 and 6 ha area were also determined using farm management practices in India.

6. Discussion of results

6.1 *Agricultural technology*

Three levels of agricultural technology *viz* high, medium and low are considered in the study. High technology would involve assured supply of all inputs such as water, fertilizers, pesticides and the use of high yielding varieties (labour has not been considered at any level in this study as explained earlier in §5). This would also require good agricultural management practices. The crop yield per unit area of land for high technology will be high. Low agricultural technology implies inadequate and inefficient use of essential inputs and use of poor agricultural practices. Medium technology indicates a midway position between high and low technologies. The crop yields and net benefits determined per hectare of agricultural land for various crops in the study

Table 5. Crop yield in tonnes and net benefits in Rs per hectare of cropped area

Crop	Computer name	Estimated farm gate price (Rs per tonne)	Expected yield in tonnes per hectare				Benefits* (Rs per hectare)		
			High technology	Medium technology	Low technology	World maximum (1966–1975 data)	High technology	Medium technology	Low technology
Sugarcane	CP1	100	80·0	60·0	40·0	218·2 (Iran)	6300	5150	3575
Cotton	CP2	2100	2·5	1·75	1·0	3·8 (Botswana)	4400	3250	1900
Millet	CP3	800	3·6	2·3	1·0	4·2 (Egypt)	2379	1580	670
Pulses	CP4	1200	1·2	1·0	0·5	4·0 (Switzerland)	1173	1040	520
Fodder	CP5	90	45·0	20·0	10·0	—	4030	1770	870
Groundnut	CP6	1400	3·0	2·0	1·0	4·3 (Mauritius)	3665	2530	1265
Paddy	CP7	900	5·0	3·5	2·0	6·8 (Australia)	3520	2650	1550
Wheat	CP8	1950	4·0	2·8	1·5	5·7 (Netherlands)	6890	4900	2695
Mustard	CP9	1750	1·6	1·0	0·5	1·8 (Denmark)	2250	1470	735
Gram/peas	CP10	900	2·5	1·75	1·0	5·9 (Israel)	1898	1390	800
Citrus fruit	CP11	0·20 paise per orange	60,000 nos per year	45,000 nos	30,000 nos	—	11350	8600	5840
Wheat Sonora (Jan to April)	MCP1	1950	3·2	2·2	1·2	—	5500	3920	2155
Maize (June to Sept.)	MCP2	1200	3·0	2·0	1·0	—	2500	1850	2925
Potatoes (Oct to Dec)	MCP3	600	16·0	12·0	8·0	47·6 (Switzerland)	7800	6300	4350

*On full development of the Rajasthan canal project (labour cost not considered)

Table 6. Agriculture and irrigation technology

Technology level		Water supplied to the plant in percent of consumptive requirements	Cropped area for the available water with alternative (mha)		Yearly benefits (excluding labour cost) with alternative (billion Rs)		Yearly agricultural production with alternative (million tonnes)	
Agriculture	Irrigation (irrigation efficiency %)		Maximize benefits	Maximize cropped area	Maximize benefits	Maximize cropped area	Maximize benefits	maximize cropped area
High yield	High (95)	100	1·6	1·77	9·1	8·6	12·1 C and P = 10·1 G = 2·1	11·4 C and P = 8·9 G and M = 2·5
High yield	High (95)	60	2·25	2·95	5·4	4·9	8·0 (plus citrus) C and P = 5·8 G = 1·2 Citrus = 0·28	8·1 C and P = 6·0) G and M = 2·1
High yield	Medium (70)	100	1·18	1·3	6·7	6·3	8·8 C and P = 7·3 G = 1·5	8·3 C and P = 6·5 G and M = 1·8
High yield	Medium (70)	60	1·65	2·18	4·0	3·6	5·1 (plus citrus) C and P = 4·3 G = 0·8 Citrus = 0·21	6·0 C and P = 4·5 G and M = 1·5

Medium	High (95)	100	1·6	1·76	6·8	6·4	8·8 C and P = 7·4 G = 1·4	8·3 C and P = 6·6 G and M = 1·7
Medium	Medium (70)	100	1·18	1·3	5·0	4·7	6·4 C and P = 5·4 G = 1·0	6·0 C and P = 4·8 G and M = 1·2
Low	High (95)	100	1·35	1·76	4·2	3·86	4·6 (plus citrus) C and P = 4·1 G = 0·5 citrus = 0·17	5·1 C and P = 4·3 G and M = 0·8
Low	Medium (70)	100	0·99	1·3	3·1	2·84	3·3 (plus citrus) C and P = 3·0 G = 0·3 citrus = 0·1	3·8 C and P = 3·2 G and M = 0·6

C = cereal; P = potatoes; G = groundnut; M = mustard model, at the three levels of agricultural technology considered in the earlier studies, (Verma 1977a, b) are given in table 5.

The results given in tables 6 and 7 indicate that the benefits from the canal water will be more than doubled if the agricultural technology level is changed from low to high, while they will be more than one and a half times if the change is from low to medium technology. The percentage increase in the total agricultural production is even more than the percentage increase in benefits for a change from low to medium or low to high technology. The strategy of maximizing benefits yields higher economic efficiency as compared to the strategy of maximizing cropped area. The yearly farm income is increased about three times (from Rs 8800 to Rs 22800 for a 4-ha farm and from Rs 13200 to Rs 34200 for a 6-ha farm) if the agricultural technology is improved from low to high and the strategy is changed from 'maximizing cropped area' to 'maximizing benefits'. The agricultural labour requirements remain the same for the three levels of agricultural technology (for the same irrigation technology) if the strategy used is of maximizing cropped area and if the water supplied to the plant equals its consumptive requirements. With the strategy of maximizing benefits the agricultural labour requirements increase with the improvement of the agricultural technology. If the total labour requirements are compared for the two strategies *viz* 'maximize benefits' and 'maximize cropped area' it is found that the difference is insignificant (when water supplied to the plant equals its consumptive requirement) for high and medium agricultural technology; however the difference is about 30% for low agricultural technology. For the price structure and the crop water requirements adopted in the study, the choice of crops in the optimum cropping pattern remains almost the same for the three technology levels.

Discussion of the policy issues of agricultural development in literature is dominated by a polarization of opinion on whether the principal objective of policy should be equity or efficiency. Hopper (1968) states the view that agricultural development policies should be based on the single-minded pursuit of the goal of increased output. He argues, particularly from the Indian context, that the production of food must be accepted as the priority objective. Hopper emphasizes that the development programmes should aim at the application of the latest in science and technology. On the other hand, Maass (1966) stresses on equity for agricultural development policies in developing countries. He suggests that government economic programmes intended to attain multiple objectives should be designed to achieve the desired distribution of income. Frankel (1969) and Ruttan & Hayami (1973) explain the problem of income distribution with technology transfer in agricultural development; it has been pointed out that the technological change is likely to contribute to the widening income disparities among farmers. Johnston *et al* (1972) consider that the objectives particularly relevant to the design of strategies for agricultural development should be (i) contributing to the overall rate of economic growth and the process of structural transformation, (ii) achieving a satisfactory rate of increase in farm output at minimum cost, (iii) achieving a broad-based improvement in the welfare of the rural population and (iv) facilitating the process of social modernization. In other words, Johnston *et al* suggest that agricultural development policies should be directed at multiple objectives.

It seems that the main criticism against technology transfer for agricultural development in developing countries is that this transfer may lead to inequality in the income distribution of the farmers and thus may result in social and political problems. The reason for this criticism appears to be that the technology change may necessitate

Table 7. Labour requirements and benefits for different holdings size at varying technology level

Technology level		Water supplied to the plant in percent of consumptive requirement	Labour requirements (million people) with alternative		Farm of 4 hectares with alternative				Farm of 6 hectares with alternative			
					Maximize benefits		Maximize cropped area		Maximize benefits		Maximize cropped area	
Agriculture	Irrigation (%)		Maximize benefits	Maximize cropped area	Labor requirement	Benefits from farm (10^3 Rs)	Labor requirement	Benefits from farm (10^3 Rs)	Labor requirement	Benefits from farm (10^3 Rs)	Labour requirement	Benefits from farm (10^3 Rs)
High	High (95)	100	0·70	0·73	1·75	22·8	1·65	19·2	2·6	34·2	2·5	28·8
High	High (95)	60	0·93	1·23	1·65	9·6	1·66	6·6	2·5	14·5	2·5	9·9
High	Medium (70)	100	0·51	0·54	1·75	22·8	1·65	19·2	2·6	34·2	2·5	28·6
High	Medium (70)	60	0·69	0·90	1·66	9·6	1·65	6·6	2·5	14·5	2·5	9·9
Medium	High (95)	100	0·70	0·73	1·75	17·2	1·66	14·6	2·6	25·8	2·5	21·9
Medium	Medium (70)	100	0·51	0·54	1·75	16·8	1·66	14·6	2·6	25·2	2·5	21·9
Low	High (95)	100	0·56	0·73	1·65	12·4	1·65	8·8	2·5	18·6	2·5	13·2
Low	Medium (70)	100	0·40	0·54	1·65	12·4	1·66	8·8	2·5	18·6	2·5	13·2

mechanization converting small holdings into bigger ones. However, mechanization is not necessary for the transfer of agricultural technology. The use of high-yielding varieties and good agricultural practices, choice of proper crops and adequate and efficient use of inputs do not require large holdings and use of agricultural machinery. Lau & Yotopoulos (1971) have found by using a profit function of the Cobb-Douglas form and data derived from the farm management studies in India that the relative economic efficiency of small farms is higher than for large farms and that small farms attain higher levels of price efficiency and/or that they operate at higher levels of technical efficiency. The problem of income distribution can have an easy solution in the case of agricultural development of arid lands. Here the proper allocation of water among the various farmers can help in manipulating equity. In many cases the arid land may belong to the central or the state governments (as is the case for most of the command area of the Rajasthan canal project). In such situations proper settlement and water allocation policies will result in even distribution of income derived from technology transfer. The results of the Rajasthan canal project study indicate that if the size of holdings is changed from 6 to 4 ha for high agricultural technology the average yearly income of a farmer is reduced from Rs 34,200 to Rs 22,800 (which is still about double the income of a 6 ha farm with low technology) but the benefits of the technology change are made available to many more people (from 0·25 million people to 0·4 million people). Also agricultural tax reforms as suggested by Kaldor (1964) should greatly help even distribution of income amongst farmers as a result of technology transfer.

The results of the Rajasthan canal project presented in this paper clearly show that the agricultural development policies of arid lands should be based on intensive agriculture and on maximizing benefits with modern technology.

6.2 *Irrigation technology*

The results given in tables 6 and 7 consider two levels of irrigation technology (i) high, with an irrigation efficiency of about 95 % using sprinklers or drip irrigation systems and (ii) medium with irrigation efficiency of about 70 % with furrow or border strip irrigation systems. The results indicate that when the irrigation technology is improved from medium to high the total benefits at every level of agricultural technology also increase by about 40 %. The total agricultural production also increases by almost the same percentage. This increase in benefits and production is the result of more water becoming available, making it possible to increase the irrigated crop area. In the case of the Rajasthan canal project it was assumed that assured and known quantities of water are available in the canal for each of the 12 months of the year. If this water is not assured, as for example in the case of dry land farming or groundwater development, the scope of improvement in irrigation technology would not be limited only by the additional quantity of water available at a certain location but also by its reliability in time and space. In this context the point stressed by Levine (1970) regarding the importance of better coordination between the operation of irrigation systems and the farmer's use of the available water and the need for improving on-farm water management practices is very significant.

A change from the furrow or border strip irrigation system to sprinklers or the drip irrigation system would require additional capital. Most of the cases of improvement in irrigation technology are capital-intensive. However, since water has a very high economic value in arid lands the capital expenditure in improving irrigation technology is usually paid off. The experiences of sprinklers or drip irrigation systems in parts of Israel and Arizona indicate that the capital expenditure is recovered by the farmers in about 5 to 10 years. The same seems to be applicable for the Rajasthan canal project.

The importance of improving irrigation technology in an arid land should not be underestimated. This may bring even higher dividends as compared to the improvement in agricultural technology (*e.g.*, the results indicate that the yearly benefits as well as the agricultural employment from the Rajasthan canal project with medium agriculture technology and high irrigation technology are greater than with high agriculture technology and medium irrigation technology).

6.3 *Water—use of less than full consumptive requirement*

The fixed quantity of water available in the canal can be used to meet the full consumptive water requirements of the plants in a limited area thereby getting maximum crop yield per unit area or this could be utilized for a greater cropped area with water use by the plants per unit area being less than their consumptive requirements and thus, with crop yields less than the maximum. This policy question was looked into by determining the benefits and agricultural employment opportunities for the high agricultural technology (using both the strategies of maximizing benefits and maximizing cropped area) for two cases (i) water supplied to the plants is for 100% of their consumptive requirements and (ii) water supplied to the plants is for only 60% of their consumptive requirements. The results indicate that when the water supplied to the plants was for only 60% of their consumptive requirements the total benefits of the Rajasthan canal project were reduced to about 40% while the cropped area of the project increased by about 50%. If the additional cost required in developing on-farm works for the increased cropped area is taken into account, the total benefits of the project with water use of 60% of the consumptive requirements should be less than half of what these will be if full consumptive requirements of the plants are satisfied from the canal water. The agricultural labour requirements increase from about 30 to 70% (from 0·7 million to 0·9 million with the strategy 'maximize benefits' and from 0·7 to 1·2 million with the strategy 'maximize cropped area') due to the increased cropped area. However, by using less water per unit cropped area farm benefits are reduced to about one-third from Rs 28,000 to Rs 9900 for a 6-ha farm and from Rs 19,200 to Rs 6,600 for a 4-ha farm (the reduction will be even more significant if the costs of farm-development works for increased cropped area are considered). These results clearly indicate that in an arid land if the water is spread too thinly even with the good intention of increasing cropped area thereby benefitting more people, this will result in highly inefficient use of a very scarce resource. It will be like going from a production level to a subsistence level for the farmers. On the other hand, Collinson (1972) while analyzing the rural-based African economies found that improved productivity requires the orientation of resources from subsistence to production for the market. In developing countries where in addition to water, land may also be a limiting factor the policy of increasing cropped area at the cost of getting significantly lower benefits and lower agricultural production will be dangerous. Statistics of land area and the GNP per capita of some countries are given in table 4. These data indicate that India is not only very low in GNP but its available area per capita (0·59 ha) is one of the lowest in the world. This suggests that on a long-term basis land will also become a limiting factor for the economic growth of the country and therefore the conclusions of Hopper (1968) that "the poor countries can feed themselves if their agriculture is modernized and their rural economies are restructured. That requires infusions of technology and capital from rich nations" is very pertinent in formulating policies for the agricultural development in India and particularly in the arid lands of India.

6.4 *Employment potential and farm size*

The agriculture labour requirements for various levels of agricultural and irrigation technologies were also determined using data from farm management practices in India. The results given in table 7 indicate that an additional 25 % labour requirement (from 0·4 to 0·51 million people for 70 % irrigation efficiency and from 0·56 to 0·70 million people for 95 % irrigation efficiency) is generated with a change in agriculture technology from low to medium. The impact of changing irrigation technology from medium to high on agricultural employment potential is even more significant as the results indicate an increase of about 40 % (from 0·4 to 0·56 million people for low agricultural technology and from 0·51 to 0·7 million people for medium and high agricultural technologies). These results suggest that if increasing employment potential is an important objective of agricultural development in an arid area then irrigation facilities should be provided to more areas and atleast medium agricultural technology should be used.

In the absence of farm mechanization, as has been assumed in this study, the size of holding for colonization will depend upon the technology level and upon the economic expectations of the farmers. For example, if on full development of the project, it is aimed that a farmer should have an annual income of atleast Rs 22,000/-, this can be achieved either with a 6 ha farm with medium agricultural technology or with a 4 ha farm holding with high agricultural technology (refer table 7).

7. Conclusions

Agricultural development policies in arid lands should be based on the principle of maximizing benefits and/or agricultural production. High agricultural and irrigation technologies should be used to maximize benefits/production per unit of water and land area. Proper settlement, water allocation and agricultural tax policies will help in achieving equity amongst the farmers. Intensive agriculture at high technology levels will result in higher economic efficiency as well as opportunities for higher agricultural employment.

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A study for optimum utilization of the Damodar water resources

BASAWAN SINHA* and P RAMAKRISHNA RAO†

* Central Flood Forecasting, Central Water Commission, "Kamata Sadan", 427/c, East Borning, Canal Road, Patna 800 001, India

† Central Water Commission, Room 514, Sewa Bhavan, Ramakrishnapuram, New Delhi 110 066, India

Abstract. The study describes the existing and proposed water resources development in the Damodar river basin and the systems study carried out for estimating the consequences of implementing a proposed set of management and development measures. A simulation model was considered appropriate for the study and a computer program developed by the US Army Corps of Engineers was used. The results of various simulation runs are discussed. The analysis of results have indicated that an integrated operation of all reservoirs on the Damodar system, both existing and proposed, would help in maximization of utilisation and benefits. It is also concluded that a simulation model would help not only the long range planning but also the day-to-day operation.

Key Words. River basin development; integrated operation; simulation model.

1. Introduction

The wandering and capricious Damodar rises in the hills of Chhotanagpur at an elevation of 2000 feet, and after flowing for 180 miles in Bihar, enters the deltaic plains of West Bengal and ultimately joins the Hooghly. The total drainage area is 8500 miles^2, of which 6960 miles^2 are the catchment of the upper Damodar, just below its confluence with the Barakar. Figure 1 shows the region through which the river flows. The river used to cause serious floods in its lower reaches lying in West Bengal. Voorduin (1945) of the Tennessee Valley Authority (TVA) prepared a preliminary memorandum on the unified development of the Damodar river, and the Damodar Valley Corporation (DVC) was set up in 1948 to implement schemes for integrated and coordinated development of the Damodar Basin.

Voorduin's plan of development of the water resources of the valley envisaged construction of seven storage dams across the Damodar and its tributaries at Tilaiya, Konar, Maithon, Panchet, Bokaro, Balpahari and Aiyar; a diversion dam at Bermo and a barrage at Durgapur with a canal network system. This development was to be carried out in two stages. The first stage was to cover the construction of four dams at Tilaiya, Konar, Maithon and Panchet and the barrage with canal system at Durgapur (figure 2). Construction of the remaining four dams was included in the second stage. The first stage was completed in 1958, and the second stage has not yet been implemented.

Subsequently, a dam at Tenughat on the Damodar river has been constructed by the Bihar Government. This envisaged utilization of 900 cusecs all the year round for

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Conversion table

1 inch = 2·54 cm; 1 foot = 0·3048 m; 1 mile = 1·609 km; 1 mile^2 = 2·59 km^2; 1 acre = 0·405 ha; 1 acre foot = 0·1234 ha m; 1 cusec = 0·02832 cumec.

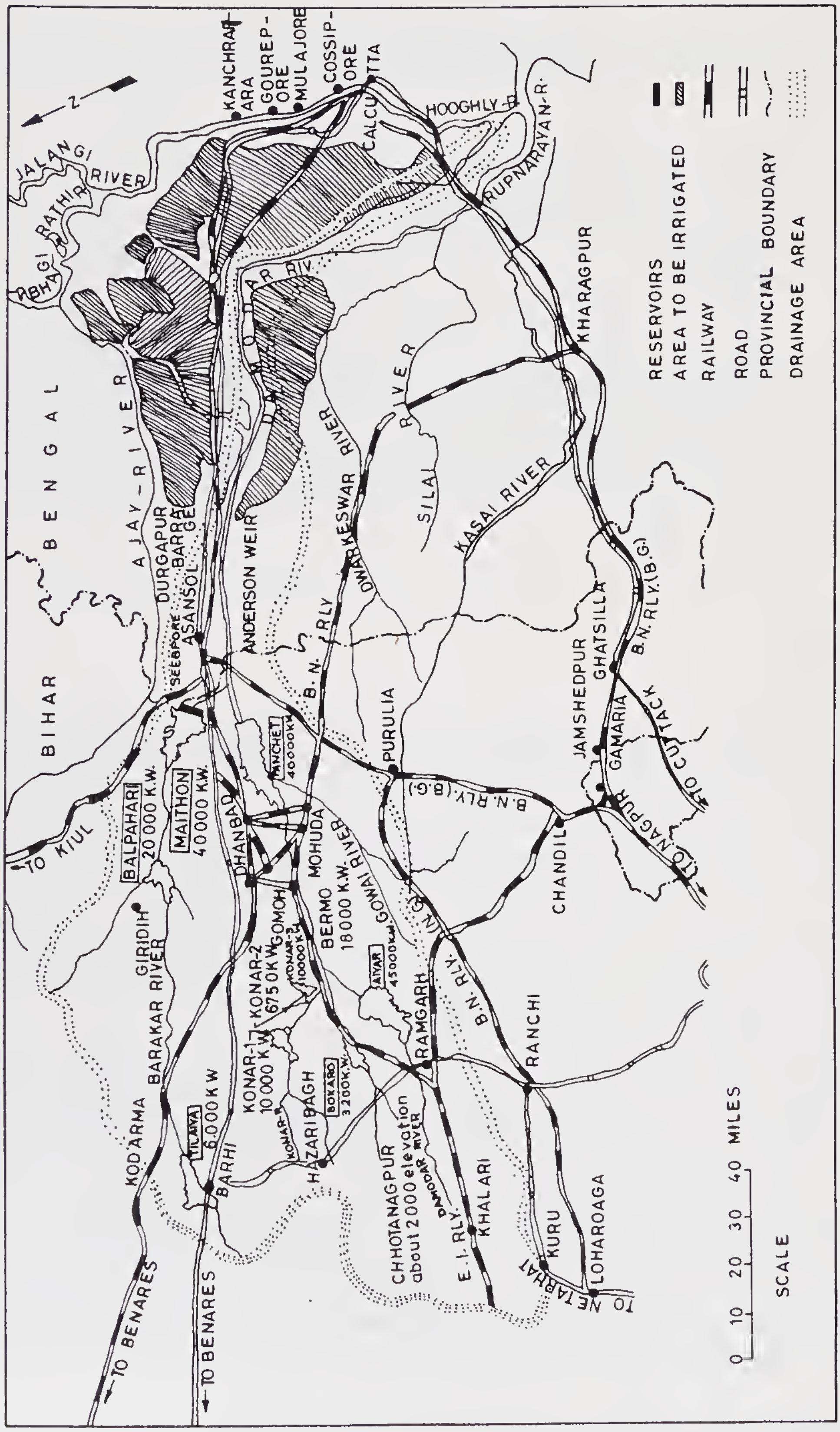

Figure 1. Damodar river: Tentative plan of development

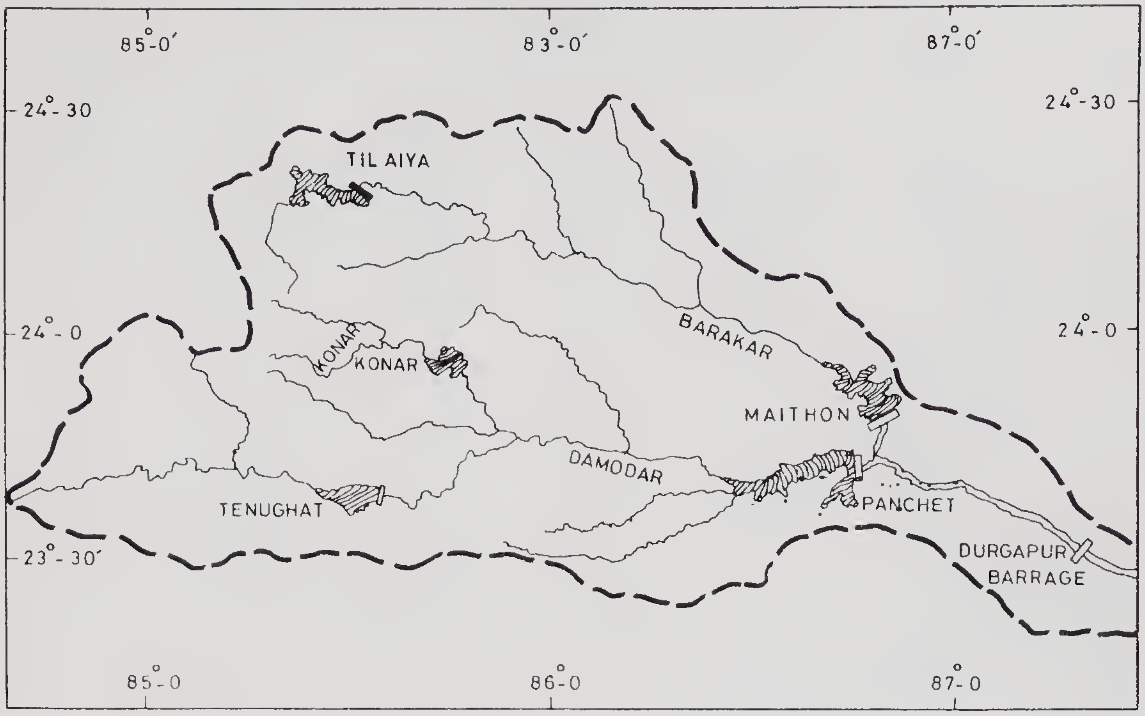

Figure 2. Damodar valley reservoirs

irrigation and industrial water supply. Upstream of this dam, yet another small dam to control about 100 miles^2 was constructed by the Bihar State Electricity Board to meet the requirements of Pathrathu Thermal Power Station. The Government of Bihar has also prepared some major, medium and minor schemes for utilization of the Damodar waters in the upper reaches for irrigation and industrial uses. This plan of utilization by Bihar includes the use of waters from the existing Konar and Tilaiya dams of DVC. Salient features of existing major projects in the Damodar Valley are given in table 1.

Voorduin's original plan of development provided for a total storage of 4·68 million acre feet (MAF) in seven storage dams, of which 2·915 MAF was earmarked for moderating floods. Against this, only four dams with a gross storage of 2·92 MAF were built in the first stage, out of which 1·52 MAF is the flood storage; 0·97 MAF is conservation storage and 0·43 MAF is the silt storage. But the whole flood storage of 1·52 MAF is not available as yet due to non-acquisition of land in the Maithon and Panchet reservoirs beyond RL (reduced level) 495 and RL 425 respectively. As a result, the effective flood storage at present is only 0·68 MAF.

2. Surface water resources in the basin

2.1 *Water utilization*

According to the regulations issued by the Central Water Commission (1969), the principal requirements for stored waters are kharif irrigation, power generation and flushing doses during the monsoon season (June to October), and rabi irrigation, navigation, power generation and water supply for industrial and domestic uses during the non-monsoon season (November to June).

Table 1. Salient features of the Damodar valley

Name of dam and river stream		Catchment area (miles^2)	Dead storage (acre feet)	Conservation storage (acre feet)	Flood storage (acre feet)	Installed capacity of power house (MW)
Tilaiya:	Barakar	380	60,680	114,800	143,900	4
Maithon:	Barakar	2430	168,090	495,540	446,370	3×20
Konar:	Konar—tributary of Damodar	385	49,530	178,770	216,370* 44,200	—
Panchet:	Damodar	4234	148,060	184,930	881,000 277,000*	1×40
Total for DVC		7430	426,400	974,000	1,515,500 681,470*	
Tenughat: Damodar		1730	170,000	621,100	—	—

* Flood storage available with land acquisition upto RL 495 and RL 425 in Maithon and Panchet reservoirs respectively; RL—reduced level

The requirement of kharif irrigation has been worked out on the basis suggested by the Water Management Division, Ministry of Food and Agriculture (table 2). The overall requirement works out to 1·792 MAF, which includes 0·579 MAF during October. According to the regulation schedule, the reservoirs have to be operated such that they are full at the monsoon storage level after meeting all the requirements. The conservation storage available in all the four dams of the DVC system is 0·974 MAF and it

Table 2. Monthly requirements of water for kharif irrigation (June to October).

Month	Irrigation requirement of the crops (in inches) on the basis suggested by Ministry of Food & Agriculture		Irrigation requirement at canal head inches	feet	Total requirement at canal head 10^3 acre ft.
June		0.2	0.286	0.024	24
July		4·0	5·714	0·476	467
August	1·3	2·2	3·143	0·262	255
September	2·6	4·0	5·714	0·476	467
October	8·2	5·0	7·143	0·595	579
Total	12·1	15·4	22·000	1·833	1792

Notes:
1. Irrigated area during kharif season = 973×10^3 acres.
2. Canal and outlet efficiencies are assumed to be 82 % and 85 %, *i.e.* overall efficiency during kharif is 70 %.
3. Monthly water requirements suggested by Water Management Division (column 2) have been suitably modified (see column 3) allowing for seed beds in June and accounting for uneven distribution of rainfall during the monsoon.

is earmarked for utilization in the following manner:

		MAF
Kharif irrigation		0·40
Navigation		0·17
Industrial		0·34
Releases below Durgapur		0·04
Rabi irrigation		0·07
	Total	1·02

The above requirement is met as follows:		MAF
Monsoon storage		0·974
Evaporation losses	(−)	0·214
Water available from storage		0·76
Utilization from dead storage of Panchet		0·10
Utilization of dry season inflow		0·16
	Total	1·02

The overall annual utilization of water in the DVC system works out to about 2·5 MAF, the monthly distribution of which is given in table 3.

2.2 *Water availability*

According to the Regulation Manual (1969) for DVC reservoirs, the estimated average annual run-offs at different dams are:

	MAF
Tilaiya	0·35
Maithon	2·12
Konar	0·45
Panchet	3·68

Observed discharge data (Banerjee 1975) at all these sites are available for the last 18 years. Analysis of these data shows that there is wide variation in the annual yields. The minimum and maximum yields on record are given in table 4.

3. The problem

At present the Damodar system has a group of four reservoirs with a terminal barrage at Durgapur in operation for over twenty years and the one at Tenughat functioning for five years. The hydrological data available indicate that 75 % dependable annual yield at Durgapur is of the order of 4·9 MAF and the mean annual inflow average for the period of operation (1956–73) is as high as 6·18 MAF. Against this, the present utilisation of water for the DVC system is only 2·50 MAF. And, yet occasionally a shortfall in irrigation and/or hydel power supply occurs. This can be obviously attributed to either inadequacy in storage capacities (including carryover storage) or deficiency in

Table 3. Water requirements

Purpose	Diversions/releases (10^3 acre feet)											
	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
Irrigation												
Kharif	24	467	255	467	579	—	—	—	—	—	—	—
Rabi	—	—	—	—	—	13	13	14	13	13	3	—
Industrial	28	29	29	28	29	28	29	29	27	29	28	29
Mandatory	—	—	—	—	—	6	6	6	6	6	6	6
Navigation	24	—	—	—	—	24	25	24	24	24	25	25
Losses	6	—	—	—	—	7	7	7	7	7	7	6
Total	82	496	284	495	608	78	80	80	77	80	69	66
(Cusecs)	1367	8000	4581	8250	9806	1300	1290	1290	1375	1290	1150	1065

Note: The above water requirements are exclusive of the evaporation losses from the reservoir.
Monsoon period (June to Sept.) = 1357×10^3 acre feet
Non-monsoon period (October) = 608×10^3 acre feet
(November to May) = 530×10^3 acre feet

2495×10^3 acre feet

Table 4. Annual runoff at different dam sites (value in thousands)

Name of dam site	Minimum on record (in acre feet) (1966–67)	Maximum on record (in acre feet) (1971–72)
Tilaiya	64	660
Maithon	655	5,009
Konar	111	690
Tenughat	608	2,644
Panchet	1,108	7,351
Durgapur	1,965	15,272

operating rules or both. Then, there is need for increasing utilization which till now is much lower than the firm yield a properly planned system for the basin can provide.

4. The simulation model

The study was undertaken with this background and a simulation model was considered more appropriate for estimating the consequences of implementing a proposed set of management and development measures, *viz* (i) increasing the storage capacities of the Maithon and Panchet dams upto the top of gates; (ii) using a portion of flood storage space for conservation; (iii) abstraction of about half-a-million acreft. of water for upstream use; (iv) utilizing the storage in Konar and Tilaiya dams for consumptive use on the upstream; (v) integrating the regulation of the Tenughat reservoir with the DVC system of reservoirs; (vi) modifying the operating rules for both flood control and water supply; and (vii) determining the operational efficiency of alternative plans of utilization.

For this purpose, a computer program (No. 723-x6-L 2030) developed at the Hydrologic Engineering Centre, US Army Corps of Engineers (1976) seemed appropriate and hence, has been chosen for the simulation studies. This program performs a multipurpose routing of flows in a reservoir system for upto twelve periods of uniform or varying lengths per year based on varying flow requirements at reservoirs, diversions and downstream control points. It can accommodate power peaking and energy requirements at reservoirs and can assign economic values to all outputs and allocate these in various ways. It can automatically iterate to optimize yield at a specified location.

5. The system

5.1 *System components*

There are five basic system components which are generally used by the program to model a reservoir system *viz.* the system hydrology, reservoirs, control points, power plants and diversions.

5.1a *Hydrologic characteristics*: The system inflows which are the primary hydrologic components of the programs, are specified by identifying their location (*i.e.* the control point where they occur), their magnitude and the period when they occur. Incremental local flows are equal to the difference between inflows at adjacent control points. Reservoir evaporation, an important part of the system's water balance computation, is input into the model by specifying a net evaporation rate (difference between evaporation and rainfall) for each reservoir.

5.1b *Reservoir characteristics*: Storage, surface area and outlet capacity are specified on 10 reservoir elevations to describe adequately the physical features (area and capacity curves given in the Regulation Manual) of each reservoir necessary to model the storage and release features of the reservoir. To simulate the operation of a reservoir system the operating criteria are expressed in quantitative terms by dividing each reservoir storage into six horizontal levels. The difference between the levels is taken as the zone of potential storage volume. The lowest level corresponds to the bottom of the conservation pool (top of the inactive pool), the second lowest level is the top of the buffer zone, the highest level is the full pool level (top of the flood control), and the second highest level is the top of conservation (bottom of flood control). Additional levels to facilitate individual reservoir operating criteria are specified.

Each reservoir is operated to meet stream flow targets at specified locations in the system. Priority of withdrawals from reservoirs serving the same location is established by specifying additional levels. The highest storage zone is withdrawn first, then the second highest and so on down to the lowest keeping all reservoirs in the system in balance to the extent possible. Other operating criteria specified in the model are initial reservoir storage and spillway surcharge.

5.1c *Hydrologic balance*: Computations in the model are based on the principle of continuity equation.

5.1d *Control point characteristics*: Control points, which are not reservoirs, are used to regulate system operation by establishing constraints and targets on streamflow. Both reservoirs and selected locations along the stream network are assigned control point numbers. There are three types of controls specified for any stream control point: maximum permissible flow, minimum desired flow and minimum required flow.

5.1e *Power plant characteristics*: Power plant characteristics which are used in the model to simulate power operations include installed power plant nameplate capacity, maximum plant factor for generation, power plant efficiency, tailwater elevation plus hydraulic loss, overload ratio for the power installation and power load requirements for each plant for each time period.

5.1f *Diversions*: One diversion exists at each control point except at Maithon and the actual flow diverted is specified. Diversion shown at Panchet actually relates to withdrawals above it and below Tenughat.

5.1g *Economic evaluation*: An economic analysis of the system operation is available at each control point by specifying a functional relationship between a hydrologic quantity such as streamflow, reservoir storage, power generation and the economic value of meeting the hydrologic quantities during a given month. In the present study, however, the economic parameters have not been assigned.

5.2 *System operation*

The simulation model operates by considering the water and power requirements at each pertinent control point in the system in a sequential fashion, beginning at an upstream point and moving in a downstream direction through each river basin. The release required to meet these requirements for all pertinent purposes is determined by evaluating each operational requirement and all physical and operational constraints at each site. Also, an index of the relative state of each reservoir (as a function of reservoir storage) is determined according to the specified operation guides. After the requirements have been met at all control points (or shortages declared if upstream water is not available), "system requirements" are examined to determine whether additional water releases for power generation will be needed to satisfy the system power demands. If so, the additional needs are proportioned among the reservoirs that have been specified to be available for meeting that system requirement in accordance with the relative state of the reservoirs as evidenced by the indices previously computed. The additional releases are added to the previously computed releases for meeting at-site requirements, and the system and at-site requirements are thus met (or shortages are declared if water is not available). This process is repeated for each period of the study, with the ending state of the reservoirs in the system for the current period being the beginning state for the next period.

Results from the successive applications of these calculations on a period-by-period basis are recorded for all points in the system (including non-reservoirs) by an accounting procedure which accounts for the movement of the water through the system by using the specified relative location of the reservoirs and downstream control points.

For the power plants included in the system, the requirements for the system as a whole as well as the minimum requirements for each plant are specified. During the first search of the system, the minimum power requirement at each plant will be established, and the total generation during the period at each plant will be computed. This total can exceed the minimum required generation if other services call for additional releases from the particular reservoir.

At the end of the first search, a summary is made of the total power generated and required and of the total power generated and used to satisfy system requirements. If the system requirement has not been satisfied, water levels at those reservoirs where additional generated power could be used for meeting system requirements would then be drawn towards a common storage-balancing level such that the full system requirement is generated. The allocated system requirements are then used in making a second search of the entire system for all purposes.

Since satisfying these additional requirements will usually change releases at many reservoirs, the average head during the second search will be different from the average obtained from the first search and used in the second search. Accordingly, accurate system power (and evaporation) computations require a third complete search of the entire water resource system for each operation period.

6. Simulation model studies

There are at present six major reservoirs in operation in the Damodar Basin, four under DVC, the fifth under the Bihar Government departmental control and the sixth under the Bihar State Electricity Board. The three agencies operate the reservoirs, constructed and maintained by them independently. Schemes for utilization of Tilaiya and Konar reservoirs for irrigation in Bihar have been formulated. There is further demand for atleast 0·5 MAF of the Damodar waters in Bihar (upstream of Maithon and Panchet dams), but the proposed schemes are not yet cleared for implementation due to the apprehension that they may adversely affect the existing DVC system, which caters to the needs of irrigation, hydel power, navigation, industrial and drinking water supply, through Tilaiya and Maithon dams on Barakar, Konar and Panchet dams on the Damodar, and Durgapur barrage on the Damodar below the confluence of the Damodar and the Barakar. The present annual utilization of water for the DVC system is only 2·5 MAF (see the breakdown given in table 3) as against the assessed 75% dependable yield of 4·9 MAF and 50% dependable yield of 6·8 MAF at Durgapur. If the inflows from catchments above Tilaiya, Konar and Tenughat are excluded, the corresponding dependable yields at Durgapur would still be 3·4 and 4·8 MAF and that at Maithon–Panchet would be about 2·5 and 3·4 MAF. Therefore, the first set of studies using simulation models is aimed at investigating the effect of the proposed schemes of upstream abstraction on the DVC system. For the sake of simplification, the entire yield from above Tilaiya, Konar and Tenughat dams has been excluded from the total catchment areas of Maithon and Panchet dams. This means that the effective catchment areas at Maithon and Panchet would be reduced to 2010 and 2100 miles^2 from 2390 and 4215 miles^2. Monthly yield data as available since 1956 have been utilized for the studies. In the first study, the reservoir capacity and the regulation schedule as at present, have been maintained.

The second set of studies was carried out keeping in view the proposal for acquisition of land up to the top of the gates in Panchet and Maithon dams to increase their effective gross storage capacity from 0·980 to 1·11 MAF in Maithon and from 0·61 to 1·21 MAF in Panchet, *i.e.* a net increase of 0·73 MAF. In these studies it was proposed that a part of the additional storage likely to be available through further land acquisition, should go for increasing the conservation storage and the rest to flood storage. Lesser flood storage than originally envisaged at Panchet seems justified in view of the fact that the Tenughat dam now controls 1730 miles^2 out of the 4215 miles^2 of its catchment; and even if there were no specific flood storage earmarked in the Tenughat dam, the system, if operated properly, will provide substantial flood moderation effect at and from Panchet. Two alternatives (studies 2·1 and 2·2) have been analysed as indicated in table 5. The results of these studies are tabulated in tables 6, 7 and 8.

The results of simulation (study 1) show that power generation during the monsoon would increase while it would decrease during the non-monsoon months. Further, water scarcity has been experienced in the critical months (July and October) of kharif irrigation in 14 years out of 18. The monsoon yield has exceeded the requirement and has been spilled. The failures in October and the following July indicate inadequate conservation storage. Also, the failures in October are due to the present regulation policy which specifies water levels to be maintained at full conservation level upto the end of October. Since the overall requirement of water from November to May is of the order of 0·53 MAF, it would be advantageous to permit a lower conservation level at the end of October or to maintain the full conservation level till the end of September only.

Table 5. Storages adopted for studies (value in thousands of acre feet)

Particulars	Panchet		Maithon	
	Storage upto conservation pool	Storage upto flood level	Storage upto conservation pool	Storage upto flood level
Study 1 (as at present)	330	610	66	980
Study 2.1	545	1214	718	1110
Study 2.2	874	1214	980	1110

Table 6. Power generated in DVC hydel system (in 10^6 kWh—average for the period 1968–69 and 1972–73)

Month	Average obtained				Simulated results		
	Maithon	Panchet	Tilaiya	Total	Study 1 (Maithon & Panchet)	Study 2·1 (Maithon & Panchet)	Study 2·2 (Maithon & Panchet)
June	10·1	8·4	0·5	19·0	10·5	11·3	13·6
July	24·1	21·3	1·3	46·7	30·6	29·5	31·9
Aug.	22·9	25·6	1·7	50·2	57·8	55·0	55·8
Sept.	26·6	25·1	2·1	53·8	62·2	65·3	64·2
Oct.	23·7	22·2	1·4	47·3	28·2	37·1	45·9
Nov.	6·7	2·8	1·6	11·2	5·9	6·9	7·7+
Dec.	3·9	2·1	1·9	7·9	6·8	6·8	8·0
Jan.	7·5	2·4	1·5	11·4	6·6	6·8	7·9+
Feb.	7·0	4·1	0·6	11·7	5·6	6·0	6·6+
Mar.	8·4	5·2	0·2	13·8	5·8	6·7	7·1+
Apr.	3·8	2·5	0·1	6·4	5·7	6·3	6·8
May	2·4	2·2	0·0	4·6	6·2	6·9	7·3
Total	147·2	123·9	12·9	284·0	232·9	244·6	262·6

Table 7. Maithon dam (power generated in 10^6 kWh)

	1968–69				1969–70				1970–71				1971–72				1972–73			
Month	A	S-1	S-2.1	S-2.2	A	S-1	S-2.1	S-2.2	A	S-1	S-2.1	S-2.2	A	S-1	S-2.1	S-2.2	A	S-1	S-2.1	S-2.2
Jun	17·9	21·2	23·6	33·7	5·7	5·4	5·4	5.4	4·7	5·4	5·4	5·4	20·6	4·6	5·0	6·6	1·9	5·4	5·4	4·6
Jul	36·2	51·3	51·3	51·3	21·4	5·5	5·5	5·5	14·5	5·6	5·6	5·6	39·0	11·1	15·6	17·2	9·6	4·8	5·6	4·8
Aug	29·7	51·3	51·3	51·3	24·0	51·3	51·3	51·3	8·5	4·8	6·0	15·5	37·2	51·3	51·3	51·3	15·1	16·4	20·5	30·8
Sep	27·3	10·3	10·5	11·5	25·4	37·1	37.1	41·6	24·3	49·7	49·7	49·7	36·1	49·7	49·7	49·7	20·0	38·5	39·5	43·3
Oct	20·3	13·3	13·6	14·8	22·2	4·3	4·3	4·6	22·0	26·6	27·2	29·8	28·9	20·3	20·7	22·7	25·0	7·3	7·4	8·1
Nov	1·9	5·4	5·4	5·4	1·0	5·4	5·4	4·6	11·7	4·6	4·6	4·6	13·5	4·6	4·6	4·6	5·9	5·4	5·4	5·4
Dec	2·3	5·6	5·6	5·6	1·8	5·6	5·6	4·8	5·2	4·8	4·3	4·8	5·4	4·8	4·8	4·8	4·9	5·6	5·6	5·6
Jan	4·0	5·6	5·6	5·6	6·2	5·6	5·6	4·8	9·2	4·8	4·8	4·8	8·2	5·6	4·8	4·8	10·1	5·6	5·6	5·6
Feb	5·6	5·0	5·0	5·0	6·9	5·0	5·0	4·3	10·1	4·3	4·3	4·3	9·2	5·0	4·3	4·3	3·2	5·0	5·0	5·0
Mar	4·7	5·6	5·6	5·6	6·6	5·6	5·6	5·6	11·5	5·6	4·8	4·8	15·9	5·5	4·8	4·8	3·1	5·6	5·6	5·6
Apr	3·2	5·4	5·4	5·4	3·0	5·4	5·4	5·4	5·2	5·4	4·6	4·6	5·2	5·4	5·4	4·6	1·7	5·4	5·4	5·4
May	3·2	5·6	5·6	5·6	0·7	5·5	5·5	5·6	4·0	5·5	4·8	4·8	2·5	5·5	5·6	4·8	1·8	5·5	5·6	5·6
Total	156	186	188	201	126	142	143	144	131	127	126	139	222	173	177	180	102	110	117	130

A = actual; S = study

Table 8. Panchet dam (power generated in 10^6 kWh)

Month	1968–69 A	S-1	S-2.1	S-2.2	1969–70 A	S-1	S-2.1	S-2.2	1970–71 A	S-1	S-2.1	S-2.2	1971–72 A	S-1	S-2.1	S-2.2	1972–73 A	S-1	S-2.1	S-2.2
Jun	10·8	2·3	2·3	2·3	6·0	2·2	2·2	2·2	2·8	2·3	2·3	2·3	22·5	3·1	2·8	2·3	0·0	0·8	2·0	3·1
Jul	20·0	26·4	15·3	2·4	18·7	6·4	6·4	6·4	22·8	4·1	4·0	4·3	30·6	34·2	34·2	34·2	14·3	3·6	3·6	24·8
Aug	21·9	34·2	34·2	34·2	27·9	24·9	14·9	2·4	27·0	9·1	8·7	5·6	29·6	34·2	34·2	34·2	21·6	11·5	2·4	2·4
Sep	18·3	14·4	23·4	28·2	21·9	27·8	32·5	26·8	28·8	33·1	33·1	33·1	28·2	33·0	33·1	33·1	27·9	17·4	17·0	3·8
Oct	17·0	5·1	11·8	30·0	21·1	15·4	30·5	34·2	27·8	17·3	20·1	23·5	25·8	19·6	3·1	27·6	19·5	11·7	26·4	34·2
Nov	0·6	0·7	7·7	2·3	0·9	1·1	1·1	3·1	4·9	3·1	3·1	3·1	5·7	3·1	3·1	3·1	2·2	1·2	1·2	2·3
Dec	0·2	0·3	0·3	2·4	1·4	0·4	0·4	3·2	3·1	3·2	3·7	3·2	5·4	3·2	3·2	3·2	0·3	0·6	0·6	2·4
Jan	1·8	0·2	0·2	1·8	1·4	0·3	0·3	3·2	4·7	3·2	3·2	3·2	7·3	1·5	3·2	3·2	2·0	0·4	0·5	2·4
Feb	2·9	0·2	·0·2	0·2	0·8	0·2	0·2	2·9	4·3	2·9	2·9	2·9	8·9	0·3		2·9	3·7	0·2	0·2	1·3
Mar	2·8	0·0	0·0	0·0	2·7	0·2	0·2	2·4	5·1	0·6	3·2	3·2	11·9	0·0	3·2	3·2	3·4	0·4	0·3	0·4
Apr	2·1	0·1	0·1	0·1	1·1	0·0	0·0	2·3	5·5	0·8	3·1	3·1	2·7	0·4	2·3	3·1	1·0	0·0	0·0	0·2
May	3·6	1·2	1·2	1·2	1·1	0·0	0·1	1·9	4·3	1·4	3·1	3·2	0·0	0·0	2·4	3·2	1·9	0·8	0·8	0·6
Total	102	85	90	105	105	79	89	91	141	81	91	91	179	133	148	153	98	49	55	78

A = actual; S = study

It is seen from the results of the simulation study 2 that the average monthly hydropower generation (based on actuals during the period 1968–73) will suffer in January, February and March, though on an annual basis there is no substantial decrease in hydel power generation. As the DVC hydel system places great emphasis on peaking power to maintain the efficiency of the overall DVC power grid comprising about 1000 MW of thermal power installation, further studies need to be carried out to ensure that hydel power generation during non-monsoon months is not affected.

In order to examine the possibility of achieving this, a third set of studies was carried out on the expanded system shown in figure 3. Table 10 summarises the various stipulations made for the four case studies. It has been assumed in all the studies that 0·201 MAF of the Tilaiya reservoir waters and 0·234 MAF of the Konar reservoir waters will be utilized for irrigation in Bihar as given in table 9. For industrial water supply, 600 cusecs throughout the year will be diverted; and for utilization above and through the Panchet reservoir, 300 cusecs will be released from the Tenughat reservoir; and 10 % of the monsoon yield (July to September) from the catchments above Panchet and Maithon reserved for utilization in Bihar. In other words, supplementing the Panchet non-monsoon yield with the Tenughat reservoir releases was envisaged providing at the same time for irrigation demands in Bihar.

The success of the scheme with respect to storage yield function is generally determined by the following criteria: (a) there is no shortage in any period of the year in 75 % of the number of years for which the annual operation table is prepared or in 75 % of the months for which the monthly operation table is prepared; (b) in any one year/season the total irrigation shortage is not to exceed 50 % of the total annual output for irrigation; and (c) in a 50-year period, the sum of all the shortages is not to exceed 150 % of the firm annual yield for irrigation. Analysing the results given in table 11, it can be seen that judged from these criteria, the outcome of both the alternative plans, that is, study 3·3 and study 3·4 is almost identical even though the plan in study 3·3 has the annual inflow reduced by over half a million acre feet from that in study 3·4 (the average river flow in study 3·3 is 6306 cusecs against 7097 cusecs in study 3·4). In study 3·3, there are failures in 14 months out of the 216 months for which the operation table has been prepared. This decreases to 11 months in study 3·4. Both come well within

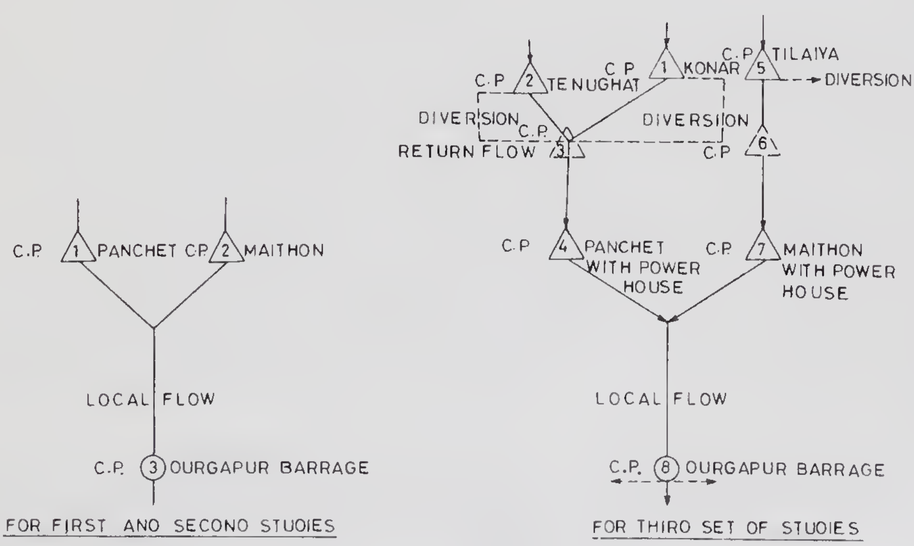

Figure 3. Schematic outline of the Damodar river basin system

Table 9. Monthly schedule of utilization (diversion) from Tilaiya and Konar reservoirs

Month	Utilization from Tilaya dam (10^3 acre ft)	Utilization from Konar dam (10^3 acre ft)
June	2	3
July	43	51
August	24	28
September	43	51
October	54	54
November	5	7
December	6	8
January	6	8
February	5	7
March	5	7
April	4	5
May	4	5
Total	201	234

acceptable limits. The maximum annual shortage in any one year is 1718 cusecs in study 3·3 and 1616 cusecs in study 3·4. This has occurred in the driest year of 1966. The average annual minimum flow being 3446 cusecs, both the alternative plans of utilization just marginally satisfy the criterion which requires that, in any one year, the total shortage should not exceed 50% of the total requirement. The third criterion requires that the sum of all shortages in a period of 50 years should not exceed 150% of the firm annual yield. In the instant study, a period of only 18 years has been considered and hence an accurate application of this criterion is difficult unless equally likely sequences for a longer period are generated and utilized. However, the average annual shortage over a period of 18 years has been obtained from the simulation studies and to compare the two plans, this can be utilized for estimating the total of shortages over a period of 50 years. In study 3·3, the average annual shortage in the desired flow is 123 cusecs and that in the minimum flow is 106 cusecs. These work out to 4·49 and 3·87 MAF respectively against the desired flow and minimum flow equivalent to 2·70 and 2·5 MAF. Thus, the total of shortage over a period of 50 years marginally exceeds 150% of the firm annual yield. In study 3·4, the corresponding average annual shortages are 103 and 93 cusecs respectively which work out to 3·76 and 3·39 MAF over a period of 50 years. These are marginally lower than the prescribed limit of 4·05 MAF and 3·75 MAF. Hence, it may be concluded that the plan of utilization envisaged in study 3·3 is slightly better than that in study 3·4. But it has to be remembered that an average of 18 years may or may not be correct for application over a period of 50 years, especially because so great a shortage is largely due to one extremely dry year (1966); and whatever deficiencies are observed in study 3·4 are due not to shortage of water but to inadequate storage capacity.

Analysis of results in table 11 also indicates that excluding the Tilaiya, Konar and Tenughat reservoirs from the integrated operation of the Damodar system as envisaged in studies 1 and 2 will not be conducive to plans for increasing utilization of the Damodar water resources. An integrated operation of all the reservoirs on the

Table 10 Details of studies made

Study 3.1	Study 3.2	Study 3.3	Study 3.4
1. Tilaiya reservoir waters to be utilized for irrigation in Bihar (Monthly schedule given in table 9)	Same as in study 3.1	Same as in study 3.1	Same as in study 3.1
2. Konar reservoir waters to be utilized for irrigation in Bihar (monthly schedule given in table 9)	Same as in study 3.1	Same as in study 3.1	Same as in study 3.1
3. Six hundred cusecs will be diverted for industrial water supply throughout the year. About 300 cusecs will be released from Tenughat reservoir for utilization above and through Panchet reservoir	Same as in study 3.1	Same as in study 3.1	Same as in study 3.1
4. 25 % of the monsoon flows (July to October) from the catchment above Tenughat reserved for utilization in Bihar	No additional utilization envisaged	Same as in study 3.1	Same as in study 3.2
5. 10 % of the monsoon yield (July to Sept) from the catchments above Panchet and Maithon reserved for utilization in Bihar	No additional utilization envisaged	Same as in study 3.1	Same as in study 3.2
6. No increase in conservation storage envisaged	Same as in study 3.1	Conservation storage increased from $495{\cdot}54 \times 10^3$ acreft to $550{\cdot}2 \times 10^3$ acreft to $397{\cdot}2 \times 10^3$ acreft in Panchet.	
7. No increase in gross storage envisaged	Same as in study 3.1	Gross storage in Maithon and Panchet reservoirs to be increased from 980×10^3 to 1110×10^3 acreft respectively.	
8. No further acquisition of land envisaged	Same as in study 3.1	With acquisition of land upto the top of gates, the flood storage increases by $75{\cdot}4 \times 10^3$ acreft in Panchet. Conservation storages increase by $54{\cdot}6 \times 10^3$ acreft in Maithon and by $212{\cdot}2 \times 10^3$ acreft in Panchet.	

Table 11. Summary of results

	Study 3.1	Study 3.2	Study 3.3	Study 3.4
Irrigation 1.	In 11 out of 18 years, there is no shortage. In three years, the shortage is only marginal. In the remaining 4 years (1957, 66, 67 & 69), the shortages are: 1967 (March to May)–1150 cusecs. 1966–Substantial shortage except in June, August & September. 1967 (May)–1040 cusecs. 1969 (March to May)–1000 cusecs.	In 12 out of 18 years, there is no shortage. In two years, the shortage is marginal. In the remaining 4 years (1957, 66, 67 & 69), the shortages are: 1957 (March to May) 950 cusecs 1966 (Substantial shortage except in June, August & September. 1967 (May)–450 cusecs 1969 (April & May) 1050 cusecs.	In 14 out of 18 years, there is no shortage. Shortages have been observed in 1957, 66, 67 and 69. In 1957, the shortages are in April and May being of the order of 210 and 1060 cusecs respectively. In 1966, there is no shortage only in the months of June, July & August. In 1967, the shortage is marginal in June and July (18 and 490 cusecs). In 1969, the shortage is in May only (562 cusecs).	In 15 out of 18 years, there is no shortage. Shortages have been observed in 1957, 66 and 67. In 1957, the shortage is in May (744 cusecs). In 1966, there is shortage in every month except in June, August & September. In 1967, the shortage is marginal (18 cusecs in June and 323 cusecs in July).
2. Averages for the period of operation (1956–73) indicate that at Durgapur:				
Unregulated flow	= 7557	8360	7557	8360
River flow	= 6383	7169	6306	7097
Desired flow	= 3706	3706	3706	3706
Shortage (in cusecs)	= 172	139	123	103

Average river flow (MAF) (regulated) at				
Durgapur:	4·6	5·2	4·6	5·2
Utilization	2·7	2·7	2·7	2·7
Surplus	1·9	2·5	1·9	2·5
Power				
3. Averages for the period of operation (1956–73) are:				
Maithon dam				
Reqd power =	37,668	37,668	37,668	37,668
System power =	111,986	109,572	109,703	107,532
Power =	147,121	154,556	148,613	156,435
Shortage =	3,308	2,853	1,648	1,525
	10^3 kWh	10^3 kWh	10^3 kWh	10^3 kWh
Panchet dam				
Reqd power =	25,112	25,112	25,112	25,112
System power =	95,448	97,862	97,731	99,902
Power =	111,484	121,622	117,136	126,973
Shortage =	2,608	2,040	1,348	1,093
	10^3 kWh	10^3 kWh	10^3 kWh	10^3 kWh

All numbers are in the FPS system.

Damodar system, both existing and proposed, will help in maximisation of utilization and benefits.

7. Conclusion

The following conclusions emerge from the simulation model studies discussed above:

(i) Hardly 50% of the available water resources of the Damodar are being utilized at present; and even after the proposed abstraction of about half a million acre feet materialises there will be surplus water to the extent of about 1·9 MAF on an annual average. This includes the inflow contributed by the uncontrolled catchment between the Maithon and Panchet dams and the Durgapur barrage.
(ii) Since over 80–85% of the run-off occurs during the monsoon months and that too erratically, the scope of improvement in utilization is only through increased conservation storages. Thus, there is need to increase the conservation storage of the existing dams, as far as practicable, and for creating additional storage in the upper catchment. In the latter case, there should be ample provision for carry-over storage.
(iii) The dams in the Damodar system should be operated as an integrated system under one unified control.
(iv) There is need for review of the existing Regulation Manual, more so because hereafter there will be utilization on the upstream of the Maithon and Panchet dams through the Konar, Tilaiya and Tenughat reservoirs. The regulation of these reservoirs should be supported by inflow forecasting to improve their efficiency.
(v) Additional dams to be constructed upstream for utilization of the Damodar waters should be planned so as to conserve the monsoon flows only. Status-quo in respect of dry-weather flows has to be maintained as the existing draws at Maithon and Panchet have limited conservation storage for meeting the demands of water supply and hydel power generation.
(vi) There are various possibilities of meeting the committed requirements of water and of increasing utilization on the upstream in Bihar. This study had limitations, inter-alia, in respect of (a) length of period for which hydrologic data were available and (b) non-availability of particulars of works proposed to be implemented in the upper catchment.
(vii) A simulation model for the Damodar system is needed not only for long-range planning of its water resources development but also for day-to-day operation.

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Planning for the Subernarekha river system in Eastern India

BASAWAN SINHA*, RAMESH BHATIA** and SUPRIYA LAHIRI†

*Central Flood Forecasting, Central Water Commission, "Kamata Sadan", 427/C, East Borning, Canal Road, Patna 800 001, India

**Institute of Economic Growth, University of Delhi, Delhi 110 007, India

†MIT Energy Laboratory, MIT, Cambridge, MA 02138, USA

Abstract. The study describes the systems studies carried out to plan a river basin in order to determine the nature and size of water storage facilities and releases for irrigation and industrial uses, and the associated cropping pattern. The model has been formulated in the framework of a linear programming model for a specific target year. This model is developed in the context of planning the Subernarekha river basin. The results are discussed and these provide information and insight suggesting the need for more disaggregated analysis of interaction between irrigation and related agroeconomic parameters.

Keywords. River basin planning; LP model; storages; Subernarekha river system; agroeconomic parameters.

1. Introduction

The Subernarekha is an inter-state river flowing through Bihar, West Bengal and Orissa. It rises in the Chhotanagpur plateau of Bihar and flows into the Bay of Bengal. The upper part of the Subernarekha and its tributaries run through the fertile land of Bihar, but the farming in this region is mainly dependent on the inadequate and untimely rains, and the water resources of the Subernarekha river system remain largely untapped. The upper basin, besides containing fertile land, also contains large reserves of minerals. A number of important industries have therefore grown along the banks of the river.

For integrated development of this basin the construction of dams, one on the Subernarekha at Chandil and the other on its tributary Karkai and two barrages, one on the Karkai at Bhua and the other on the Subernarekha at Galudih, is proposed. The gross irrigated area envisaged under this programme is about 2,30,000 ha in Bihar.

This study aims at an economic appraisal of the scheme in a coordinated manner to determine the nature and size of the water storage facilities and the releases for irrigation and industrial uses as well as the associated cropping patterns such that the water potential in this region is exploited optimally.

Detailed systems analysis studies are required for this purpose which incorporate the interactions of hydrological, agronomic and economic considerations in an integrated manner. Initially the model was formulated in the framework of a linear programming (LP) model for a specific target year which would take into account some of the chief interrelated factors affecting the optimum utilization of the water potential in this area. Since the projects mainly benefit the agricultural sector, both the cropping pattern and

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A list of symbols & indices is given at the end of the paper.

the capacities of the dams and barrages with their associated canals were considered as choice variables in the model. The idea was to provide a logical framework so that the initial results could provide some useful information and insights for subsequent systems studies with detailed (multiperiod) programming models or simulation models which may be useful for obtaining the capacities and operational schedule of the system.

2. An overview of the model

The target year LP model for 1980 as outlined above is disaggregated over space and considers temporal differentiation (in terms of the 12 months) over a year. A schematic diagram of the Subernarekha river system is presented in figure 1. The objective of our model is to maximise the annual additional benefits considering returns from the crop, the supply of industrial water, net project costs, farm costs and benefits foregone. All such benefits and costs have been computed from society's point of view.

2.1 *Decision variables*

The LP problem determines the following investment decision variables:

(i) Capacities of the reservoirs to be built at each of the two sites,
(ii) Delivery capacity of the associated canal system.

The associated operating decision variables evaluated by the model are the following:

(i) For each crop, the area sown, where production activities are differentiated by site,
(ii) The amount of industrial water to be supplied from each site during each month.

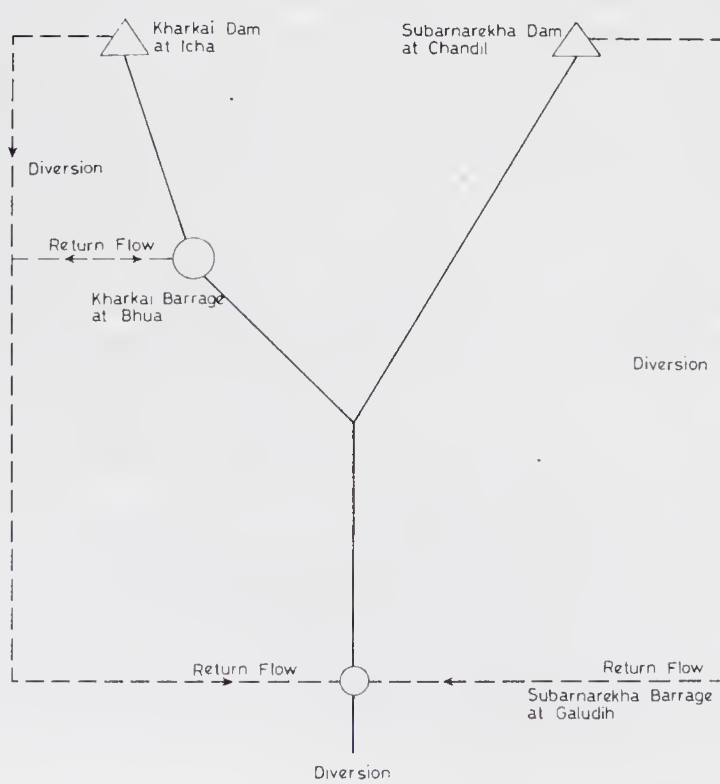

Figure 1. Schematic outline of the Subernarekha river basin

(iii) The downstream flows from each of the dams and barrages during each month.
(iv) The diversion for irrigation purposes from each site in each month.
(v) Volume of water to be stored by the end of each month for the subsequent periods.

2.2 *Constraints*

The levels of both the investment decision variables and operating decision variables are simultaneously determined in the model such that the total additional benefit to society, less the project costs, is maximized subject to the following constraints of continuity, capacity, agronomy and land area.

(i) The flow continuity constraint for the dams for each period states that the inflows should equal the outflows plus the water that is stored for the next period. The water that is stored for the next period should not go below a minimum level (*i.e.* the dead storage level). Since there are no storage facilities in barrages, the flow continuity constraints simply require that the inflows should equal the outflows from such modes.
(ii) The capacity constraints for dams require that the volume of water to be stored in each decision period should not exceed the capacity of the dam to be built at that site. Similarly, the amount of water for irrigation purposes in each period should not exceed the delivery capacity of the canal.
(iii) The irrigation flow constraints state that the amount of water diverted for irrigation purposes each month should be at least as large as the water requirements of perennial and non-perennial crops.
(iv) The land area constraint requires that the total planting in each season should be restricted to the culturable command area less the acreage required for fodder crops and the area left fallow in a particular season.
(v) Certain limits have also been imposed on the production of certain crops (for example, vegetables) as commodity demand functions have not been included in our model. Certain constraints have also been introduced on the acreage under paddy to reflect consumer preference for rice.

Detailed sensitivity analyses have also been carried out on different assumptions with respect to the river flow data and detailed parametric programming has also been performed on the coefficients of the objective functions (especially with respect to changes in the relative price of wheat to that of other crops) for mapping out the different patterns of irrigation development with respect to changes in the above parameters.

3 The algebraic formulation of the model

The mathematical model is described by (A1)–(A14) (appendix A). There are four sites considered in the model which are differentiated by the subscript i (see list of symbols & indices).

Fourteen crops have been considered indexed by t. Irrigated crops with different levels of irrigation have been designated as different crops. The figures in brackets denote water supplied corresponding to which appropriate yields are adopted.

The activities or choice variables, of which the two land use activities are measured in thousand hectares and all the remaining which are hydrologic activities, are measured in million cubic metres.

4. Data base

The main data inputs for the model are: benefit and cost coefficients in the objective function, water requirements of various crops for each month, hydrological inputs for different months at various sites, downstream flow requirements at the Subernarekha barrage for downstream use, coefficients of return flows from irrigation and industrial water supplies and coefficients of reservoir losses in each month.

In the objective function, the coefficients required are: value of each crop net of variable farm costs, fixed farm costs, unit revenue from the sale of industrial water, the annualized investment costs of reservoirs and canals and annual maintenance costs of reservoirs and canals. Gross value of each crop has been estimated as the sum of the value of grain output and the value of fodder. The assumptions regarding yield rates, prices and value of output have been given in table 1. The yield rates are based on the data obtained from the Agriculture Department (Ministry of Agriculture 1971) and from the Project Report (Ministry of Irrigation and Power 1972). The yield of paddy is assumed to decline by 10% when the total water requirements (at canal head) are reduced from 75 to 67·5 cm. Similarly, the yield of wheat is assumed to be 10% lower when the total water input is reduced from 70 to 57·5 cm. The accounting (or shadow) prices used to estimate benefits from major crops are expected to reflect the social value of these agricultural commodities since these prices take into account (i) economic cost of production of additional foodgrains in a surplus region of the country plus (ii) the economic cost of transportation (including cost of distribution and storage) of these commodities to the project region. We have used prices of foodgrains fixed by the Agricultural Prices Commission in the nearest surplus region plus the average cost of transporting these commodities to the project region (Sinha & Bhatia 1976). Valuation of agricultural output on this basis is expected to reflect the need for increasing agricultural output in regions away from the granaries of the country. The net value of each crop has been estimated by deducting the cost of seeds, fertilizers and manures, pesticides and human labour. To reflect the relatively higher levels of unemployment of unskilled agricultural labour in the region, we have used shadow wage rates which are lower than the market wages. We have assumed the ratio of shadow wages to market wages to be 0·25. The estimated values for various elements of variable costs and net benefit for each crop are given in tables 2 and 3. The fixed farm costs are assumed to include the following elements: (i) annualized costs of additional bullocks and implements required in irrigated agriculture, (ii) annual costs of maintenance of bullocks, command area development costs such as those of land levelling and shaping, field channels, field drains, improvement in facilities for storage, marketing, transport and communication. These costs have been estimated to be Rs 136 per acre and are relevant for the culturable command area at different sites (Sinha & Bhatia 1976).

The social cost of investment for the dams and canals has been calculated by giving due consideration to the foreign exchange component, wage component due to unskilled labour and the construction period of the project. The social investment cost per unit has been calculated by applying the following formula.

$$I = \sum_{t=1}^{\theta} \sum_{i} P_i I_i(t) (1+r)^{\theta-t} \tag{1}$$

Table 1. Yields, prices and benefits for different crops (at social prices)

Crops	Yield (Q/hectare)	Shadow price (Rs/Q)	Value of grain output (Rs)	Fodder (Q/hec.)	Shadow price of fodder (Rs/Q)	Value of fodder (Rs)	Value of output (per hectare) (Rs)
Paddy (75 cm)	29·6	95	2812	29·6	3	88·8	2900
Paddy (67.5 cm)	26·7	95	2536	26·7	3	80·0	2616
Maize (K)	19·8	90	1782	12·3	2	24·6	1806
Maize (R)	19·8	90	1782	12·3	2	24·6	1806
Wheat (70 cm)	24·7	135	3335	24·7	15	370·5	3705
Wheat (57.5 cm)	22·2	135	2997	22·2	15	333·0	3330
Pulses and oilseeds	12·4	130	1612	6·2	3	18·6	1630
Vegetables (potatoes)	296·0	30	8880	—	—	—	8880
Vegetables (S)	247	40	9880	—	—	—	9880
Paddy (S)	24·7	110	2717	24·7	3	74·0	2791
Sugarcane	500	12	6000	50·0	5	250·0	6250
Paddy (unirrigated)	10	95	950	10·0	3	30·0	980
Maize (unirrigated)	7	90	630	4·3	2	8·6	638
Pulses and oilseeds (unirrigated)	7	130	910	3·5	3	10·5	920

Q = quintal (100 kg); K = kharif; R = rabi; S = summer (this is so for all the tables)

Table 2. Input costs of different crops (variable farm costs) (Rs/hectare) (at social prices)

Crops	Seeds	Human labour	Fertilizers and pesticides	Total
Paddy (75 cm)	74	149	1093	1316
Paddy (67.5 cm)	74	149	1093	1316
Maize (K)	52	104	765	921
Maize (R)	52	104	765	921
Wheat (70 cm)	346	119	1201	1666
Wheat (57.5 cm)	346	119	1201	1666
Pulses & oilseeds	242	83	841	1166
Vegetables (R)	1853	141	2298	4292
Vegetables (S)	1853	141	2298	4292
Paddy (S)	74	149	1093	1316
Sugarcane	642	206	3632	4480
Paddy (unirrigated)	45	129	62	236
Maize (unirrigated)	31	90	43	164
Pulses and oilseeds (unirrigated)	111	60	86	257

Table 3. Net benefits (at social prices) for different crops (Rs/hectare)

Crops	Benefits	Cost	Net benefits
Paddy	2900·8	1316·5	1584·3
Paddy (67.5 cm)	2616·0	1316·5	1299·5
Maize (K)	1806·6	921·9	884·7
Maize (R)	1806·6	921·9	884·7
Wheat (70 cm)	3705·5	1666·3	2039·2
Wheat (57.5 cm)	3330·0	1666·3	1663·7
Pulses & oilseeds	1630·6	1166·2	464·4
Vegetables (potatoes)	8880·0	4292·0	4588·0
Vegetables (S)	9880·0	4292·0	5588·0
Paddy (S)	2791·0	1316·5	1474·5
Sugarcane	6250·0	4480·0	1770·0
Paddy (unirrigated)	980·0	236·8	744·2
Maize (unirrigated)	638·6	164·3	474·3
Pulses & oilseeds (unirrigated)	920·5	258·0	662·5

A construction period of 7 years has been assumed for the Kharkai and the Subernarekha dams. The investment cost has been annualised by assuming a capital recovery factor of 10·01% *i.e.* 10% social rate of discount and a 50-year life for the dams. We have also added the annualised maintenance and operating cost with the annualised investment cost of dams. The annualised maintenance and operating cost has been taken to be 2% of the investment cost. This includes labour, maintenance and overhead costs. The resulting estimates for annual costs are Rs 32·05 and Rs. 22·52 per thousand cu m for the Kharkai and the Subernarekha dams respectively. The capital costs of canals have also been annualized using the capital recovery factor mentioned above. These costs also include the cost of the Subernarekha and Kharkai barrages.

The revenue from the sale of industrial water has been taken to be Rs. 61·32 per thousand cu m.

The yield series for water for the two dams and the two barrages have been developed on the basis of rainfall series computed at each site separately. The rainfall runoff correlations which have been used for computing the yield series have been developed for Mango Weir (Jamshedpur site) at which runoff data were available for the period June 1961 to October 1973, assuming that the same will hold good at these dam and barrage sites. Since the Subernarekha waters have been allocated to the three cobasin states on the basis of an estimated 75% dependable annual water yield, the hydrological input in this model for the year in which the annual yield corresponded to 75% dependability is different for different control points. Therefore the adoption of different years for different sites in a static linear programming model could neither be considered appropriate nor consistent with the principle underlying the sharing of waters among the States on the basis of water yield as estimated at Kokpara at 75% dependability. Accordingly, the year corresponding to 75% dependability at the terminal structure, that is, the Subernarekha barrage site, was first found out in the 32-year series and the computed month wise yield in this year separately at each site has been utilized for this study. This procedure has also facilitated earmarking or reserving water for utilization from above the control points by excluding catchment areas in proportion to the 75% dependable water yield.

In this study for 75% dependability, the monthly runoffs net of project/protected utilization on the upstream of each site, corresponding to the year 1957–58 have been considered. An alternative solution considers the yield series for 1946–47 which corresponds to 50% dependability at the terminal structure *i.e.* at Subernarekha barrage.

The economic and hydrologic data are given in tables 1 to 9.

5. Results

The results obtained from the model have been presented in the form of a Reference Solution (RS) as well as in terms of sensitivity analysis. The RS is based on the following assumptions: (i) 75% dependability factor for water availability (ii) no bounds on area under major irrigated crops such as paddy, wheat and maize, except for vegetables in rabi and summer (5% of culturable command area (CCA) in each case); (iii) no upper bounds on capacities of dams and canals; (iv) minimum flow required at Subernarekha barrage for downstream use; (v) bounds have been imposed on industrial water supply using exogeneously given estimates; (vi) upper bounds have been imposed on the following unirrigated crops: paddy (25% of CCA), maize (15% of CCA) and pulses and oilseeds (5% of CCA). The sensitivity analysis is presented mainly in terms of changes in relative prices of crops and area under different crops.

The results of the RS have been analyzed with respect to the following: (i) optimum cropping pattern suggesting area allocated to different crops in various seasons (*i.e.* in kharif, rabi and summer): (ii) the optimum capacities of the two reservoirs and the associated releases for irrigation, industrial water supply and downstream uses; and (iii) the associated diversions from the two barrages for the above-mentioned uses.

Table 5 presents the optimum cropping pattern in the RS and tables 6–9 give the corresponding water balances at each of the 4 sites. It may be seen that irrigation intensity (gross area irrigated as a ratio of culturable command area) for the two dams

Table 4. Monthly requirements of water for different crops (in cm)

Crops	July	August	September	October	November	December	January	February	March	April	May	June	Total
Paddy (75 cm)	20	15	15	22·5								2·5	75
Paddy (67.5 cm)	20	11·25	11·25	22·5								2·5	67·5
Maize (K)	8·8	5	9·8	6·1	0·3								29·6
Maize (R)							15	15	15				45
Wheat (70 cm)					12·5	17·5	17·5	12·5	10				70
Wheat (57.5 cm)					5	12·5	17·5	12·5	10				57.5
Pulses & oilseeds						10	12·5	10					32·5
Vegetables (potatoes)					15	15	15	15					60
Vegetables (S)										25·0	12'5	7·5	45
Paddy (S)	10·0									45	35	30	120
Sugarcane	15·3	15·3	7·9	17·7	14	8·3	5·8	6·2	9·5	19·8	40·6	34·6	195

varies from 108% for the Kharkai dam and 129% for the Subernarekha dam. The irrigation intensity for the Kharkai barrage is 136% while it is 179% for the Subernarekha barrage. The crops in the kharif (monsoon) season are irrigated maize, unirrigated maize and unirrigated paddy for the Kharkai and Subernarekha dams.

Table 5. Optimum cropping pattern in the reference solution (75% dependability factor) (in thousand hectares)

	Kharkai dam	Kharkai barrage	Subernarekha dam	Subernarekha barrage
Kharif				
Unirrigated paddy	16·2	0	19·5	2·4
Irrigated paddy (75 cm)	0	8·5	0	7·3
Irrigated paddy (67·5 cm)	0	0	0	0
Unirrigated maize	9·7	0	11·3	0
Irrigated maize	28·3	0	34·8	0
Rabi				
Irrigated wheat (70 cm)	35·2	0	58·3	0
Irrigated vegetables	2·8	0·4	3·3	0·4
Unirrigated pulses & oil seeds	3·3	0·4	4	0·4
Wheat (57·5 cm)	0	3·6	0	9
Summer				
Irrigated vegetables	2·8	0·4	3·3	0·4
Irrigated paddy	0	0·4	0	3·3
Gross cropped area (A)	98·4	13·8	134·4	23
Gross irrigated area (B)	69·2	13·4	100	20·2
Culturable command area (C)	64	10	77	11·3
Intensity of cropping (A/C) (%)	154	136	175	204
Intensity of irrigation (B/C) (%)	108	132	129	179

Table 6. Inflow and outflow balances for the Kharkai dam in the reference solution (m cu m)

Month	Inflow	Diversion to		Reservoir losses	Storage at the end of the month
		Irrigation	Kharkai barrage		
July	393·5	26	0	–	361·4
August	130·0	14·8	0	2·5	467·5
September	278·8	28·4	0	3·7	708·0
October	5·0	17·3	140	3·7	546·5
November	3·7	49·3	0	6·15	488·5
December	1·23	66·6	2·5	6·15	408·3
January	2·5	66·6	2·5	3·7	331·8
February	18·5	48·0	0	5	291·0
March	3·7	48·0	1·23	3·7	248·0
April	2·5	7·4	0	3·7	233·0
May	0	3·7	0	6·15	217·0
June	0	2·5	0	5	203·5

Diversion to industrial water supply during all the months has been taken as 6·15 m cu m.

Table 7. Inflow and outflow balances for the Kharkai barrage in the reference solution (m cu m)

Month	Hydrological input	Inflow from Kharkai dam	Return flow from irrigation by Kharkai dam	Total Inflow	Diversions to		Total diversion
					Irrigation	Flow for downstream use at Subernarekha barrage	
July	50·6	0	1·23	56·8	19·7	33·4	56·8
August	146·8	0	0	151·8	19·7	128·4	151·8
September	251·6	0	1·23	257·8	19·7	234·4	257·8
October	5	125·8	0	135·8	19·7	122·1	145·5
November	0	0	1·23	6·23	2·5	0	6·2
December	0	2·5	2·5	10	5	0	8·7
January	2·5	2·5	2·5	12·5	7·5	1·23	12·5
February	2·5	0	1·23	8·7	5	0	8·7
March	1·23	1·23	1·23	8·7	3·7	0	7·4
April	1·23	0	0	6·23	2·5	0	6·2
May	1·23	0	0	6·23	2·5	0	6·2
June	2·5	0	0	7·5	3·7	0	7·4

Return flow from industrial water supply by Kharkai dam during all the months is 5 m cu m. The diversion to industrial water supply is 3·7 m cu m in all cases.

Table 8. Inflow and outflow balances for Subernarekha dam in the reference solution (m cu m)

Month	Inflow	Diversions to		Reservoir losses	Storage at the end of the month
		Irrigation	Subernarekha barrage		
July	680·6	30·8	0	1·23	606·6
August	177·6	17·3	0	6·2	718·8
September	617·7	34·5	0	6·2	1254
October	50·6	21	21	10	1211
November	12·33	80	16	13·6	1071·5
December	3·7	108·5	25	15	885·3
January	5·0	108·5	28·4	13·6	698
February	34·5	39·5	0	11·1	640
March	2·5	59·2	0	10	531·4
April	0	8·6	0.	11·1	470
May	0	3·7	0	15	409·4
June	0	2·5	0	13·6	351·4

Diversion to industrial water supply is 42 m cu m in all cases.

Irrigated paddy is the main crop for the two barrages. For rabi (winter) season, the major crop is irrigated wheat (around 60–70% of CCA) along with some area under pulses and oil seeds and vegetables. The crops for the summer are irrigated paddy at the Subernarekha barrage and vegetables at the other sites. Crops with higher water

Table 9. Inflow and outflow balances for Subernarekha barrage in the reference solution (75% DF) m cu m

Month	Hydro-logi-cal input	Inflow from Subernarekha dam	Inflow from Kharkai barrage	Return flow from irrigation from Subernarekha dam	Total inflow	Diversion to: Irrigation	Diversion to: Flow for downstream use at Subernarekha Barrage	Diversion to: Total Diver-sions	Desired flow at Subernarekha barrage
July	301	0	30	1·23	367·0	17·3	341·6	366·4	161·8
August	175	0	116	0	326·8	11·1	310·6	329·3	107·9
September	330·5	0	210·8	1·23	578·3	17·3	561	585·8	107·5
October	17·3	18·5	109·7	1·23	182·5	17·3	161·5	186·3	161·8
November	3·7	15	0	2·5	57·0	5	38·2	50·7	38·5
December	2·5	22·2	0	3·7	64·2	12·5	38·2	58·2	38·5
January	2·5	26	1·23	3·7	69·2	16	38·2	61·7	38·5
February	12·5	0	0	1·23	49·5	12·5	26	46	23·1
March	1·23	0	0	1·23	38·2	17·3	10	34·8	0
April	0	0	0	0	35·8	17·3	7·5	32·3	0
May	0	0	0	0	35·8	17·3	7·5	32·3	0
June	0	0	0	0	35·8	12·5	12·5	32·5	12·3

The return flow from industrial water supply (IWS) by Kharkai barrage is nil, from Subernarekha 29·6 m cu m, from IWS by Kharkai barrage 2·5 m cu m and IWS by Kharkai dam 3·7 m cu m requirements had a substantially greater yield than crops with lower water requirement although the fixed costs were the same. For this reason the former crops have been preferred to the latter.

The solution suggests that the optimum economic use of water would be to use it mainly on maize in the kharif season (around 45 % of CCA) and wheat in the rabi season. It is economic to add adequate storage capacities in the two reservoirs such that available water yield in the monsoon period is carried over to the next season for use in the rabi crops. This is because the net social value of wheat per hectare is Rs 2040 compared with Rs 1584.30 per hectare of paddy, although the total water requirement for wheat (70 cm) is less than that for paddy (75 cm). Even within kharif crops, irrigated maize is preferred over irrigated paddy on account of lower water requirements although the yield (and the benefit) for maize is lower than that for paddy.

These results have to be analyzed further by changing the assumptions regarding (i) net benefit from wheat to net benefit from other crops (ii) preference of consumers for rice *vis-a-vis* wheat or maize. In table 10 we have presented the results of changes in optimum cropping pattern when the net benefit from wheat is parametrically decreased up to 40 % of the estimated value in the RS. There is no significant change in the cropping pattern until the net benefit from wheat is decreased to 60 % of its level in the RS. When the wheat benefit is reduced by 40 %, substantial area is allocated to irrigated paddy in the kharif and irrigated maize in the rabi seasons. In the rabi season, the entire area under wheat gets shifted to irrigated maize and in the kharif, area under maize gets reallocated to paddy. The area under irrigated paddy during the kharif also increases mainly on account of the total available area in the rabi season going to irrigated maize. If additional crop area was available, the model may have preferred to store more water in the kharif to be used later in the rabi season.

Table 11 shows the optimal cropping pattern when at least 65 % of the land is assumed to be under paddy cultivation to reflect the consumer preference for rice. When comparing this table with table 5 we see that: (i) the irrigated maize has been almost totally replaced by irrigated paddy in both dams and (ii) the irrigated wheat (70 cm) cultivated has been decreased by half in the Kharkai Dam and by about a third in the Subernarekha dam, while the unirrigated crops have not been affected.

Although the benefit from irrigated maize is about two times that from unirrigated maize, it is substantially lower than that of irrigated wheat. So the cropping pattern is in favour of using the kharif land for unirrigated maize and saving the water for wheat in the rabi season. Since the requirement of water for paddy is about twice that for irrigated maize, the increase in paddy cultivation increased the diversion of water from the dams for irrigation. Thus the water yield in the kharif season carried over to the rabi season is less than before. This in turn reduces the irrigated area under wheat as reflected in the results.

The capacities of the two reservoirs do not change significantly until the net benefit from wheat decreases by 35 to 40 %. In the RS the optimum storage capacity of the Kharkai dam is 707·8 m cu m (table 6). This is lower than the capacity planned at present, which also takes into account the carryover storage from year to year besides carryover from season to season. The optimum storage capacity for the Subernarekha dam is 1254 m cu m (table 8). This is only marginally less than the 1470 m cu m planned. The optimum capacities in the solution with lower net benefit (60 % of that in the RS) are 616·5 m cu m and 1233 m cu m (table 10).

Table 10. Sensitivity analysis of cropping pattern to relative price of wheat (Class I) (in thousand hectares)

	$P = 1·0, 0·95, 0·90, 0·85$				$P = 0·80, 0·75, 0·70, 0·65$				$P = 0·60$			
	KD	KB	SD	SB	KD	KB	SD	SB	KD	KB	SD	SB
Kharif												
U Paddy	16·2	0	19·5	2·4	16·2	0	19·5	0	16·2	0	19·5	0
I Paddy (75 cm)	0	8·5	0	7·3	0	8·5	0	9·7	32	8·5	8·5	9·7
U Maize	9·7	0	11·3	0	9·7	0	11·3	0	6·5	0	11·3	0
I Maize	28·3	0	34·8	0	28·3	0	34·8	0	0*	0	26·3	0
Rabi												
I Wheat (70 cm)	35·2	0	58·3	0	48·4	0	45·3	0	0*	0*	0	0
I Vegetables	2·8	0·4	3·3	0·4	2·8	0·4	3·3	0·4	2·8	0·4	3·3	0·4
U Pulses & oilseeds	3·3	0·4	4	0·4	3·3	0·4	4	0·4	3·3	0·4	4	0·4
I Wheat (57·5 cm)	0	3·6	0	9	0	4	0	0	0	0	0	0
I Maize	0	0	0	0	0	0	0	9	48·6	3·6	58·3	9
Summer												
I Vegetables	2·8	0·4	3·3	0·4	2·8	0·4	3·3	0·4	2·8	0·4	3·3	0·4
I Paddy	0	0·4	0	3·3	0	0·4	0	4·4	0	0·4	0	—
Capacity of dam (live storage) m cu m	707·8		1254		707·8		1254		615·3		1232	

KD-Karkai Dam, KB-Karkai Barrage, SD-Subernarekha Dam, SB-Subernarekha Barrage, I-Irrigated, U-Unirrigated.

Table 11. Optimum cropping pattern in Reference Solution with lower bounds on paddy (in thousand hectares)

	Kharkai dam	Kharkai barrage	Suberna rekha dam	Suberna rekha barrage
Kharif				
Unirrigated paddy	16·2	0	19·5	2
Irrigated paddy (75 cm)	25·5	8·5	30·8	7·7
Irrigated paddy (67·5 cm)	0	0	0	0
Unirrigated maize	9·7	0	11·3	0
Irrigated maize	2·8	0	4	0
Rabi				
Irrigated wheat (70 cm)	18	0	38	0
Irrigated wheat (57·5 cm)	0	3·3	0	8·9
Unirrigated pulses and oil seeds	3·3	0·4	4	0·4
Irrigated Vegetables	2·8	0·4	3·3	0·4
Summer				
Irrigated vegetables	2·8	0·4	3·3	0·4
Irrigated paddy (75 cm)	0	0·4	0	3·7
Gross cropped area (A)	80·3	13·4	114·2	23·5
Gross irrigated area (B)	52·2	13	79·3	21
Culturable command area (C)	64	10	77	11·3
Intensity of cropping (A/C) (%)	127	132	148	207
Intensity of irrigation (B/C) (%)	82	128	103	186

To summarize, the tentative results do indicate the importance of analyzing the possible choices available in utilization of water for different crops. It seems more economical to increase the storage capacities mainly for use in the rabi season when rainfall is relatively lower than in the kharif season. Since optimum cropping pattern depends on many other agro-economic variables besides water supply, such as size and ownership of land, availability of inputs, farmer's attitude to risk, home-consumption requirements and consumer's preferences, there is need for more disaggregated analysis of interaction between irrigation planning and related agroeconomic variables.

Appendix A. The model.

Objective function

Maximize

$$\sum_{t,i} a_{ti} C_{ti} \quad - \sum_i b_i k_i \quad - \sum_i d_i X_i \quad + \sum_{i,j} f_{ij} I_{ij} \quad - \sum_i c_i \qquad \text{(A1)}$$

(Net value of crops net of variable farm costs)	(Annualized cost of dams)	(Annualized cost of irrigation canals)	(Net value of industrial water supply)	(Fixed farm costs)

The constraints

1. Flow continuity constraints:

Kharkai dam $\quad V_{i1} = \bar{Q}_{i,1} + \bar{V}_{i0} - X_{i1} - I_{i1} - Q_{i1,1} \quad J = 1$ (1^{st} period) (A2)

Subarnarekha dam $\quad V_{ij} = \bar{Q}_{i,j} + \beta_{ij} V_{i,j-1} - X_{ij} - I_{ij} - Q_{ik,j} \quad j = 2, \ldots 12,$ (A3)

(Storage at site i at the end of the jth period)	(inflow at site i during the jth period)	(storage at site i at the beginning of the jth period, net of evaporation losses)	(diversion for irrigation at ith site for the jth period)	(diversion for industrial supply during the jth period)	(release from ith site to kth site during jth period.

for $\quad i = 2$ and 3.

Capacity-constraints for dams

$$V_{ij} - K_i \leqslant 0 \qquad \text{(A4)}$$

$$V_{ij} \geqslant \bar{D}_i \qquad \text{(A5)}$$

(dead storage level of the reservoir)

Continuity constraint for Kharkai barrage

$$\underbrace{\bar{H}_{2.j}}_{\substack{\text{(Hydrological input at 2nd}\\ \text{site in } j\text{th period)}}} + \underbrace{\rho_{12} X_{ij}}_{\substack{\text{(Regeneration from irrig-}\\ \text{ation use from } i\text{th site/}j\text{th}\\ \text{period)}}} + \underbrace{\gamma_{12} Q_{12.j}}_{\substack{\text{(Inflow from 1st site to 2nd}\\ \text{site in } j\text{th period)}}} + \underbrace{\phi_{12,j} I_{ij}}_{\substack{\text{(Return flow from indus-}\\ \text{trial water from } i\text{th site in}\\ j\text{th period)}}}$$

$$= \underbrace{X_{2j}}_{\substack{\text{(diversion for irrigation}\\ \text{from 2nd site in } j\text{th period)}}} + \underbrace{Q_{24,j}}_{\substack{\text{(outflow from 2nd site to}\\ \text{4th site during } j\text{th period)}}} + \underbrace{I_{2j}}_{\substack{\text{(diversion for industrial}\\ \text{water supply from 2nd site}\\ \text{in } j\text{th period)}}} \tag{A6}$$

Continuity constraint for Subernarekha barrage

$$\underbrace{\bar{H}_{4,j}}_{\substack{\text{(Hydrological input}\\ \text{at 4th site in } j\text{th}\\ \text{period)}}} + \underbrace{\rho_{14} X_{1j}}_{\substack{\text{(regeneration from}\\ \text{irrigation use diver-}\\ \text{ted from 1st site in}\\ j\text{th period)}}} + \underbrace{\rho_{24} X_{2j}}_{\substack{\text{(regeneration from}\\ \text{irrigation use from}\\ \text{2nd site in } j\text{th}\\ \text{period)}}} + \underbrace{\rho_{34} X_{3j}}_{\substack{\text{(regeneration from}\\ \text{irrigation use from}\\ \text{3rd site in } j\text{th}\\ \text{period)}}} + \underbrace{\gamma_{24,j} Q_{24,j}}_{\substack{\text{(inflow of water}\\ \text{from 2nd site to}\\ \text{4th site in } j\text{th}\\ \text{period)}}} + \underbrace{\gamma_{34,j} Q_{34,j}}_{\substack{\text{(inflow of water}\\ \text{from 3rd site to 4th}\\ \text{site}}}$$

$$+ \underbrace{\phi_{14.j} I_{ij} + \phi_{24,j} I_{2j} + \phi_{3,4j} I_{3j}}_{\substack{\text{(return flow from industrial water supply from}\\ \text{sites 1, 2 and 3 to site 4 during } j\text{th period)}}} = \underbrace{X_{4j}}_{\substack{\text{(diversion for irrigation}\\ \text{from 4th site)}}} + \underbrace{E_j}_{\substack{\text{(flow for downstream}\\ \text{use at 4th site)}}} + \underbrace{I_{4j}}_{\substack{\text{(diversion for industrial}\\ \text{supply of water from}\\ \text{4th site)}}} \tag{A7}$$

2. Irrigation Flow Constraint

$$\underbrace{X_{ij}}_{\substack{\text{(Diversion for irrigation from } i\text{th site}\\ \text{in } j\text{th period)}}} \geqslant \underbrace{\Sigma \delta_{itj} C_{ti}}_{\substack{\text{(Water requirement for non-perennial}\\ \text{crops)}}} + \underbrace{\Sigma \lambda_{itj} P_i}_{\substack{\text{(Water requirement for perennial}\\ \text{crop/sugarcane)}}} \tag{A8}$$

3. Canal capacity constraint

$$X_{ij} - X_i \leqslant 0$$

$$X_i \leqslant \overline{X}_i \qquad \text{(A9)}$$

4. Constraints on culturable command area

Kharif

$$\sum_{t=1}^{5} C_{ti} + P_i \leqslant \overline{C}_{Ki}, \quad \text{for} \quad i=1 \text{ to } 4 \qquad \text{(A10)}$$

(land used by crops at site i) (land used by sugarcane at site i) (total available land during the Kharif season)

Rabi

$$\sum_{t=6}^{11} C_{ti} + P_i \leqslant \overline{C}_{Ri}, \quad \text{for} \quad i=1 \text{ to } 4. \qquad \text{(A11)}$$

(land used by Rabi crops at site i) (land used by sugarcane at site i) (total available land during the rabi season)

Summer

$$\sum_{t=12}^{13} C_{ti} + P_i \leqslant \overline{C}_{Hi}, \quad \text{For} \quad i=1 \text{ to } 4. \qquad \text{(A12)}$$

(land used by summer crops) (total available land during the summer season)

$$A_i = \overline{C}_{Ai}, \quad \text{for} \quad i=1 \text{ to } 4$$

(land prepared for sowing at site i) (culturable command area at site i)

$$\sum_{t=1}^{3} C_{ti} \geqslant 0{\cdot}6\,\overline{C}_{Ki}, \quad \text{for} \quad i=1 \text{ to } 4 \qquad \text{(A13)}$$

(land used by Paddy)

5. Industrial water supply constraints

$$I_{ij} \leqslant \overline{I}_{ij} \qquad \text{(A14)}$$

List of indices and symbols

Indices

$i = 1$	Kharkai reservoir at Icha
2	Kharkai barrage at Bhua
3	Subernarekha reservoir at Chandil
4	Subernarekha barrage at Galudih

$t = 1$	kharif unirrigated paddy.
2	kharif irrigated paddy (75 cm).
3	kharif irrigated paddy (67·5 cm).
4	kharif unirrigated maize.
5	kharif irrigated maize.
6	rabi irrigated wheat (70 cm)
7	rabi irrigated wheat (57·5 cm)
8	rabi irrigated pulses and oilseeds,
9	rabi unirrigated pulses and oilseeds,
10	rabi irrigated maize
11	rabi irrigated vegetables,
12	summer irrigated vegetables
13	summer irrigated paddy
14	perennial sugarcane

(The figures in brackets denote water supplied corresponding to which appropriate yields are adopted)

Symbols

a_{ti}	—net value of crop t at site i (Rs million per thousand hectares)
b_i	—annualised cost of reservoir i (Rs million per m cu m) for $i = 1,3$)
C_{ti}	—land used by crop t ($t = 1$ to 10) at site i ($i = 1$ to 4)
c_i	—coefficient of fixed cost at site i
d_i	—annualised cost of canals, including cost of barrage at sites 2 and 4, at site i (Rs million per m cu m)
E_j	—flow for downstream use at Subernarekha Barrage during the jth period
f_{ij}	—unit value of industrial water supply at site i during the jth period (Rs million per m cu m)
I_i	—investment per thousand cu m
I_{ij}	—Industrial water supply from site i during period j ($j = 1$ to 12)
$I_i(t)$	—investment cost due to the ith element in the tth period
K_i	—capacity of the ith reservoir
P_i	—land used by the perennial crop (sugarcane) at site i (in (A1)–(A14); the appropriate shadow price of the ith element in investment cost (in (1)).
$Q_{ik,j}$	—flow of water from site i to site k during the jth period

r	—the rate of interest
t	—the running time variable
V_{ij}	—storage of water at site i at the end of the jth period
X_i	—capacity of irrigation canal at site i
X_{ij}	—flow of irrigation water from site i during period j
β_{ij}	—reservoir losses at the ith site during the jth period
$\gamma_{ik,j}$	—efficiency coefficient for flow from site i to site k during the jth period
$\delta_{it,j}$	—water required by crop t at site i during the jth period (cm)
$\phi_{ik,j}$	—coefficient of return flow from industrial water supply from the ith site to the kth site/jth period
$\lambda_{it,j}$	—water required by sugarcane during the jth period (cm)
$\rho_{ik,j}$	—coefficient of return flow from the ith site to the kth site during the jth period
θ	—the total number of years for the construction of the project

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Study of a complex water resources system with screening and simulation models

M C CHATURVEDI* and D K SRIVASTAVA†

* Applied Mechanics Department, Indian Institute of Technology, Hauzkhas, New Delhi 110016

† School of Hydrology, University of Roorkee, Roorkee 247 667, India

Abstract. The study describes a sequential iterative modelling process for a complex water resource system. Two types of analytical models are used to find a reasonably small set of possible systems optimal design alternatives for a complex river basin. These models are a linear programming deterministic continuous (LPDC) model and a linear programing deterministic discontinous (LPDD) model. Linear programing has been used with linear approximation of the nonlinear functions. A simulation program has been developed which continues screening on the basis of the information obtained from the linear programing model. The models are developed in the context of analysis of the Narmada river, a large river basin in India, for which in the first instance alternative combinations and capacities of six major dams have to be decided.

Keywords. River basin planning; LP models; simulation techniques.

1. Introduction

Although considerable interest has developed of late in systems planning of water resources and it has been generally accepted that real-life applications are required to validate the efficacy and worthwhileness of certain techniques, studies of real-life complex systems are still relatively rare. For instance, it is well known that in view of the non-linearities and discontinuities in the objective function, the final analysis of a complex large real-life system could be best carried out by simulation. On the other hand, simulation over even a promising feasible set would be computationally impossible. Preliminary screening by a mathematical programming technique on the basis of which simulation could be planned has often been recommended (Dorfman 1962; Hufschmidt & Fiering 1966; Roefs 1968; Roefs & Bodin 1970; Loucks 1969). In this context, it is profitable to investigate the value of mathematical programming in preliminary screening and how it should be coupled with a simulation study. For instance it may be instructive to ascertain how deterministic linear programming models would help in identifying the optimal set in view of the stochastic inputs. An attempt was therefore made to study a real-life large scale complex system, the Narmada basin in India, by a combination of a mathematical programming screening model and a simulation model.

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2. A list of symbols and indices is given at the end of the paper

3. *Conversion table*

1 inch = 2·54 cm; 1 foot = 0·3048 m; 1 mile = 1·609 km; 1 mile^2 = 2·59 km^2; 1 acre = 0·405 ha; 1 acre foot = 0·1234 ha m, 1 cusec = 0·02832 cumec.

In view of the large number of reservoirs being involved and the preliminary planning nature of the study a deterministic linear programming (LP) technique was adopted. However, two types of models—continuous and discontinuous—linear programming deterministic (LPDC and LPDD) models were used following the suggestion of Loucks (1969). In continuous models the reservoir release always equals the difference between the water available (initial reservoir storage plus net inflow) in one period and the initial reservoir storage in the following period. But discontinuous models violate this continuity law for one or more periods, which may provide insights about excess storage and excess reservoir capacity needed for dry and wet years respectively. The simple deterministic programming models were used as preliminary screening models. A simulation technique was used for further analysis, to obtain a near optimum solution in terms of the objective function.

The approach was adopted independently of a similar approach to a combined screening-simulation study of a real-life large scale complex system by Jacoby & Loucks (1972). The results of the present study, carried out under different conditions, confirm and extend their findings.

2. The problem

The Narmada river basin (805 miles long and 50 miles wide) is located in Central India, within the state of Madhya Pradesh primarily, as shown in figure 1. The population density is 190 persons/mile^2. The basin, with a potential of mean flows of about 28 million acre ft (MAF) at 75 % availability and outstanding storage sites has undergone no development at all so far except for one dam recently constructed. There are 32

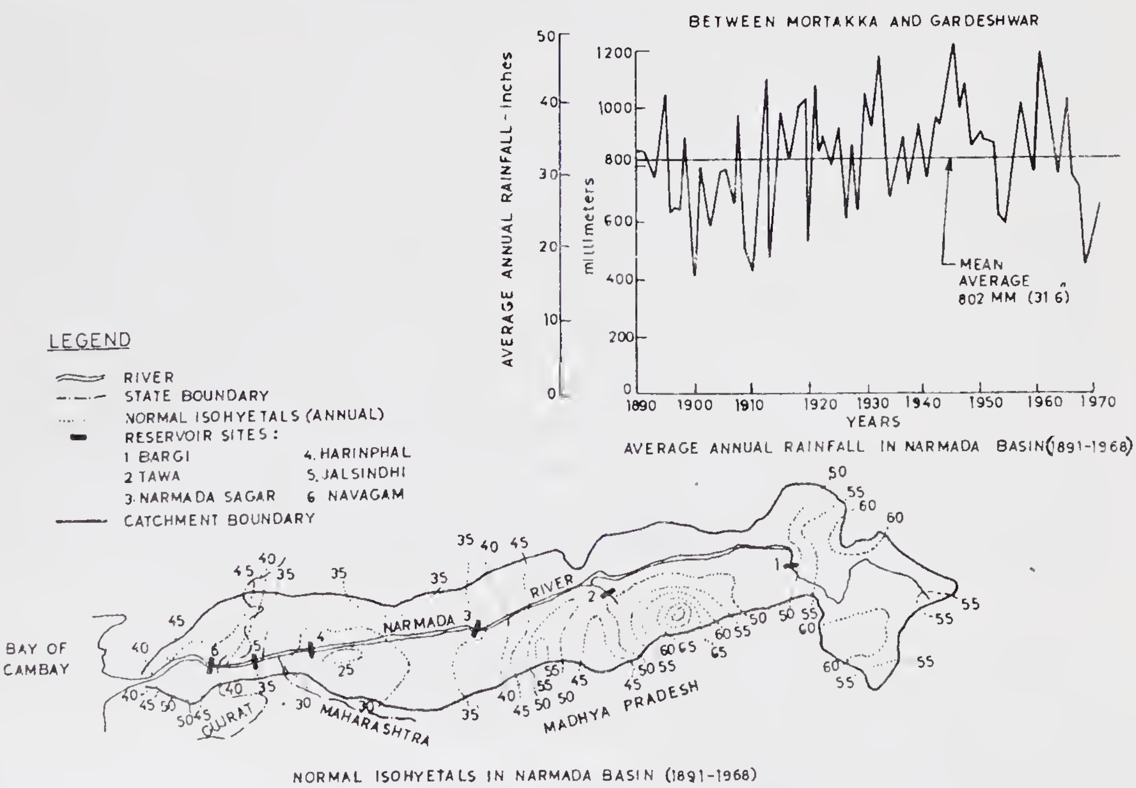

Figure 1. Hydrological characteristics of the Narmada system

proposed reservoir sites, of which six are major ones. Thirty one lie in Madhya Pradesh and the last one, Navagam lies on the border of Madhya Pradesh and the downstream state of Gujarat. The sharing of waters between the two states and the proposed height of this dam are controversial. The yearly rainfall, and typical yearly rainfall pattern are shown in figure 1. The data have been collected from different reports (Master Plan 1972; Narmada Water Resources Development Committee 1965; and various Project Reports). The observed river flow data are over a period of 16 years.

In the first instance, alternative combinations, capacities and operating policies of six major dams—Bargi, Tawa, Narmadasagar, Harinphal, Jalsindhi and Navagam, as shown in figure 2, are proposed to be investigated. There are three distinct alternatives listed in table 1 for this set of dams as three possible values for the height of the last dam, Navagam, have been chosen for analysis. In the first alternative shown in figure 2, Navagam dam has the lowest height. In the second case, the height is raised till the first upstream dam, Jalsindhi, is submerged. In the third case the height is further increased till the next upstream dam, Harinphal, is also submerged. With increased water requirements at Navagam in the latter two cases, irrigation diversions of the upper dams would have to be modified. Two more alternatives, shown in table 1 are tried by replacing the single-purpose irrigation projects to single-purpose hydropower projects as suggested by some engineers. Multipurpose use has not been considered feasible for the first two dams.

The capacity, cost and net benefits at the various sites vary considerably because of hydrological and geological conditions. The average monthly flows based on a record of 16 years at the dam sites are shown in figure 3. The reservoir capacity and capital costs are shown in figure 4 for illustration. For each of the alternatives the maximum permissible capacity is given from the physical configuration.

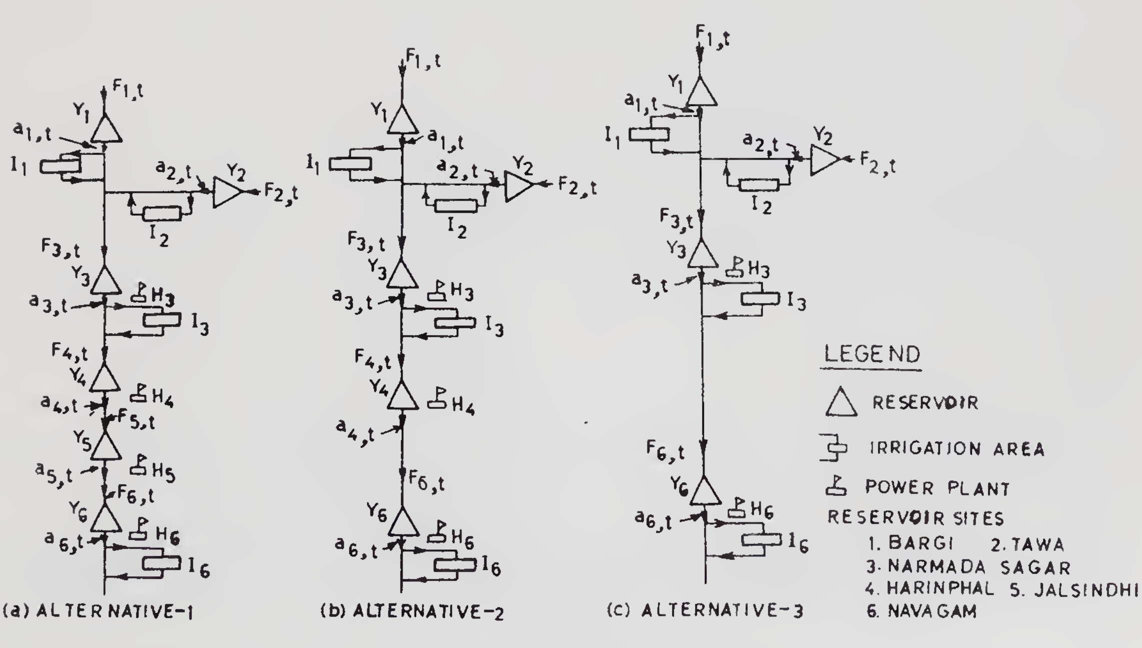

Figure 2. Alternative configurations of the Narmada system

Table 1. Alternative configurations of the Narmada system

Alternative 1		Alternative 2		Alternative 3	
Project name	Purpose	Project name	Purpose	Project name	Purpose
1. Bargi	I*	1. Bargi	I	1. Bargi	I
2. Tawa	I	2. Tawa	I	2. Tawa	I
3. Narmadasagar	I and E**	3. Narmadasagar	I and E	3. Narmadasagar	I and E
4. Harinphal	E	4. Harinphal	E	4. Navagam	I and E
5. Jalsinghi	E	5. Navagam	I and E		
6. Navagam	I and E				

Alternative 4		Alternative 5	
Project name	Purpose	Project name	Purpose
1. Bargi	E	1. Bargi	E
2. Tawa	I	2. Tawa	E
3. Narmadasagar	I and E	3. Narmadasagar	I and E
4. Harinphal	E	4. Navagam	I and E
5. Navagam	I and E		

* I = irrigation; ** E = energy production

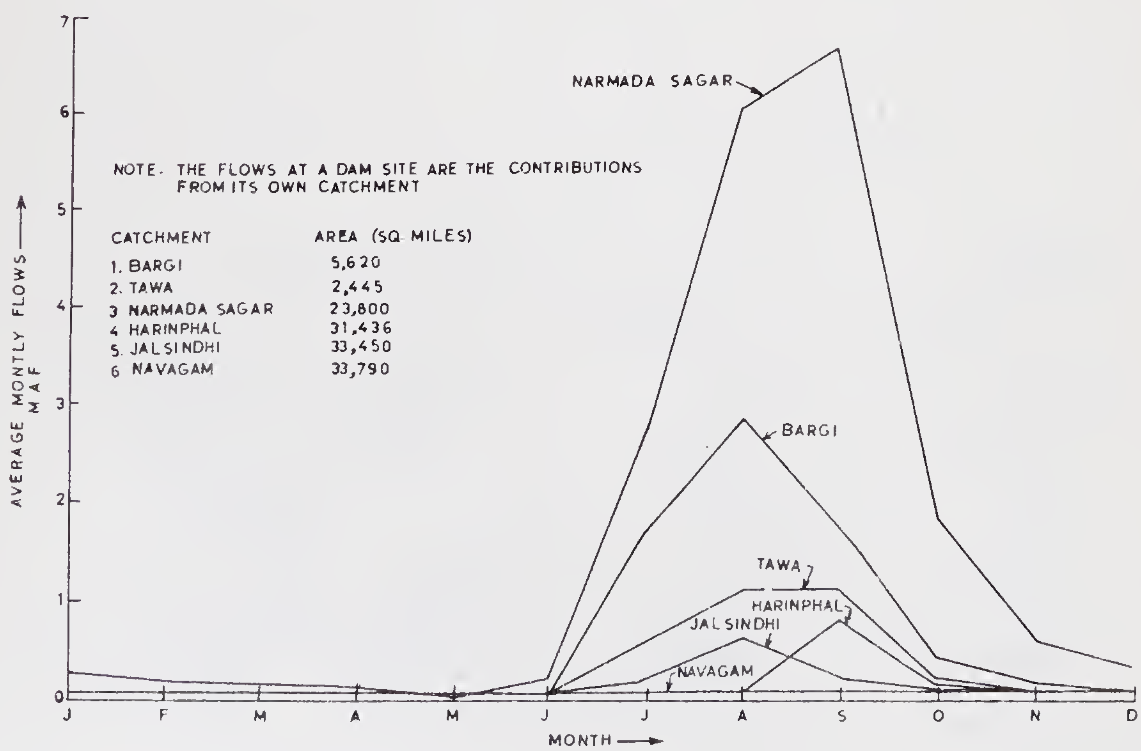

Figure 3. Average monthly flows at dam sites

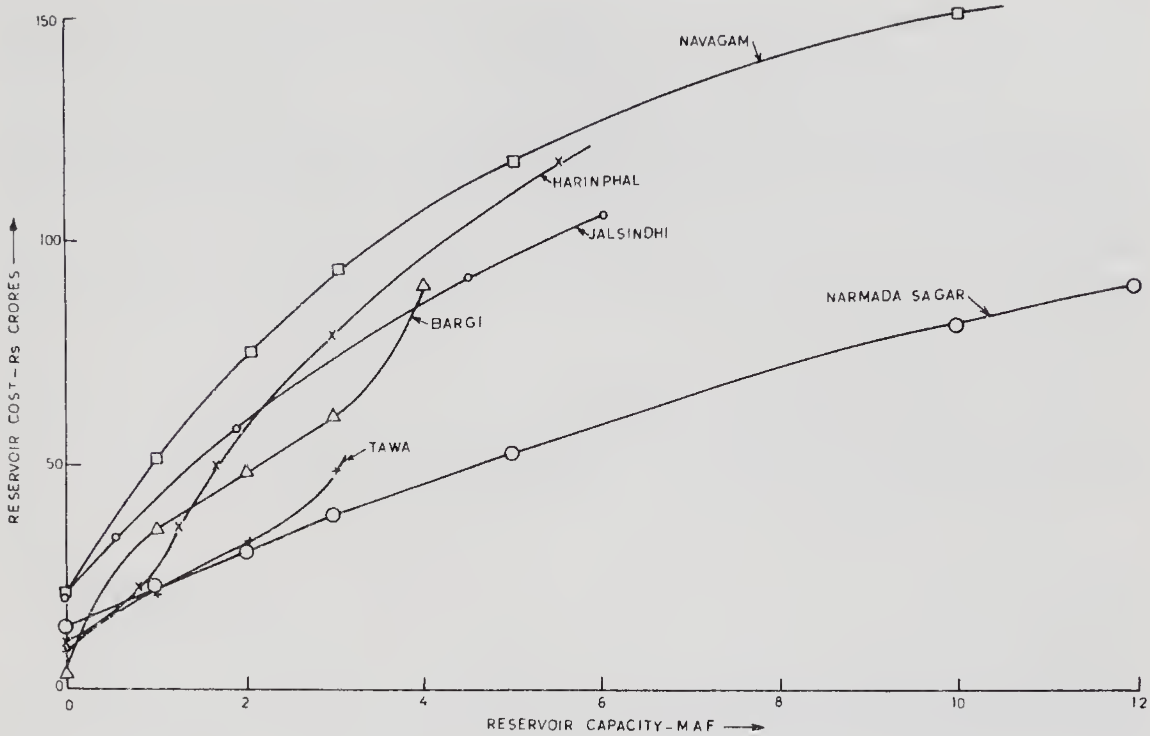

Figure 4. Reservoir capacity *vs* capital cost curves

3. The models

3.1 *Linear programing models*

The objective function is to maximize the total annual net benefits at all sites i.

$$\text{Maximise: } \sum_i [B_{1,i}+B_{2,i}-(C_{1,i}+C_{2,i}+C_{3,i})-(O_{1,i}+O_{2,i}+O_{3,i})].$$

The first subscript 1, 2 or 3 represents power, irrigation, or reservoir capacity respectively, and the second subscript i represents a site in the system.

The maximization of the objective function is subject to the following constraints:

(a) The volume of water released from the reservoir must be sufficient to meet the irrigation demand in that period, *i.e.*

$$a_{i,t}+f_{i,t} \geq K_{i,t}I_i, \quad \text{for all } i \text{ and } t. \tag{1}$$

(b) The volume of water released during any period cannot exceed the contents of the reservoir at the beginning plus the flow into the reservoir during the period, *i.e.*

$$a_{i,t} \leq S_{i,t}+F_{i,t}, \quad \text{for all } i \text{ and } t. \tag{2}$$

$F_{i,t}$ is given by

$$F_{i,t}=f_{i,t}+\sum_{j=1}^{z_i}(a_{j,t}+f'_{j,t}-K_{j,t}I_j+K'_{j,t}I_j), \qquad \text{for all } i \text{ and } t. \tag{3}$$

(c) The continuity equation for each reservoir site is defined as

$$S_{i,t+1} = S_{i,t} + F_{i,t} - a_{i,t}, \quad \text{for all } i \text{ and } t. \tag{4}$$

In the continuous (LPDC) model the reservoir contents at the end of the year, $S_{i,t+1}$, are assumed equal to the reservoir contents at the starting of the year $S_{i,1}$, for all reservoir sites, but discontinuous (LPDD) models violated this continuity law for one or more periods.

(d) The contents of the reservoir at any period cannot exceed the capacity of the reservoir, or

$$S_{i,t} \leqslant Y_i, \quad \text{for all } i \text{ and } t. \tag{5}$$

(e) The flow through the turbines should meet energy generation demand. Variation of generation efficiency at different sites is neglected at this stage

$$\delta_t E_i - (1{,}025)(e)(\mathrm{He}_{i,t})(a_{i,t}) \leqslant 0, \quad \text{for all } i \text{ and } t, \tag{6}$$

where 1,025 converts million acre feet-feet to megawatt hours (MWh). At variable head sites, $\mathrm{He}_{i,t}$ is not a known constant. Therefore, together with $a_{i,t}$ it makes (6) a nonlinear one. Appropriate $\mathrm{He}_{i,t}$ was determined by trial and error as discussed later.

(f) Power production is also limited by the percent of time that the plant will produce power specified by the load factor

$$\alpha_{i,t} h_t(H_i) - \delta_t E_i \geqslant 0, \quad \text{for all } i \text{ and } t. \tag{7}$$

3.2 *Simulation model*

A simulation program has been developed which continues the screening on the basis of information obtained from the LP models given above. The rationale for adopting a particular operating procedure, *i.e.* a set of rules for storing and releasing water in reservoirs, is discussed later; it depends upon the alternative found most suitable for simulation.

4. Computation

In the first instance and also because of limited hydrologic data, historic hydrologic flows have been adopted for analysis. Hydrologic risk, evaporation losses, and flood control benefits were not included in these models, while seasonal flows were used. The LP model had 4 periods of equal length each year and the standard simplex program, the mathematical programing system (MPS) available with the IBM 360 Computer was used for solving the LP problem. The simulation model considered 12-monthly periods and the simulation program was developed on an International Computers Limited (ICL) 1909 computer.

The design values for cost and benefit were available for one capacity. These were therefore estimated for different possible ranges for each of the six projects on the basis of appropriate engineering approaches and suitable functions were developed (Srivastava 1976). On the basis of the project design and with the help of project authorities, sections for concrete dams (overflow and non-overflow section) and earth dams were developed and quantities and costs were worked out. The cost of auxiliary works was developed on a unit cost basis. The costs for the generating plant and equipment and auxiliary works were developed on a unit cost basis. The cost of irrigation and diversion works was also developed on a unit cost basis. Under these three major heads both direct and indirect charges were estimated for 1973 prices. Although they involved considerable work, it must be understood that the estimates are for a methodological study rather than for detailed design. The reservoir functions are given in figure 4. All capital costs were converted to annual costs for the linear programs. A time horizon of 16 years was used in the analysis and annual costs were calculated from the capital costs as the sum of the following items: (i) Interest on the capital cost of irrigation and power projects at 7 % per annum; (2) depreciation on the capital cost of irrigation projects at 1 %; (3) annual depreciation and replacement of the power plant at 2 % of the total cost of power plants; (4) maintenance cost of irrigation at Rs 6 per acre for the area to be irrigated; (5) annual cost of operation and maintenance for hydropower at Rs 10 per kW of installed capacity. In simulation the present value of net benefits extending over the period of study for the system was calculated.

4.1 LP *computations*

For both types of LP model, constraints were written only for one year. The decision variables were namely $a_{i,t}$; $S_{i,t}$; Y_i; H_i and E_i. LPDC models were the first type to be used and mean monthly flows were used as the input, as shown in table 2. Values of $K_{i,t}$ and δ_t for each time period are given in table 3.

Table 2. Mean flows at dam sites ($f_{i,t}$)

Time period	Mean flow* average taken for 16 years historic flow data (MAF)					
	Bargi	Tawa	Narmadasagar	Harinphal	Jalsindhi	Navagam
t	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$	$i = 6$
1	0·08101	0·04118	0·54620	0·01405	0·03768	0·00288
2	0·10043	0·04232	0·37251	0·07613	0·02936	0·00492
3	6·23475	2·78181	15·29213	0·86832	1·26628	0·12533
4	0·62159	0·29899	2·73611	0·19188	0·16823	0·02666
Total	7·03778	3·16430	18·94695	1·15038	1·50155	0·15979

* The flows at a dam site are the contribution from its own catchment and are the sum of average monthly flows.

Table 3. Values of $K_{i,t}$ and δ_t

Time period	Percentage of total annual irrigation requirement $K_{i,t}$				Total annual energy requirement* (%)
	Bargi	Tawa	Narmadasagar	Navagam	
t	$i = 1$	$i = 2$	$i = 3$	$i = 6$	t
1	24·87	19·49	30·52	9·39	27
2	21·73	5·55	32·01	28·07	21
3	15·65	51·12	11·06	30·93	24
4	37·75	23·84	26·41	31·61	28
Total	100·00	100·00	100·00	100·00	100

* At 60 % load factor

Table 4. Values of cost and benefit functions

i	$\beta_{2,i}$	$C'_{1,i}$	$C'_{2,i}$	$C'_{3,i}$	$O'_{1,i}$	$O'_{2,i}$	$O'_{3,i}$
			All values are in Rs 10 million/unit item				
1	47·70	0·00574	1·870	1·560	0·001	0·2075	—
2	22·45	0·00432	1·632	—	0·001	0·2345	—
3	18·75	0·00504	3·370	0·640	0·001	0·1488	—
4	—	a*	—	1·377	b**	—	—
5	—	c†	—	1·400	d‡	—	—
6	36·80	0·01500	3·105	1·272	0·001	0·2130	—

* $H_4 = H_{4,1} + H_{4,2}$, $H_{4,1} \leqslant 470$, $C_{1,4} = 0{\cdot}00641\ H_{4,1} + 0{\cdot}00722\ H_{4,2}$
** $D_{1,4} = 0{\cdot}001\ (H_{4,1} + H_{4,2})$; † $H_5 = H_{5,1} + H_{5,2}$, $H_{5,1} \leqslant 470$,
$O_{1,5} = 0{\cdot}00612\ H_{5,1} + 0{\cdot}00791\ H_{5,2}$; ‡ $O_{1,5} = 0{\cdot}001\ (H_{5,1} + H_{5,2})$

$O'_{3,i} = 0$, in all cases.

The nonlinear objective function was made piecewise linear and the values of cost and benefit functions are shown in table 4. In view of the preliminary nature of analysis for screening purposes, only linear functions approximating the concave or convex preliminary estimates were assumed or in hydropower plant cost functions, piecewise linearisation was assumed. The piecewise-linearised function is as follows:

$$\text{Maximize:}\ \sum_i \Bigg[\left\{ \sum_t^T \delta_t \beta_{1,i,t} \sum_{s(i)} E_{i,s(i)} \right\} + \left\{ \sum_{s(i)} b_{2,i,s(i)} I_{i,s(i)} \right\}$$
$$- \left\{ \sum_{s(i)} l_{1,i,s(i)} H_{i,s(i)} + \sum_{s(i)} l_{2,i,s(i)} I_{i,s(i)} \right.$$
$$\left. + \sum_{s(i)} l_{3,i,s(i)} Y_{i,s(i)} \right\} - \left\{ \sum_{s(i)} m_{1,i,s(i)} H_{i,s(i)} \right.$$
$$\left. + \sum_{s(i)} m_{2,i,s(i)} I_{i,s(i)} + \sum_{s(i)} m_{3,i,s(i)} Y_{i,s(i)} \right\} \Bigg] \tag{8}$$

where, $E_{i,s(i)}$; $H_{i,s(i)}$; $I_{i,s(i)}$; and $Y_{i,s(i)}$ are portions $s(i)$ into which each target i is divided, given by

$$E_i = \sum_{s(i)} E_{i,s(i)}, \qquad I_i = \sum_{s(i)} I_{i,s(i)},$$
$$H_i = \sum_{s(i)} H_{i,s(i)}, \qquad Y_i = \sum_{s(i)} Y_{i,s(i)}.$$

Similarly, the nonlinear constraint (6) was linearized by assuming an effective head and comparing it with the head specified in the model solution. Totally two runs were needed to match the effective head with the actual head. The gross reservoir capacity of the Tawa reservoir was taken as 1.874 MAF since it was already under construction in the system. The return flow ($K'_{j,t}$) was taken as 10% of the annual irrigation demand, as given in project reports.

A few more constraints were added on the basis of some design criteria:

(i) In the Report of the Narmada Water Resources Development Committee (1965), it was recommended that sharing of water for irrigation between Madhya Pradesh and Gujarat should start when the total storage in all Madhya Pradesh reservoirs including Navagam reservoir is less than 16 MAF on 1 October. This fixes a lower limit of 16 as the total storage in all reservoirs on 1 October, *i.e.*,

$$\sum_i S_{i,4} \geqslant 16. \tag{9}$$

(ii) It is also recommended that the total irrigation water used by Madhya Pradesh should be at least 1·442 times that used by Gujarat in view of the greater area of the former, *i.e.*

$$\sum_{i=1}^{5} I_i \geqslant 1{\cdot}442\, I_6. \tag{10}$$

(iii) The maximum irrigation water used by Gujarat should not exceed 10·65 MAF out of consideration of respective irrigable areas, *i.e.*

$$I_6 \leqslant 10{\cdot}65. \tag{11}$$

(iv) The total energy constraint fixed by the project authorities from consideration of hydropower component of total energy supply gave

$$\sum_i E_i \geqslant 5{,}214{,}000, \quad \text{for all } i. \tag{12}$$

(v) The dead storage of a reservoir puts a lower limit on the reservoir storage in case of its producing power.

$$S_{i,t} \geqslant D_i, \quad \text{for all } i \text{ and } t. \tag{13}$$

The values used were $D_1 = 0{\cdot}6$, $D_3 = 2$, $D_4 = 0{\cdot}342$, $D_5 = 0{\cdot}15$, and $D_6 = 0{\cdot}31$ all in MAF, as determined from usual engineering practice in design reports.

The results of the LPDC model when applied to various alternatives of table 1 are given in table 5. The computational time taken by the largest problem containing 142 rows and 211 variables inclusive of slack variables was approximately 2 minutes. Results show that the maximum present value of net benefit of Rs 9,200 crores is obtained for alternative 3. The difference in the first three alternatives is not appreciable because the cost and contribution of the two replaced projects is comparatively small. Similarly, in schemes 4 and 5 replacement of irrigation by energy in projects 1 and 2 respectively is not economical. It is significant to note that benefits of energy go to project 1 at the cost of project 6 in scheme 4 while additional benefits accrue to project 3 in scheme 5. Their results could not be anticipated by judgement as costs and benefits are not correlated in a simple transitive manner.

Alternative 3 identified as the optimal was chosen for analysis by the LPDD model. Dry years were defined using 0·95 and 0·75 of the mean flow, whereas only one wet year was considered using 1·25 of the mean flow. The results obtained are shown in table 6 as well as in figure 5 as percent of average flow figures for each item. Bounds were also included for the reservoir contents $S_{i,t}$ to avoid unbounded solutions, such that

$$S_{i,t} \leqslant Y_i, \quad \text{for all } i \text{ and } t. \tag{14}$$

Table 5. Results of linear programing deterministic continuous (LPDC) model .

Variables*	Alternative (refer table 1)				
	1	2	3	4	5
Y_1	5.133	5·133	5.133	4·545	0·884
I_1	7·037	7·037	7·037	—	—
H_1	—	—	—	121	38
E_1	—	—	—	944,273	297,857
Y_2	1·874	1·874	1·874	1·874	1·874
I_2	1·506	1·506	3·164	3·164	—
H_2	—	—	—	—	23
E_2	—	—	—	—	181,074
Y_3	12·466	12·466	12·796	13·598	17·289
I_3	10·638	10·637	10·957	20·849	19·002
H_3	433	433	446	446	526
E_3	3,384,086	3,384,086	3,490,689	3,643,199	4,114,292
Y_4	0·342	0·342	—	0·342	—
H_4	0·0	0·0	—	0·0	—
E_4	0·0	0·0	—	0·0	—
Y_5	0·15	—	—	—	—
H_5	0·0	—	—	—	—
E_5	0·0	—	—	—	—
Y_6	2·882	2·882	2·379	2·507	2·564
I_6	10·65	10·65	10·65	10·65	10·65
H_6	234	234	220	80	159
E_6	1,829,914	1,829, 914	1,723,321	626,528	1,242,381
ΣE_i	5,214,000	5,214,000	5,214,000	5,214,000	5,835,604
ΣI_i	29·892	29.832	31.809	34.637	29.652
Benefit**	8,910·0	8,910·0	9,200·0	7,510·0	6,550·0
Benefits as % of max.	96·7	96·7	100·0	81·5	71·0

* Y, gross reservoir capacities (MAF); I, annual irrigation targets (MAF); H, the hydropower capacities (MW); E, annual energy targets (MWh), subscripts 1 to 6 refer to the six sites.
** Benefits are present value of net annual benefits for 16 years in crores ($\times 10^7$) of rupees.

It is seen from figure 5 and from table 6, that for both dry and wet years the reservoir capacity of each reservoir was more than that needed for average flow. On the other hand, each irrigation target for dry years was less and for wet years it was more than what was required for average flow as was to be expected. However, the variation from one project to another is large, which could not be anticipated. Therefore, it can be said that the LPDD model estimates the complex variations required in capacities and targets during drought and wet years. It is then possible to fix ranges of design variables based on these results for simulation by random sampling as shown in table 7.

4.2 *Simulation computations*

Simulation continued the screening on the basis of information obtained from LP models. The period of analysis of 16 years was chosen because of the availability of data. All the nonlinearities in the benefit-loss and cost functions were incorporated in the simulation model in an effort to keep the model real. The simulation model is static in

Table 6. Results of linear programming deterministic discontinuous (LPDD) model (for alternative-3)

Variables	Dry and wet years			
	0·75 Average flow (dry)	0·95 Average flow (dry)	Average flow†	1·25 Average flow (wet)
Y_1	5·408	5·188	5·133	7·975
I_1	5·278	6·685	7·037	8·797
Y_2	1·874	1·874	1·874	1·874
I_2	0·000	3·006	3·164	3·769
Y_3	14·495	12·896	12·796	19·284
I_3	8·507	9·502	10·957	19·166
H_3	458	436	446	672
E_3	3,582,611	3,407,902	3,490,679	5,252,965
Y_6	4·687	2·551	2·379	3·994
I_6	9·560	10·650	10·650	10·650
H_6	209	231	220	95
E_6	1,631,389	1,806,098	1,723,321	741,137
ΣE_i	5,214,000	5,214,000	5,214,000	5,994,102
ΣI_i	23·345	29·843	31·808	42·382
Benefits	6,460·0	8,280·0	9,200·0	9,350·0
Benefits as percent of average flow	67·5	90·0	100·0	101·5

† Alternative 3 from table 5.

nature. The computer program for the Narmada simulation represents a considerable coding effort. It consists of a main routine, 26 subroutines and 9 function subprograms. Details are given in Srivastava (1976) and a simplified flow chart is given in figure 6.

For further screening with the help of a simulation model, alternative 3 of table 1 was found most suitable as was shown in the first part of the computation. Therefore the rationale of adopting a particular operating procedure for this alternative is derived below and discussed in detail by Srivastava (1976).

As far as possible, target outputs are met by unregulated flows in the system and by water that would otherwise spill or be released (basic release) from reservoirs to draw them down to flood-storage levels. Because energy deficits can be made up by purchase from outside the system or by thermal power plants, first preference is given to irrigation. Therefore, water is first drawn from reservoirs 1, 2 and 3 to meet the target outputs for their respective irrigation areas. Water is released from reservoirs 1 and 2 by using the 'space rule' (Hufschmidt & Fiering 1966) for combined releases, so that neither of them becomes empty nor remains full and to make the operating procedure variable, if the target for irrigation area 3 is not met. Water is drawn from reservoir 6 to meet the target output for irrigation area 6. If the target output is not met the space rule is applied to reservoirs 1 and 2. If the target is still not met water is released from reservoir 3. Energy is calculated from all the releases made upto now and if the energy target is not met water is drawn from reservoir 3 and then from 6 by using the 'compensating procedure' (Hufschmidt & Fiering 1966).

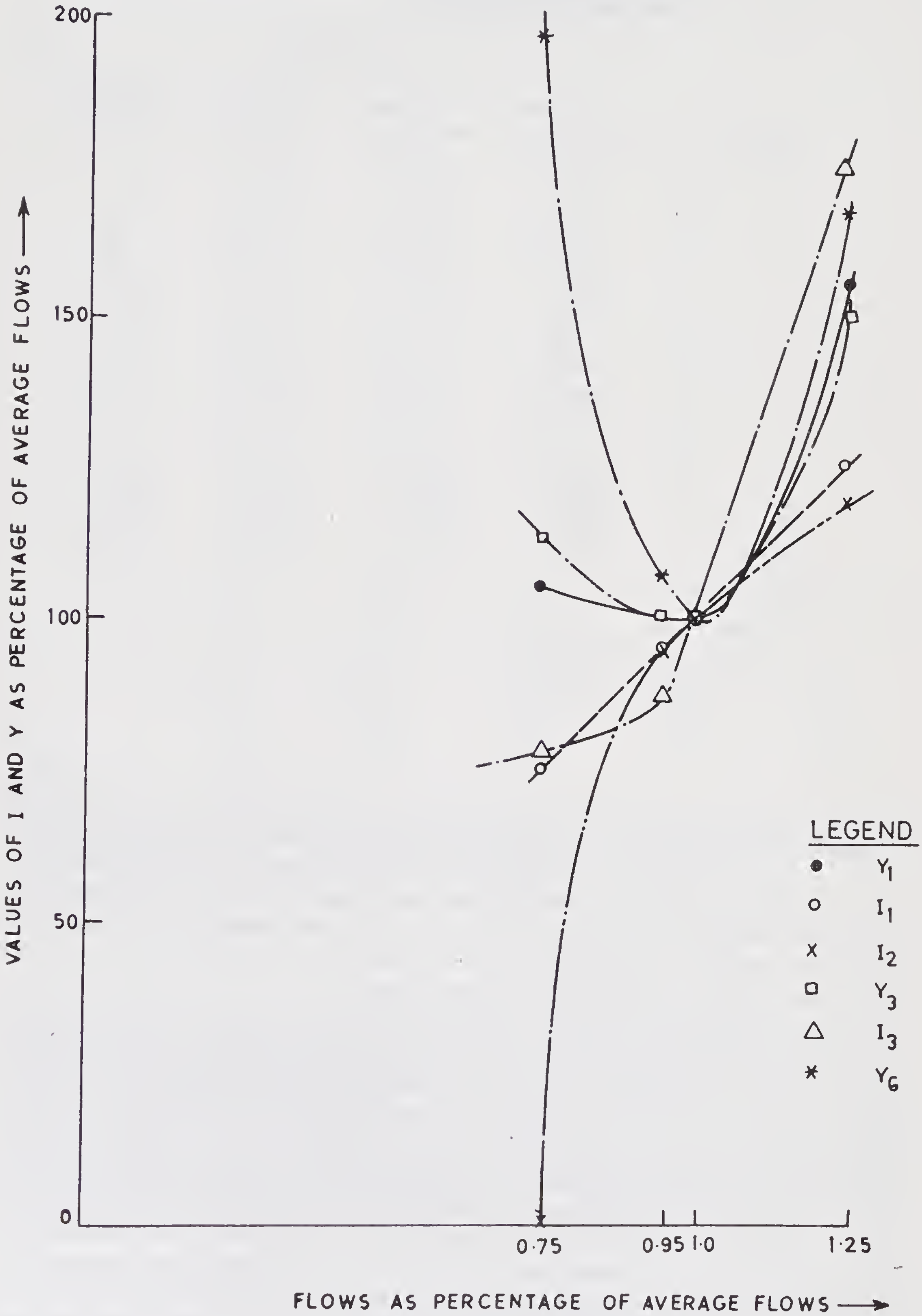

Figure 5. Variation of I and Y values for dry and wet years as percentage of average flows

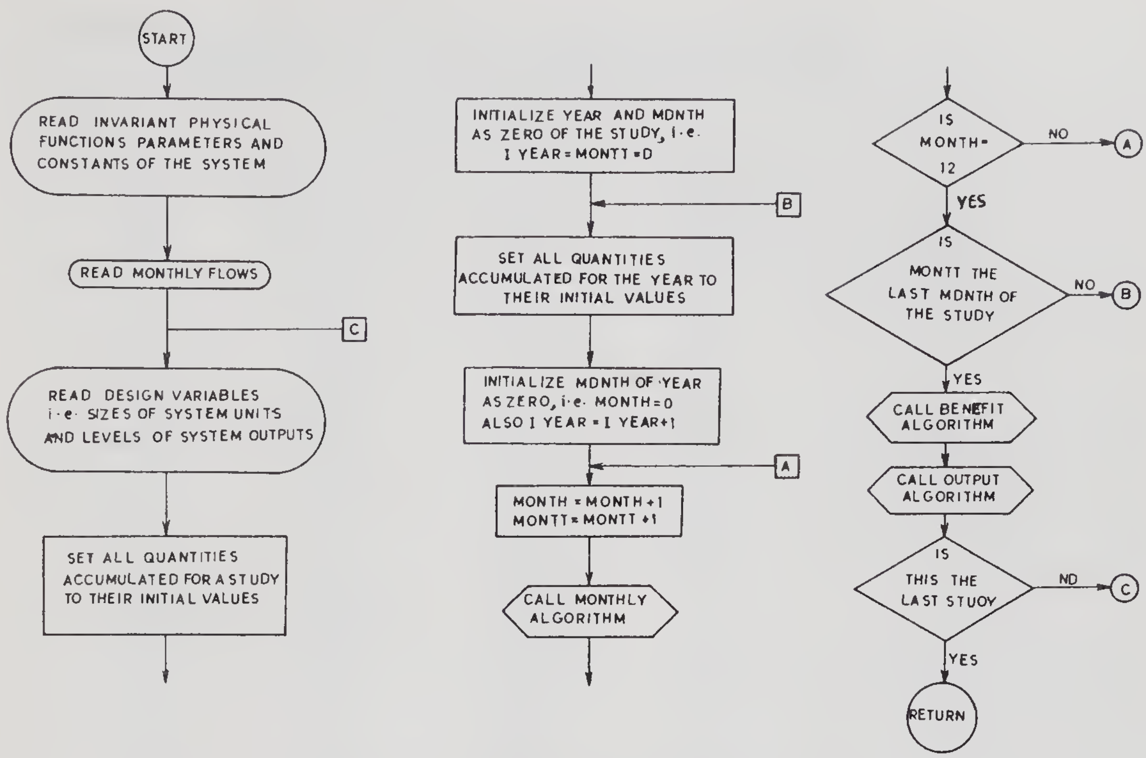

Figure 6. General flow chart of the Narmada simulation program

Table 7. Ranges and values of variables assigned for first random sample

Variables	Ranges of variables	Values of variables assigned for combination 42*
Y_1	4–9	5·746
Y_2	1·874	1·874
Y_3	8–22	19·063
D_3	2–5	3·743
Y_6	2–6	4·471
D_6	0·31–2·0	0·760
I_1	3–9	6·070
I_2	0–4	2·338
I_3	6–20	12·547
I_6	9–10·65	10·635
ΣE_i	2,000,000–5,214,000	3,437,100
H_3	300–1,200	808
H_6	50–800	382
FS_1†	0–2	0·464
FS_3	0–4	2·947
FS_6	0–1·5	1·334

* This combination resulted in highest present value of net benefits of Rs 7,873 crores (*i.e.* $\times 10^7$ among the combinations simulated.

† *FSi* is the flood storage capacity in MAF for reservoir *i*.

Table 8. Values of variables for combinations resulting in maximum present value of net benefits (in Rs crores) for different samples

Variables	Types of samples: Second random sample	Third random sample	Fourth random sample (from LPDC model)	LPDC model solution
Y_1	6·559	6·230	4·730	5·133
Y_2	1·874	1·874	1·874	1·874
Y_3	20·656	17·633	11·072	12·797
D_3	3·401	2·163	2·082	2·000
Y_6	5·150	3·186	1·624	2·380
D_6	1·205	0·353	0·343	0·310
I_1	7·383	6·504	7·181	7·039
I_2	2·003	2·027	2·541	3·164
I_3	13·279	12·105	8·647	10·957
I_6	9·836	10·616	10·605	10·650
ΣE_i	2,383,961	1,999,670	1,999,670	5,214,000
H_3	532	758	607	446
H_6	164	266	214	220
FS_1†	0·702	0·550	1·114	1·000
FS_3	2·445	2·200	1·920	2·000
FS_6	0·766	0·700	0·509	0·750
B†	7,998·0	7,914·0	7,468·0	7,830·0

D = dead storage capacities
† FS_i = flood storage capacity provided in MAF in reservoir i.

Simulation was carried out with the help of random sampling. Computational time for each simulation run was of the order of 40 seconds. In the first random sample ranges were selected for each variable as shown in table 7, based on the results of the LPDD model from table 6. Fifty one combinations of 16 system variables were sampled at random. These were reservoir capacities, dead storage capacities, irrigation requirements, energy requirements, hydropower plant capacities and flood constraints. This was done by assigning values to the variables in combinations through a computer program RANDOM, such that the allocations for flood and dead storages were not more than the gross reservoir capacity at each site individually or combined depending on the types of allocations to be made. The values of variables assigned in a first random sample to combination 42 which resulted in the highest present value of net benefits of Rs 7,873 crores are given in table 7. Three more random samples were tried and their values of variables for combinations resulting in maximum present value of net benefits are given in table 8. Their present values of net benefits were Rs 7,998, Rs 7,914 and Rs 7,468 crores respectively. Similarly, the values of variables obtained by the LPDC model solution were also simulated. The present value of net benefits obtained was Rs 7,830 crores.

5. Analysis of results

An LP screening technique was developed to determine the optimal configuration, capacities and multipurpose releases. It may, however, be noted that since linearization of concave cost functions is involved, there is a possibility of being trapped into local optimals. Looking at the results of the LPDC model in table 5, alternative 3 gave a maximum net annual benefit of Rs 9,200 crores. Results for other alternatives show that the capacities of reservoir Harinphal (no. 4) and Jalsindhi (no. 5) were restricted to their dead storage values in all the alternatives. This necessarily follows from the formulation adopted and to avoid this deficiency mixed integer programing would be required at subsequent more detailed analysis. The same holds for the power plants at these reservoirs. Hence, alternative 3 gives the probable optimal configuration of the physical facilities as well as their probable near optimal values.

If the results obtained in table 5 for alternative 3 and their corresponding values from the conventional design methods as shown in table 9 are compared the results from the LPDC model are reasonable and distinctly improved. The conventional design method is used here as the basis for comparison of the LPDC model results because it is the only one available as the system as such does not exist. This shows that the LPDC model is useful in choosing from the large number of alternative combinations of design, which would result in maximum net benefits.

Table 8 shows that the maximum present value of net benefits obtained in simulation for each case of random sampling and LPDC model simulation were nearly equal. On the other hand all combinations were efficient due to no excess reservoir capacity but inadmissible due to monthly irrigation and energy deficits (not shown in table 8 but for this refer to Srivastava 1976). The number of monthly deficits for irrigation in the LPDC model simulation was more than that obtained in the random sampling simulation, the reason being that the LPDC model specified higher annual output targets for irrigation. For energy the case was very much different: in most combinations the total energy deficits were large. This is because the relationship between the power plant capacity and the output is very complex and the LPDC model

Table 9. Comparison between LPDC and conventional design methods

	Reservoir capacity (MAF)				Annual irrigation requirement (MAF)	
	From report*		From LPDC model**			
Upto No.	Gross capa-city	Live capa-city	Gross capa-city	Live Capa-city	From report†	From LPDC model**
1. Bargi	5·548	5·548	5·133	5·133	6·01	7·037
2. Tawa	1·874	1·874	1·874	1·874		3·164
3. Narmada sagar	12·689	10·023	12·796	10·796	14·97†	10·957
4. Navagam	4·435	2·728	2·379	2·069	11·02	10·650
Total	24·546	20·173	22·182	19·872	32·00	31·808

* Diagram 18·1, and Table 18·1, Vol. Ia (Master Plan for Development, 1972);

** Table 5 for Alternative 3;

† Statement 18·1 Vol. II (Master Plan for Development of water resources of the Narmada in Madhya Pradesh, 1972);

† Between Bargi and Narmadasagar.

specified very low power plant capacities. Hence the values between power plant capacity specified by the LPDC model and that actually needed for simulation could vary. Even with the deviation between these results, it is seen that the LPDC model provided values of variables which were quite close to their corresponding values obtained by simulation.

6. Conclusion

For the systems analysis of a large complex water resources system a screening-simulation model was developed. The Narmada river basin was taken as the system. Two types of LP screening models were used to find a reasonably small set of possible optimal design alternatives. These were LPDC and LPDD models. Simulation was used for further analysis to obtain the near optimum solution in terms of objective function.

The results showed firstly that the LPDC screening model gave realistic results as compared with those determined by the conventional design methods of project-by-project analysis. Second, the results of this model were helpful in simulation. Third, due to the introduction of some design and practical aspects as constraints in the LP model, the results obtained were more realistic and the solution was nearly optimal in terms of objective function. Fourth, this model specified output targets and capacities so as to better regulate mean monthly flows at all sites. Lastly, the LPDD model gave some idea of the excess storage and the reservoir capacity needed for drought and wet years respectively and helped in selecting the ranges of variables for simulation by random sampling for the alternative selected by the LPDC model.

The results of the simulation run from the LPDC model showed good resemblance of the design variables and results of simulation as did the results of simulation runs obtained by random sampling also. Within the limitations of the models, it may be concluded that the solution resulting from the LPDC model may be assumed to be near optimum in terms of objective function and can serve as an input or as an initial base for further screening by simulation.

List of symbols

$a_{i,t}$	water release from reservoir i in time t
$B_{1,i}$, $B_{2,i}$	gross annual hydropower benefits and irrigation respectively at site i
$b_{2,i,s(i)}$	slope of linear segment $s(i)$ of the benefit function $\beta_{2,i}$ for irrigation i
$C_{1,i}$, $C_{2,i}$, $C_{3,i}$	annual capital cost of hydropower plant, irrigation and reservoir capacity respectively at site i
$C'_{1,i}$, $C'_{2,i}$, $C'_{3,i}$	capital cost function for hydropower plant capacity, irrigation work and reservoir storage capacity respectively at site i
D_i	dead storage capacity of reservoir i
E_i	yearly firm power target at site i
$E_{i,s(i)}$, $H_{i,s(i)}$, $I_{i,s(i)}$, $Y_{i,s(i)}$	a linearised target portion of power, hydropower capacity, irrigation and reservoir capacity respectively
e	turbine and generator efficiency
$F_{i,t}$	total inflow to the reservoir i in time t
$f_{i,t}$	natural flow at site i from its catchment area in time t

$\mathrm{He}_{i,t}$	average storage head at site i for period t
h_t	number of hours in the particular period t
H_t	hydropower capacity at site i
I_i	yearly target amount of water to be provided for irrigation for the ith irrigation area
i	site, irrigation
$K_{i,t}$	proportion of irrigation demand I_i to be diverted for irrigation in time t from site i
$K'_{j,t}$	proportion of irrigation demand I_j as irrigation return flow from the jth irrigation area in time t
$l_{1,i,s(i)}$, $l_{2,i,s(i)}$, $l_{3,i,s(i)}$	slope of linear segment $s(i)$ of the capital cost function for hydropower plant, irrigation work and reservoir storage capcity respectively
$m_{1,i,s(i)}$, $m_{2,i,s(i)}$, $m_{3,i,s(i)}$	slope of linear segment of the OMR cost function for hydropower plant, irrigation work and reservoir storage capacity respectively
$O_{1,i}$, $O_{2,i}$, $O_{3,i}$	annual OMR cost of hydropower plant, irrigation work and reservoir capacity respectively, at site i
$O'_{1,i}$, $O'_{2,i}$, $O'_{3,i}$	OMR cost function at site i for hydropower plant, irrigation work and reservoir storage capacity resepctively
$S_{i,t}$	content of the reservoir i at the beginning of period t
$s(i)$	number of portions into which target i is divided for linearization of benefit and cost functions
t	time
Y_i	capacity of the ith reservoir
Z_i	set of reservoir sites upstream of site i from where water can reach the site i (or the sites that contribute to the inflow at the site i)
$\alpha_{i,t}$	load factor at each hydropower site i and for each period t is an indicator of the energy demand
$\beta_{1,i,t}$	benefit per unit of firm energy for site i in time t
$\beta_{2,i}$	the long run benefit function for irrigation at site i
δ_t	proportion of annual firm hydropower target E_i for period t

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Overview and reflections

M C CHATURVEDI† and PETER ROGERS*

†Applied Mechanics Department, Indian Institute of Technology, Hauz Khas, New Delhi 110016

*Department of Environmental Engineering, Harvard University, Pierce Hall, 121, Cambridge Mass. 02138 USA

1. Introduction

Modern technology is becoming increasingly large scale and powerfully pervasive. Although, in the last analysis, technology is mediated through specific projects, often these projects are part of a large-scale complex system. For instance, a number of power projects of varying types and capacities are interconnected through power grids to act as one system. Several dams and barrages on a river are interconnected through continuity of the hydrological flow. To give another example, the surface water development is interlinked with groundwater development as both serve the purpose of meeting the water demand and one has to think of conjunctive surface and ground water development. Further, since surface waters generate energy and provide irrigation, while development of groundwater sources consumes energy, conjunctive surface-groundwater-energy systems planning becomes attractive.

New technical advances are being introduced at an increasingly rapid rate leading to what has been said to be a discontinuous world. In view of the scale, pervasiveness and uncertainty of modern technology, it becomes increasingly important that its development is undertaken creatively and in a scientific manner. Secondly, in view of the relationship between technology in space and time it is necessary that a comprehensive though dynamic view of the technology be attempted. It is also equally necessary that the impacts of technology are creatively assessed and the technological choices are scientifically evaluated.

Of late, a new scientific discipline known as systems analysis has evolved through developments in the separate disciplines of engineering, economics and mathematics. Rapid developments have taken place in this science and the availability of high-speed, efficient and economical computers has contributed to its development. As the science of systems analysis has advanced over the last two decades and as the scale of modern water resources projects has grown, systems planning of water resources has been made mandatory by law in many developed countries. International agencies also emphasize systems planning. For instance, at the United Nations Water Conference held in Argentina in 1977, the need for water resources planning was promulgated as follows (UN document E/Conf. 70/29, 1977).

"Systems analysis and modelling techniques should be applied to improve efficiency and efficacy in storage operation and distribution systems. Studies should explore the possibility of effecting interbasin transfer of water and special attention should be paid to environmental impact studies . . . Water management plans may be prepared by using systems analysis techniques and developed on the basis of already adopted indicators and criteria taking into account the economic and social evolution of the basin . . . Master plans should be formulated for countries and river basins to provide a long term perspective for planning, using such techniques as systems analysis and mathematical modelling as planning tools wherever appropriate . . . ".

Systems planning of water resources is particularly important in India for a number of reasons. First the scale of development is monumental. According to the proposed targets for the Sixth Five Year Plan, irrigation at the highest level in the world, and almost five times the present level in USA, would be achieved. Second, the magnitude of the contemplated work is also very great. For instance, development of the Ganga-Yamuna basin envisages construction of five very high dams and 22 hydroelectric run-of-river schemes which have to be planned integrally. As another example, under the National Water Plan, interbasin interlinkage of several river basins is being planned. Third, while the water resources development is extremely important and critical, there are competing demands from other sectors. With water resources development accounting for almost 20% of the National Plan allocations it is necessary that the development is carried out in an efficient manner.

In contrast to the need for efficient development, the present achievements, as noted in the Sixth Five Year Plan, are not efficient. We do not mean to negate the scale of technological development or their rate of development. Irrigation works of India have been, and continue to be, some of the wonders of the world, but their technological functioning is not one of the best. If the present state continues there will be a serious problem of resource depletion and environmental degradation, both in surface water and groundwater (Chaturvedi 1976). It is, therefore, necessary that an appropriate policy and systems plan be followed. This will require integrated planning from the micro-level to the macro-national level.

Importance of systems planning has been recognized by decision makers in India. One of the present authors (MCC) was invited for the systems planning of the Ganga basin as far back as 1968 by the Indian government and a preliminary study was carried out. From the Fourth Plan onwards, the need for systems planning has been emphasized in the National Plan. The author was also invited by the Planning Commission to carry out the systems planning of Punjab. The Expert Committee of the National Committee of the International Hydrological Programme on Research and Education strongly recommended scientific development of water resources through systems analysis. But the development in real life continues to be fairly *ad hoc*.

The reasons for the present approach are understandable. Not many professionals are yet aware of the potential and scope of these modern approaches. The institutional constraints are such that specialisation in different activities of engineering *viz* research, planning, design, construction and management, of course with due interlinkage, is not developed. While in the last analysis institutional modernisation is the most important requirement for modernization of water resources development, it is necessary to develop widespread indigenous capability of systems planning amongst the professionals and academicians and demonstrate the applicability of systems analysis techniques to Indian conditions. It was in this context that the present project was undertaken and it is hoped that some contribution has been made to this end.

2. Systems analysis

Systems analysis is often taken to mean mathematical modelling and it is necessary that this misunderstanding is removed. Systems analysis is a body of concepts, approaches and techniques. We shall try to give a brief introduction to systems analysis and for details reference may be made to Klir (1969), Sage (1977), Hall & Dracup (1970), Meta Systems Inc. (1975), Biswas (1976) and Chaturvedi (1984).

Although technology has been practised since the early history of man, a new understanding of technology is gradually developing. Technology is not merely a set of constructed facilities, tools or processes, but it is a totality of activities transforming the environment. This transformation involves resources, energy or/and information according to certain technological laws. While technological activities in the context of art and science of different disciplines have to be carried out, in the last analysis technology basically results in a change of environmental state and processes. With this change there is a concomittant change in the scope of life activities. Confining this to the human system, our perceptions, values and opportunities may change. For instance, with the availability of transportation and communication systems, the concept of space and time changes. Similarly, with the availability of modern energy systems, the scope of human power and opportunities of action dramatically change. With the availability of modern production capability a new world of action is unfolded.

Modern technology is interconnected. Various elements or projects operate in the context of certain technological objectives. Even when they are differentiated in space and time they are integrated in terms of these overall objectives. These systems are organic-dynamic as they evolve over and decay with time.

Technology interacts with society in a circular manner. On the one hand technology is brought about by the capabilities of society. Technology, by providing a new environment, shapes the perceptions, opportunities and values of society. In the final analysis, technology acts as an agent of social change. There is thus another commonality of objectives, the socio-economic objectives interlinked with technological-environmental objectives.

It becomes necessary that the development and evaluation of technology be undertaken integrally as one set of activities. Technology has to be created through a sensitive understanding of technological sciences and arts and evaluated critically so that hopefully we move into a better future. There is a paradox here. With the increasing scale and the discontinuity in the development of technology, there is going to be an increasing uncertainty about opportunities and impacts. It is thus all the more necessary that we try to instill as much certainty as possible in the choice of technology and its concomittant effects. This paradox is not a contradiction, but is a continuation of the paradox of life.

The perceptions vary from individual to individual, from group to group, and furthermore are not constant over time. It thus becomes necessary that technology is evaluated through a participatory open mechanism. A new body of approaches and techniques for evaluation has also developed as will be discussed later.

Technology involves development of hardware and software, but in addition it involves development of institutional systems and motivational mechanisms. It is this set of three issues which defines the technological system and not mere hardware as was often the view of the past.

To sum up, technological projects are part of an organic-dynamic system brought into being for transforming environment in terms of certain techno-environmental and socio-economic objectives. The system consists, besides the software and hardware, of appropriate institutional and motivational mechanisms.

Systems analysis emphasises an approach so that technology is developed scientifically and creatively. A five-step systems approach has been developed. First, we try to identify the various issues. In that context we next try to be precise by specifying the objective and developing a set of measures to evaluate the objectives. In the third step, in the context of these objectives, various technological options are developed which in the totality of a system define the technological system. The system consists of a portfolio of projects which will have to be taken over time and space and the evolution has to be not in terms of the project, but in the totality of the system. In the fourth step we try to evaluate the various alternative technological options, and finally in the fifth step we select one of the systems in terms of quantified and non-quantified objectives.

There is a morphology in systems planning. Starting with an idea one tends to become more and more specific in a set of hierarchical evolutionary stages. In the first instance, we have the feasibility study where the techno-economic feasibility is identified so that a decision could be taken on the investment of further resources of time and of man, if deemed appropriate. In the second phase we have detailed planning leading to detailed design. These three stages of planning and design lead to the fourth stage of construction following which, we have the management of the constructed facilities. The environment in which the technological system functions, the functioning of the technological system along with man who is involved in the physical system, and the demands placed on the technological system are probabilistic or uncertain. Hence the need for scientific management. Technological systems planning embraces all these stages including the management.

The evaluation relates to several aspects of the impact of the technological system. One is thus the issue of economic evaluation basically deciding the allocation of scarce resources. Over a period of time attempts have been made to make the evaluation more and more comprehensive leading to the social-benefit cost analysis (UNIDO 1972, 1978). Attempts have been made to develop an evaluation approach from the point of view of economic efficiency and equity. Attempts have also been made to take into account the nonlinearities of demands and supply functions, the externalities, the multiple objectives, the inter- and intra-temporal impacts, and the uncertainties.

Besides the socio-economic evaluation we have the environmental impact analysis which tries essentially to take a long term view of the situation in the context of the complex facets of environment and ecology. In view of the large scale and pervasiveness of technology with possible significant changes in environment which may be irreversible and the possibility of resource depletion, it becomes necessary to take this comprehensive view. The third evaluation which has not yet been fully systematised is that of trying to assess and visualise the social impact of technology in terms of values. This is a difficult subject and is still in an initial stage of development.

The central point is that technology has to be developed creatively and scientifically, accessing all technological possibilities and socio-economic-environmental impacts. The development and evaluation are integral activities and have to follow systematically so that, like science, they are reproducible activities.

In view of the complexity of developing technology, a large number of complex alternatives have to be developed and evaluated. This is considerably facilitated by computer-oriented mathematical models and simulation. The value of these models and techniques lies in the following: (i) they allow, so to say, 'thought experiments' to be effected with generation of alternatives and evaluation of their performance under different configurations and policies; (ii) they allow decisions on the sensitivity to varying input assumptions and system parameters; (iii) they provide a monitoring device that helps to ensure internal consistency among projects and plans and (iv) they depict qualitative relations among the various factors affecting the supply and demand. It is important to caution that the models do not usually provide the qualitative assessment, but illustrate them schematically (CONES 1981).

The techniques have become possible only due to the availability of modern high-speed computers. Systems analysis does not by any chance negate modern engineering analysis. In fact, these form the input to the systems studies which try to develop alternative options or study the sensitivity.

There is always the danger in the use of models that the numerical results will be taken literally. It must be emphasized that real life issues are extremely complex and not always quantifiable and commensurate. Many simplifications and uncertain assumptions must be made to construct models and a great deal must be simplified and left out of consideration. Judgement alone decides whether some factors are important or whether effects can be separately included, atleast in the first approximation. Models do not negate judgement but complement creativity and judgement by enabling painting over a wide canvas and carrying out the analysis over a wide range. Judgement is also a pre-requisite for modelling, otherwise models can become caricatures of reality.

A variety of techniques are used for modelling such as linear programing, dynamic programing, non-linear programing, queueing theory, graph-theoretic approach, calculus of variations, etc. Each one may be suitable in certain situations. Much work has gone into this area to apply these to different systems and the practitioner has to learn through much detailed study in this area.

One of the reasons why the systems approach has not been adequately applied in real life studies is that examples of applications are generally not available to administration. In this context Rogers (1979) analysed some studies and 22 cases were summarised. The list was not exhaustive and was only meant to provide examples of work that has been used or is in the process of being used and is easily accessible in literature. Some of the studies reported in the book have not been included in the above cases. These cases, given in the appendix, have been summarized under ten separate headings.

(i) Origin and purpose: This is to give some idea of the history of the problem and the purposes of the study.
(ii) Sponsors: Attempts to identify agencies which have sponsored the studies and who may be contacted for further information by persons interested in a particular study.
(iii) Organization of study: How the study was organized. Who did what and where, are important aspects of any systems study.
(iv) Technical team: The details of the technical manpower, leadership and the amount of time from each discipline are given wherever possible.
(v) Structure of analysis: How the original problem was rearranged and structured for analysis.
(vi) Mathematical models: Details of the mathematical models used are given where appropriate.
(vii) Boundaries of study: The real and conceptual scope of the study is given.

(viii) Evaluation and critique: An evaluation is attempted based on available documentation. Whether the application was used or not for an actual decision is emphasized.
(ix) Study results: Based upon the documentation itself, the pertinent results are outlined.
(x) Documentation: Only readily available documentation is listed.

In tables 1 and 2 all these cases have been summarised to show the issues they were concerned with and the systems analysis techniques that were employed. In these tables the studies are ordered by the date of major publication. The reader should be aware that, based upon the reports alone, it is quite difficult to fill in these tables. A fair amount of judgement has to be exercised. This tends to favour the studies that we are familiar with over those we only know from literature.

The most important observation about table 1 is that despite the fact that we have carefully chosen from literature those studies purporting to be the actual case studies performed in, or on, developing countries we feel confident in stating that only 7 out of the 22 studies (or about 1/3) have ever been used in making decisions on water planning and management by the sponsoring agencies. Is this a poor batting average?

Table 2, which shows which of the cases use the major systems analysis techniques is, very instructive. Fifteen of the studies (about 2/3) used linear programing techniques, none used queueing theory, inventory theory and statistical decision theory and only one used any kind of stochastic model and one used the game theory. There must be some implications here for how one would organize a training programme for professionals interested in applying systems analysis to water planning and management in developing countries.

In concluding this section it should be re-emphasized that the listed case studies are not the only applications made or known to the authors of this report. Numerous other studies are known to have been completed but their documentation is either not available or incomplete. We have chosen to present only those cases which have readily available documentation.

3. Overview

An attempt has been made through the studies in this volume to illuminate the systems approach of water resources development. First, the environment and resource availability of water in India and the background of development in a historical context have been given (Chaturvedi 1985a). Formulation of issues for future development, currently proposed policies, a scientific approach to development of the river basin at a national level, and systems approaches for further policy studies have been tried.

Following these general formulations, an issue for a large river basin has been identified and modelled. The particular river basin selected is the Ganga-Brahmaputra basin which is one of the largest basins of the world in hydrological terms. To start with, therefore, a general description of the system follows (Chaturvedi 1985b). Next the approach to planning has been formulated and as a first step a coordinating-screening model is developed to assist in identifying the possible developmental scenarios, taking into account the hydrologic-environmental-economic-interlinkages (Chaturvedi *et al* 1985). The methodology for trade-offs amongst multi objectives is demonstrated by considering trade offs between different seasons of irrigation and between irrigatton

Table 1 Some characteristics of reported case studies

Country	Reported utilization	Interdisciplinary team	Geographical area				Type of study				
			Project	Region	Country	River basin	Policy	Parameter estimation	Operation	Investment planning	Other
Pakistan	×	×	×	×	×	×	×		×	×	
Egypt		×			×	×	×		×		
Pakistan	×	×	×	×	×	×	×		×	×	
India/Bangladesh		×			×	×	×				
Bangladesh		×	×	×	×		×	×	×	×	×
Peru			×							×	
Mexico	×	×		×	×		×		×	×	×
Brazil			×							×	
Burma		×		×		×				×	
Thailand			×						×	×	
Iran							×	×	×		
Mexico			×	×					×	×	
Sahel region		×		×			×				
India	×		×						×		
Malawi			×						×		
India				×					×		
Algeria	×			×			×		×	×	
Argentina	×					×		×			
Israel				×	×		×		×		
Panama			×				×		×		
Algeria	×								×	×	
Chile				×	×		×		×		

Table 2. The use of systems analysis techniques in the reported case studies

	Case study number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Analytic optimization models	Linear programing	×	×	×	×	×		×	×	×		×	×		×		×	×		×			×
	Non-linear programing	×				×		×															
	Integer programing					×		×		×													
	Dynamic programing												×			×							
	Goal programing		×			×									×			×			×		
	Stochastic programing					×																	
	Control theory														×								
	Lagrangean analysis																		×				
	Geometric programing																					×	
Probabilistic Models	Queueing theory																						
	Inventory theory																						
	Statistical decision theory																						
	Multivariate analysis					×																	
Statistical techniques	Regression analysis					×		×			×					×							
	Factor analysis																						
	Principal component analysis					×																	
Simulation	Simulation	×		×		×	×					×									×		
	Systems dynamics														×								
	Search techniques	×																					
Other techniques	Game theory				×																		
	Input/output analysis		×																				
	Benefit-cost analysis	×		×		×	×	×	×	×	×	×									×	×	

and power. This coordinating-screening model is extended to more detailed analysis by dividing the system in terms of hydrological sub-basins (Rogers & Kung 1985) or administrative-political units of development (Karady & Rogers 1985). A marginal incremental model has accordingly been formulated. Thus these three studies contribute to an approach for assisting in planning the development of large scale complex river basins.

We have emphasized that the systems approach, first and foremost, is an aid to creative engineering in a scientific manner. In this context we have tried to emphasize the importance of developing all possible technological options. An attempt has been made to develop an unconventional technique of mitigating floods on the one hand and enhancing the water resources on the other through induced groundwater recharge (Revelle & Lakshminarayana 1985). It is shown that flood flows can be stored by heavy pumping along the perennial rivers for irrigation during the prior low river flow season.

The concept proposed by Revelle was only one of the possible techniques. Other technologies are also possible, such as pumping along non-perennial rivers, and kharif irrigation. Furthermore, these technologies require regional groundwater-aquifer interaction modelling and estimation of optimal groundwater pumping configuration. Therefore, in the following study more refined analysis and in this context three additional alternatives over the basic theme have been proposed and modelled for analysis through a sophisticated regional groundwater simulation-optimization programing model (Chaturvedi & Srivastava 1985b). This is an important component of the possible technological options in the Ganga Basin. In terms of systems approach principles it demonstrates the opportunity for creative engineering even in conventional areas.

In large scale systems, differences are always likely to arise amongst different uses and users in different parts of the river basin. These could be at the national level or at the international level and an approach to aid in the resolution of these differences through scientific analysis designed to identify optimal systems development in the context of identified mutual interests through bargaining processes has been developed through Game theoretic analysis. This is the pioneering study in the Ganga Basin carried out way back in 1967 by Rogers.

In the development of water resources, generally, emphasis is laid either on the upland water resources for diverse demands or the water quality modelling at the waters edge in terms of the estuary. The fact that a river represents the continuity of the land-water system is very often neglected. For instance, as more and more upland development takes place the flows available at the waters edge are likely to be modified and it would be necessary to take an integrated picture of the upland and the deltaic region estuarine development. In this context a study at the waters edge has been carried out by Rogers. This issue is equally applicable to other river basins of the country.

As we have tried to identify at the outset, systems planning studies require a considerable set of integrated studies. For instance, a detailed analysis of the water demand, particularly of the agricultural demand has to be carried out. While this has not been done for the Ganga Basin, the studies have been carried out for a number of other river basins of the country, such as, Rajasthan Canal (Verma 1985) and the Rangola Irrigation Scheme (Basu *et al* unpublished). In estimating the water demand and the application principal for irrigation, diverse factors such as economic efficiency, economic equity and/or assurance of food requirement for nutritional considerations in a dynamic context of developing agriculture technology are required. Some of these issues have been analysed in the two studies mentioned above.

A variety of problems arise which have a lot of commonality as well as specificity. The commonality is in terms of the integrality of these large scale projects. The specificity stems from the unique configuration of the systems and the specific supply and demand specifications. To illuminate these points several river basins have been studied. These include the two studies for the Indus basin as well as a large component of the Indus basin and the Bhakra dam (Rao & Ramaseshan 1985a, b), studies of the Cauvery basin (Vedula 1985), Damodar river basin (Sinha & Rao 1985) and Subernarekha river system (Sinha *et al* 1985).

A variety of techniques can be used for systems modelling. In the last analysis perhaps simulation will be most convincing and convenient, particularly the stochastic aspects of the development; however, simulating the entire system in the diverse conditions would be extremely time-consuming. A reasonable approach is that a programing model may first be used to find out the range over which simulation studies should be carried out particularly taking into account the stochastic nature of inputs and outputs. This methodologic approach has been tried and applied successfully to the Narmada system (Chaturvedi & Srivastava 1985a).

4. Reflections

Although the present studies do not represent a complete and detailed picture of one particular river basin, the studies taken together, to a large extent cover the diverse problems likely to be encountered in large scale systems planning and we consider that the set of studies would contribute to the art and science of systems planning. We are aware of the shortcomings of the studies reported, which are inherent in the manner in which they were carried out with the essential purpose of developing appreciation and capability in systems analysis amongst some scientists in this field. It is hoped that an integrated study of a real life situation will be carried out at the earliest to contribute to the science and art of the subject and for developing appropriately trained engineers for planning. Water resources development in India is crucial to the development of the country, as emphasized in the 20-point programme of the late Prime Minister as well as in the Planning Documents. A large number of persons are required to carry out this task as sensitive professionals and scientists trained in the best use of the tools of analysis. It is hoped that the present study would contribute to the tremendous challenge posed to the professionals in the country and abroad.

It is unfortunate that much time has been lost. A historic incident may be nostalgically mentioned at the end. Following Rogers study entitled, "A game theory approach to the international aspects of the Ganga Basin", the Indian author was asked by the government in 1968 to carry out the study independently as stated earlier. Following this he was convinced that systems studies of the river basins were required for their efficient development and it was decided that systems studies of the Ganga basin be carried out by the Indian author. A three-month summer school, sponsored by the Ministry of Irrigation was held at the Indian Institute of Technology, Delhi in 1972 to train about 30 officers also in this context. But the activities did not continue and more than a decade has already been lost.

We believe that the development of trained manpower is the most important pre-requisite for water resources development and the present volume is dedicated towards this end.

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Appendix

Case 1 Waterlogging and salinity in the Indus Plain

Origin and purpose	To suggest methods to solve waterlogging and salinity in the groundwater of the Indus Plain in West Pakistan. Pakistan President requested help from President Kennedy.
Sponsor	White House and Government of Pakistan
Organization of study	Highlevel panel for one year period. Most of analysis performed at various locations in the US. Report written by Professor Revelle and Harvard University group who performed the systems analysis.
Technical team	Panel drawn from Government and universities consisting of scientists, engineers, agronomists and economists.
Structure of analysis	To make a detailed investigation of possible approaches to the waterlogging and salinity problems. Problem broken down into several pieces, solution undertaken by different groups and then integrated at the end by a core group of the panel.

Mathematical models	Linear and quadratic programing, simulation models for groundwater movement and mixing.
Boundaries of study area	The basin of the Indus river and its major tributaries in Pakistan (then West Pakistan).
Study results	Showed that the waterlogging and salinity could be most effectively controlled through vertical drainage using tubewells. In addition, it demonstrated how this drainage water could be used to further develop irrigation.
Evaluation and critique	A benchmark study using systems analysis in water management. Many new models were developed. Even though some of the detailed findings and recommendations were later not upheld, the report has been the fundamental policy document of the development of irrigation in Pakistan.
Documentation	White House—Department of Interior Panel on Waterlogging and Salinity in West Pakistan, *Report on Land and Water Development in the Indus Plain*, White House, Washington, D.C., Jan. 1964. Dorfman R, Revelle R, Thomas H A Jr 1965. *Pakistan Dev. Rev.*, 5: 331–372 Fiering M B 1965 *Water Resources Res.* 1: 41–61.

Case 2 Use of Aswan High Dam in Egypt for hydropower and irrigation

Origin and purpose	Studies of operation of the new Aswan High dam. Particular emphasis on the resolution of conflicts between energy and irrigation uses.
Sponsor	Ministry of the Aswan High dam, Egypt and Ford Foundation, Cairo.
Organization of study	Performed by Center for Population Studies, Harvard University. Small team; most of work performed in the US. Period 1 year.
Technical team	2 engineers, 1 economist, 1 regional planner and 1 population scientist on a part-time basis.
Structure of analysis	To establish the ultimate resource potential of the Nile in Egypt.
Mathematical models	Goal programing (linear programing) use of I/0 models
Boundaries of study	Nile river basin within Egypt
Study results	Established the degree of complementarity between conflicting uses for power and irrigation. Identified possible developments of downstream underground storage to achieve 100% complementarity of water use.
Evaluation and critique	An early application of goal programing to water management. Raised interesting research questions about alternative investments. Was not continued because of lack of follow up by the government departments.
Documentation	Thomas H A Jr, Revelle R 1966 *Manage. Sci.* 12B: 296–311

Case 3 Water and power resources of West Pakistan

Origin and purpose	Part of the Indus Water Treaty. A sector plan for water and power for Pakistan was needed to evaluate the further development of the system, particularly, the decision to build Tarbela dam.
Sponsor	Government of Pakistan, World Bank.
Organization of study	Bank provided an interdisciplinary group to coordinate a series of specialist studies which were then integrated into a coherent study by the Bank.
Technical team	Cordinating group mainly administrators, and development economists, consultants from many other disciplines.
Structure of analysis	A macroeconomic model was made to coordinate separate studies of the power

	and agricultural sectors. Agricultural sector chooses water technology as well as cropping pattern *via* a linear programing model. The power model simulates the detailed functioning of the electrical energy system.
Mathematical models	Linear programing models of the agricultural sector and simulation models for the hydrology and the power sector.
Boundaries of study	Province of West Pakistan
Study results	Confirmed the strategy of groundwater exploitation and the timing of the construction of Tarbela dam
Evaluation and critique	A large and complex study. Extremely well carried out. This is probably *the* landmark study of the 1960's. In addition to the Bank and the consultants work, the officials of the Government of Pakistan were deeply involved in the interpretation of the results. The cost of the overall study which is not reported in the literature must have been substantial (in millions of US dollars).
Documentation	Lieftinck P R, Sadove A R, Creyke T C 1969 *Water and power resources of West Pakistan: A study in sector planning*, 3 vols., (Baltimore: Johns Hopkins).

Case 4 Resource potential of the lower Ganga-Brahmaputra basin

Origin and purpose	Study to find the resource development potential in the Lower Ganga-Brahmaputra Basin and the costs and benefits of international cooperation between the riparian states.
Sponsors	Ford Foundation and Harvard University with the collaboration of the Governments of India and Pakistan.
Organization of study	Performed as a desk study by a small team at the Center for Population Studies, Harvard University.
Technical team	One engineer and one economist part time for one year.
Structure of analysis	To search for the ultimate development potential of the Lower Basin of the Ganga-Brahmaputra rivers for irrigation, flood protection, hydropower, navigation and water supply. To examine the costs and benefits of international cooperation on the ultimate development.
Mathematical models	Game theory, Linear Programing (720 variables and 450 constraints)
Boundaries of study area	Basins of the Ganga and Brahmaputra rivers including Bangladesh and Nepal but not China or the Indian states further upstream than Bihar.
Study results	The study showed that the problem was a classical "prisoners-dilemma" game problem. The benefits for cooperation were large (about 25% of total) but not overwhelming.
Evaluation and critique	Innovative approach to this class of problem. The data used were, however, very unreliable and the study was never acceptable to the Government of India for further elaboration although the Government of Pakistan supported (with UNDP support) elaboration of the East Bengal part of the study area.
Documentation	Rogers P 1969 *Water Resources Res.* 5: 749–760.

Case 5 Land water and power studies for Bangladesh

Origin and purpose	Part of a proposed larger study of the entire Ganga and Brahmaputra basins. This study attempted to look at the integrated development of land, water and power in East Bengal from 1969 to the year 2000.
Sponsors	Government of Pakistan (later Government of Bangladesh), UN Development Program with the International Bank for Reconstruction and Development as their executing agents.

Organization of study	Model work was carried out at the Harvard University Center for Population Studies. Extensive collection of secondary data in the field.
Technical team	Small team of 2–3 engineers, 2 economists, 1 geographer and 1 population scientist.
Structure of analysis	The emphasis was on the human ecology of the region. The analysis started with an elaborate population prediction model which responded to the rates of economic development.
Mathematical models	A variety of mathematical programing and simulation models were made. The major model was a two level mixed integerquadratic programing model of the entire agricultural sector. These models had 100 integer and 1300 continuous variables and 1000 constraints.
Boundaries of study	Entire region of Bangladesh excluding the Chittagong hill tracts.
Study results	The studies indicated a water resources development strategy relying on small pumps and tubewells in the next decade. While indicating self sufficiency in food as a possibility for Bangladesh the models indicated severe energy/fertilizer shortages in the near future.
Evaluation and critique	An ambitious study integrating population, land, water and energy. There were too many models made with consequent integration problems. The hydrological constraints were explored in great detail. Due to the change of governments the transfer of the model studies application by the various government agencies in Bangladesh has not yet (1979) taken place 7 years after the study was completed.
Documentation	Rogers P *et al* 1972 *Bangladesh land water and power studies* Draft Report, Harvard University Center for Population Studies; Rogers P, Smith D V 1970 *Am. J. Agric. Econ.* 52: 13–24; Rogers P 1974 *ITCC Rev.* 111: 110–119.

Case 6 Project selections and macroeconomic objectives: A methodology applied to Peruvian irrigation projects

Origin and purpose	An attempt to bridge the gap between macroeconomic objectives and detailed project investment criteria. The methodology was tested on 11 public irrigation projects in Peru.
Sponsors	Not mentioned.
Organization of study	Details not given. Eleven projects were selected on the basis of completed feasibility reports, covering a range of project sizes, and geographical zones.
Technical teams	Details not given.
Structure of analysis	Four classes of investment criteria were investigated in addition to a fifth method putting together the income balance of payments, and the employment objectives.
Mathematical models	No formal models used. Simple national preference function was hypothesized and the project selection rankings simulated under a variety of weights on the objectives.
Boundaries of study	All irrigation projects within the national boundary.
Study results	The study showed that the ranking of the projects was very insensitive to quite large variations in the weights on goals.
Evaluation and critique	The study is a good example of the combined use of various economic and social criteria for choosing irrigation projects. There were no constraints on resource use nor were there any interactions either economic or hydrological allowed between the projects. Hence, a large part of the "systems approach" could not be applied.
Documentation	McGaughey E, Thorbeke E 1972 *Am. J. Agric. Econ.* 54: 32–40.

Case 7 Programing models of Mexican agriculture

Origin and purpose	These studies were part of an integrated multi-level national planning model for Mexico. The irrigation models were just one part of the overall study.
Sponsors	International Bank for Reconstruction and Development (IBRD) (Development Research Center).
Organization of study	Mainly carried out in Washington, DC by a group of agricultural and development economists with collaboration on data from various Mexican government agencies.
Technical team	Exact details not given, mainly economists.
Structure of analysis	A very elaborate multi-level structure was given to the study. Each of the sectors (agriculture and power) had to choose its best investment schedule subject to resource availabilities predicted by a multi sector input/output model.
Mathematical model	Variety of simulation, integer programing and linear and quadratic programing models. Main model was solved as a linear program (with 2,345 variables and 1,500 constraints).
Boundaries of study area	All the agricultural regions of Mexico.
Study results	Elaborate projections detailing expected regional demand for water, crop production, and the market equilibrium prices for the products were made. These were also shown to be consistent with expected macroeconomic growth in the other major economic sectors.
Evaluation and critique	The study received the Lanchester Prize of the Operations Research Society of America for the best OR publication of 1976. The study is very innovative in the handling of some of the economic features such as endogenous prices and in the models to check sectoral consistency. The multi-level models only worked in an *ad hoc* way and the resource constraints particularly the water constraints, are handled casually. The authors claim that the models are in use by the Ministry of the Presidency in Mexico. There is, however, some dispute whether the water agencies are indeed using the models to guide investments.
Documentation	Goreux L, Manne A S 1973 *Multi-level planning: Case studies in Mexico* (Amsterdam: North Holland); Bassaco L M, Norton R D, Silas J S 1974 *Water Resources Res.* 10: 1071–1079.

Case 8 Cost-benefit analysis of irrigation projects in Northeastern Brazil

Origin and study	The study examined irrigation projects in Northeastern Brazil which had been found acceptable by the Ministry of Interior and re-evaluated them using an empirically estimated shadow price on labour.
Sponsor	Brazilian Planning Ministry.
Organization of study	Carried out by Cline as Visiting Professor in the Planning Ministry with the help of Tahal for data and engineering advice.
Technical team	Development economist aided by engineering consultant.
Structure of analysis	Reviewed 24 major projects out of a possible 56 available. Recomputed benefit cost ratios with shadow prices on labour and optimal cropping patterns obtained from a linear programing model.
Mathematical models	Linear programing (119 constraints, number of variables not given).
Boundaries of study area	Northeast Brazil.

Study results	Of the 24 projects studied only 14 had a benefit-cost ratio greater than unity when the shadow prices and optimal cropping were applied. Only about 55% of the total predicted area could, therefore, be justified on the revised economic basis.
Evaluation and critique	A unique study. It clearly demonstrates an effective way to generate the shadow prices to evaluate projects in the water sector.
Documentation	Cline W R 1973 *Am. J. Agric. Econ.* 55: 622–627.

Case 9 Mu river valley multipurpose scheme, Burma

Origin and purpose	Irrigation feasibility study for the Mu river valley multipurpose scheme, also considered hydro power production. Study area 1,000,000 acres* with 8 possible dam/reservoir alternatives and pumped and gravity flow irrigation systems considered.
Sponsors	Burmese Government and the United Nations.
Organization of study	Details not reported.
Technical team	Booz, Allen, and Hamilton and Italconsult
Structure of analysis	Both conventional and systems analysis methods were used. Choose that system of dams, reservoir, river diversion points and major irrigation canals and determine which crops to grow, where, when and in what quantities in order to maximize the internal rate of return of project over its first 50-year period.
Mathematical model	Mixed integer programing (750 continuous variables, 50 integer variables, and 250 constraints)
Boundaries of study	Basins of the Mu, Chindwin and Irrawaddy.
Study results	The systems analysis studies chose a smaller capital cost, $142 instead of $179 million with the same level of steady state net annual benefits but with an 11% internal rate of return rather than 9%. The developed area also declined from 5 lakh to 3 lakh acres. Acceptance of results by sponsors not reported.
Evaluation and critique	Valuable exercise in comparing conventional methods with system analysis methods. Some problems with completing the integer programing algorithm.
Documentation	Rose C J 1973 *Manage. Sci.*, 20: 423–438.

Case 10 Rural water supply program effectiveness in Thailand

Origin and purpose	To improve the methodology of impact evaluation of rural water supplies looking *ex post* at a variety of completed projects.
Sponsor	Ministry of Public Health, Thailand, USAID and the Asian Institute of Technology.
Organization of study	79 rural water supply plants were evaluated in Northeast Thailand. 3 man-years went into visiting each of the villages and rural areas where the plants were located. Six typical village plants were studied in detail.
Technical team	Department of Environmental Engineering, Asian Institute of Technology (AIT), Bangkok.
Structure of analysis	Systems analysis was used mainly to structure the problem being studied.
Mathematical models	Only simple statistical models were utilized.

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*1 acre = 0·405 ha

Boundaries of study	Northeast region, Thailand.
Study results	Showed the need for broader impact analysis than those based entirely upon conventional benefit/cost analysis.
Evaluation and critique	This study is a "soft" use of systems analysis. The systems approach being used to "structure the problem" to be analysed, the analysis itself being rather trivial in nature.
Documentation	Trankel R J 1974 *Water Resources Res.* 10: 163–169.

Case 11 Pricing irrigation water in Iran

Origin and purpose	In 1968 Iran nationalized water supplies. The study is part of a methodology for the government to set water charges for irrigation.
Sponsor	Industrial Management Institute, Tehran, Iran
Organization of study	Joint study by groups at the Industrial Management Institute. Organizational details not given.
Technical team	Economists
Structure of analysis	The study was based upon an exploration of classical economic theories of public sector investments.
Mathematical models	A simulation model was derived to simulate alternative pricing rules.
Study results	A framework for evaluating irrigation water pricing was derived based upon ability to pay, costs of supplying water and covering reimbursable costs.
Evaluation and critique	Reported work is based upon theoretical consideration only. No empirical tests of the model are reported. The system appears to be reasonably easy to implement.
Documentation	Gardner B D, Madhi Y, Partovi S, Martega H, Mehdi S 1974 *Water Resources Res.* 10: 1080–1084.

Case 12 Groundwater management and salinity control: A case study

Origin and purpose	The primary policy issues in coastal groundwater development are the rate of groundwater use, allocation between irrigation and leaching, and the selection of crops.
Sponsor	Resources for the Future
Organization of study	Details of organization not reported.
Technical team	1 resource economist
Structure of analysis	Study looked for the optimal rate of exploitation of the scarce groundwater resource when consideration is given to future costs and benefits including the impact of salt-water intrusion.
Mathematical models	Dynamic programing and parametric linear programing
Boundaries of study area	Sahvarsal irrigation district, Sonora, Mexico.
Study results	The groundwater stock should be mined at a rapid rate for the first decade. The leaching rate should be between 33% and 43%. Soil salinity is maintained below 6 mmho/cm over the entire decision horizon of 30 years. Substantial changes in the current cropping patterns are recommended. Salt water intrusion is increased by 8 km.
Evaluation and critique	A clever combination of linear and dynamic programing. The author expressed a major concern regarding the availability of sufficient data to use this

	method. No indication if it has been used by the Mexican government to evaluate its proposed major interbasin water transfer.
Documentation	McFarland J W 1975 *Am. J. Agric. Econ.* 57: 457–462.

Case 13 Long term policies for the recovery of the Sahel

Origin and purpose	An attempt to study the 1969–72 drought in the Sahel of West Central Africa and look to long term policies for recovery and restoration.
Sponsor	USAID
Organization of study	Professors and students at the MIT Center for Policy Alternatives organized around the use of Forrester models. Details not reported.
Technical team	Multi-disciplinary team, predominantly engineers.
Structure of analysis	To analyze the historical pattern of animal husbandry and use them to predict future behaviour under a variety of management scenarios.
Mathematical models	Systems dynamics simulation models used.
Boundaries of study area	Pastoral zone of Niger north of Tahoua
Study results	Sudden collapse of the human and animal population were predicted if present policies were pursued. The proposed solution was to concentrate on range conservation with the cattle population being adjusted each year to the carrying capacity of the range.
Evaluation and critique	The approach is innovative but the models are highly aggregated. The "sudden collapse" syndrome of thse types of models is suspicious. The study did not address practical implementation problems.
Documentation	Picardi A C, Seifert W W 1976 *Technol. Rev.* 78(6): 42–52.

Case 14 Joint operation of Bhakra reservoir for power and irrigation

Origin and purpose	An attempt to view the operations of the Bhakra Management Board from the point of view of goal programing.
Sponsor	Indian Institute of Technology (IIT), Kanpur.
Organization of study	This was a desk study carried out at IIT Kanpur and Harvard University as a PhD thesis.
Technical team	1 civil engineer and his advisor (a hydrologist).
Structure of analysis	The studies focussed on the detailed operation of the system starting in September until February. The models were arranged to compare actual operations with hypothetical ones.
Mathematical models	Goal programing model (200 variables and 150 constraints) and control model.
Boundaries of study	Bhakra dam and reservoir.
Study results	Study showed that the current operations of the dam could be changed slightly to increase both the amounts of energy produced and the irrigation water available.
Evaluation and critique	This is an extremely simple and elegant study. Since its completion the Bhakra Management Board has been considering testing it out to modify their release rules.

Documentation	Rao P S 1977 *Multiobjective analysis of Punjab water resources system*, Ph.D. Thesis, Indian Institute of Technology, Kanpur, India. Rogers P, Rao P S, Ramaseshan S 1976 Multiobjective analysis for planning and operations of water resource systems: Some examples from India, Presented at the 1976 Joint Automatic Control Conference, Purdue University, Lafayette, Indiana, mimeo.

Case 15 Irrigation system operating policies for mature tea in Malawi

Origin and purpose	To appraise the economic return to investments in irrigation systems for mature tea in Malawi. To test the hypothesis that distribution of soil moisture within the root zone is an important determinant of the irrigation response of tea.
Sponsor	Tea Research Foundation of Central Africa, Overseas Development Administration (UK), and Tea Research Foundation.
Organization of study	Details not given.
Technical team	1 agricultural economist.
Structure of analysis	The yield of tea as a function of soil moisture was established by conventional agronomic methods. This was then used to evaluate the objective function of the major optimizing model.
Mathematical models	Regression models and Dynamic Programing.
Study results	Optimal irrigation policy does *not* attempt to refill the whole root zone to field capacity.
Evaluation and critique	Not many systems studies are available for non-cereal crops. This study is an interesting combination of empirical data generation and theoretical modelling.
Documentation	Palmer-Jones R W 1977 *Water Resources Res.* 13: 1–7.

Case 16 Optimal cropping pattern for a basin in India

Origin and purpose	Part of a larger study of the conjunctive use of ground and surface water in the Punjab state of India.
Sponsor	Punjab Irrigation Department.
Organization of study	Joint study between Punjab Irrigation Department and IITs Delhi and Kanpur. Data provided by the Irrigation Department engineers to university teams.
Technical teams	Engineers.
Structure of analysis	A study of the optimal cropping pattern and water release from canals and tubewells. The object is to determine the amount of seasonal water releases from the two sources during a 1-year period of operation.
Mathematical model	Linear programing (size not given).
Boundaries of study	Ravi Doab tract in Punjab
Study results	Canals are used to maximum capacity in all months. Tubewells are used to maximum capacity only in October. Sensitivity analysis was carried out on tubewell capacity, area available for irrigation, and the operation costs for canals and tubewells.

Evaluation and critique	A empirical test of some models already in literature. There are some problems with the crop responses as cotton does not enter the solution at all and an increase in available irrigable area reduces the area sown with rice. These may be artifacts of the linear program.
Documentation	Lakshminarayana V, Rajagopalan S P 1977 *J. Irrig. Drainage Div. ASCE* 103: 53–70.

Case 17 An application of interactive multiobjective water resource planning in Algeria

Origin and purpose	As part of the planning for large scale diversion of water for irrigation away from the coastal plain in Algeria the need for appropriate planning objective arose. This study, which is part of the larger study, specifically addresses the setting of planning goals.
Sponsor	Ministry of Industry, Government of Algeria.
Organization of study	Designed as an interactive study in which goal programing produces sets of solutions which government officials discuss and accept or reject. This is then the basis for another iteration in which the objectives are slightly modified in response to the governments initial reaction.
Technical team	Details not given. Predominantly engineers.
Structure of analysis	The analysis was arranged specifically to allow for administrative interaction throughout the study. Explicit use of political judgements were made use of throughout the study.
Mathematical models	Linear goal programing (the STEM method).
Study results	Details not given. During the iterative process new objectives and new constraints were identified and the models modified. Trade-offs were made among the targets for irrigation, the yield reliability, and the costs of the projects.
Evaluation and critique	This case is unusual in that it reports the use of socio-political evaluation during the study itself. Work on the engineering designs based upon this study is now under way.
Documentation	Loucks D P 1977 *Interfaces* 8: 70–75.

Case 18 Optimization method for estimating aquifer parameters

Origin and purpose	Future development of aquifers requires reliable calibration of transmissivity and storage coefficients. Several large groundwater basins in Argentina needed quantitative evaluation. Scarcity of data required good calibration of the groundwater models.
Sponsor	United Nations, Office of Technical Cooperation, Government of Argentina.
Technical team	Groundwater hydrologists.
Structure of analysis	The appraoch taken was to assume a model and optimize the fit of this model to the observed data. In doing so, the optitum estimates for the aquifer characteristics are generated.
Mathematical models	Lagrangean analysis (unconstrained optimization)
Boundaries of study area	Tulum Valley (80,000 ha), and Mendoza Valley (100,000 ha), Argentina.
Study results	Model calibrated extremely well within estimated field parameters.
Evaluation and critique	First developing country application of these methods. The result shows the power of those techniques to argument poor quality data bases.

Documentation	Navarro A 1977 *Water Resources Res.* 13: 935–939.

Case 19 Water shortage in Israel

Origin and purpose	Israel faces limited water supply and increasing demands. Study analyses the policy of reducing allocations of water to irrigation.
Sponsors	Ministry of Agriculture, Israel.
Organization of study	Details not given.
Technical team	Agricultural economists.
Structure of analysis	In each of the regions the economic impact of reducing water quotas was derived using an optimizing model which was constrained by water constraints. These constraints were then varied parametically.
Mathematical models	Linear programing for each of 16 regions.
Boundaries of study	Israel.
Study results	Shows that response of income to water reduction is "inelastic", 10%, 20% or 30% reduction in water quotas to irrigation will result in 6%, 12% or 18% reduction in farm income if no technological change is assumed. If technological changes are assumed then reductions in agricultural income will be 1%, 7% and 12%.
Evaluation and critique	A very simple yet elegant approach to a very serious problem (agriculture uses 70% of total water supply). No indication that the policy assumptions will be followed.
Documentation	Gisser M, Pokaryles S 1977 *Water Resources Res.* 13: 865–872.

Case 20 The economic value of the Panama Canal

Origin and purpose	An attempt to assess the worldwide economic consequences of the Panama Canal becoming unavailable. This is part of the analysis of the costs of the new Panama Canal treaty between the US and Panama.
Sponsor	Details not given.
Organization of Study	Details not given.
Technical team	Commodity Transportation and Development Laboratory, Massachusetts Institute of Technology (MIT).
Structure of analysis	A variety of plausible alternative scenarios were assumed and the economic consequences of them evaluated.
Mathematical models	Simulation and multiobjective analysis.
Boundaries of study	World ocean trading system.
Study results	Shows the net present economic value to the world of US$6 billion and to the US of $1.6 billion.
Evaluation and critique	Despite some heroic assumptions in the analysis the results are probably sufficient to arrive at the nature of the trade-offs which could potentially face the US.
Documentation	Gibbs S R *Water Resources Research* 14: 185–189.

Case 21 Algerian agricultural water conveyance system

Origin and purpose	Engineering feasibility for transporting water to the inland Setif region of Algeria from several rivers flowing north into the Mediterranean. 50,000 hectares are expected to be brought under irrigation.
Sponsors	Algerian Government.
Organization of study	Details not reported.
Technical team	Bechtel Inc., San Francisco, details not reported.
Structure of analysis	To select the most efficient design parameters for a 30 km water transport pipeline.
Mathematical models	Geometric programing.
Boundaries of study area	From coastal reservoir to inland irrigation system.
Study results	Savings of over $1 million per year were predicted using the parameters selected over the best "hand" designed system. Project results accepted by Algerian Government and are now in detailed engineering design phase.
Evaluation and critique	The system was narrowly defined and only the costs considered (cost minization objective function), however, the predicted savings are substantial.
Documentation	Wyman F P 1978 *Interfaces* 8: 1–6.

Case 22 Water utilization and reallocation in Chile

Origin and purpose	1967 Water Code requires equalization of water rights per hectare in each homogeneous farming area. This study was made to assess the income redistribution impacts that would result from such equalization.
Sponsor	Ford Foundation and National Institute of Agricultural Research of Chile.
Organization of study	Details not given.
Technical team	2 agricultural economists.
Structure of analysis	118 farms of 5 hectares and larger were surveyed and broken down into 3 categories. One typical farm from each category was modelled using a deterministic linear programing model.
Mathematical model	Linear programing at farm level (size not given).
Boundaries of study area	Pirque Valley in Central Chile.
Study area results	Equality pursued on a per hectare basis will result in economic inefficiency and a worsened income distribution.
Evaluation and critique	An elegant approach to the problem of equity in irrigation water allocation. However, conclusions are based upon a relatively small sample of farms. No indication that the results have been utilized by the Government.
Documentation	Parks L L, Hansen D E 1978 *Am. J. Agric. Econ.* 59: 207–213.

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