(REVISED)

# PLANNING FOR OPTIMAL INTER BASIN WATER TRANSFER

## A THESIS

*Submitted in fulfilment of the*
*requirements for the award of the degree*
*of*
DOCTOR OF PHILOSOPHY
*in*
HYDROLOGY

*By*

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DECEMBER, 2005

6th Annual Convocation- 2006
Degree conferred on 11.11.2006

Supdt. (PGS&R)

# CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"PLANNING FOR OPTIMAL INTER BASIN WATER TRANSFER"** in fulfillment of the requirement for the award of the degree of Doctor of Philosophy and submitted in the **Department of Hydrology, Indian Institute of Technology Roorkee, Roorkee**, is an authentic record of my own work carried out during a period from July, 2001 to December, 2005 under the supervision of **Prof. D. K. Srivastava**.

The thesis has been revised as per suggestion of the examiners.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute/University.

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Dated: December 20 ,2005 **(Bibhash Sarma)**

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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The Ph. D. viva-voce examination of Mr. Bibhash Sarma, Research Scholar has been held on ...22/09/06......

Signature of Supervisor Signature of H. O. D. Signature of External Examiner

# ACKNOWLEDGEMENTS

At the outset, I would like to express my profound sense of gratitude and indebtedness to my respected guide Dr. D. K. Srivastava, Professor, Dept. of Hydrology, IIT Roorkee, for his meticulous guidance, continual encouragement, keen interest, invaluable suggestions, and, most of all for giving me fundamental knowledge and constructive criticism throughout the course of present investigation, which strengthened my skills in research methodology. I have been deeply influenced by his penetrating insight, sound judgments, novel teaching ability, and his well-balanced humane personality. During this period, I have enjoyed the academic freedom I was offered, by the Dept. of Hydrology, in general, and by him in particular.

I am grateful to my parents for their encouragement and blessings offered to me.

I take this opportunity to express my thanks to the Secretary, Education Dept., Govt. of Assam for deputing me to pursue the present study, and to All India Council for Technical Education (AICTE), Ministry of Human Resources, Govt. of India for sponsoring.

It is my great pleasure to acknowledge the useful discussions offered by the members of my Ph. D. Scrutiny Committee.

I would like to express my gratitude to Dr. D. C. Singhal, Prof. and Head, Dept. of Hydrology, Dr. Ranvir Singh, Prof. and Dean, Students Welfare, and Dr. B. S. Mathur for their parental love and guidance bestowed upon me. I am thankful to Dr. N. K. Goel, Dr. H. Joshi, Dr. M. Perumal and Dr. D. S. Arya, faculty members of Dept. of Hydrology; and Dr. S. K. Jain, Scientist F, National Institute of Hydrology, Roorkee for their encouragement.

It is difficult to find words to express my gratefulness to my friends and co research scholars Dr. J. Jena, Dr. T. Awchi, Mr. R. K. Panigrahi, Dr. M. D. Patil, Mr. S. K. Srivastava, Mr. A. A. Alhello, Mr. H. M. Hussain, Mr. R. K. Rai, Mr. B. Sahoo and all other research scholars of Dept. of Hydrology. I will remember both the intellectually stimulating discussions and the lighter moments we shared together. Special thanks are due to Mr. U. K. Misra, Mr. R. D. Misra, Mr. S. Lahkar, Ms. S. Choudhury, Ms. M. Goswami, Dr. D. Goswami, Dr. J. Pathak and Dr. B. Sarma for giving me a family environment away from my family at Roorkee.

I am thankful to Mr. Sandeep Jain, Software Applications, Roorkee for maintaining my computer. Thanks are due to office staff members of the Dept. of Hydrology for their cooperation in various occasions.

I express my deep sense of love and gratitude to Dr. Munmum Sharma, my wife, who has provided me all kinds of moral and emotional supports. During my stay at Roorkee, she has faced many hardships while raising our daughter alone along with her professional obligations, in a remote corner of the country. I will always remember her patients and courage, while facing and responding to some of the crisis that my family encountered in my absence. Last, but not the least, I thank my little daughter Meghna, who sacrificed in her own way by missing her dad. May she live well and grow into a complete woman, loved and respected by all.

**Bibhash Sarma**

# ABSTRACT

The National Water Development Agency (NWDA), Ministry of Water Resources, Govt. of India has carried out studies on inter basin water transfers in India. It has identified 30 links for preparation of feasibility reports and has prepared feasibility reports of 6 such links. The study got momentum due to a recent Supreme Court verdict directing the Government of India to inter-link all the major rivers in India for inter basin transfer of water. This entails construction of large river linking projects, which warrants sound investigation, careful planning and huge expenditure. A faulty implementation of these projects may be more harmful than doing nothing at all. The studies for most of these rivers linking are at their initial stages. It is felt that the application of system analysis techniques will help in better planning for these Herculean task. The proposed Parbati-Kalisindh-Chambal link under the peninsular rivers development plan is considered for this study. Three proposed reservoirs, namely, Patanpur in Parbati river, Mohanpura in Newaz river and Kundaliya in Kalisindh river are proposed to transfer surplus waters of Parbati and Kalisindh basins either to Upper Chambal basin (Gandhi Sagar reservoir) or to Lower Chambal basin (Ranapratap Sagar). The Newaz river is a tributary of Kalisindh river.

Optimal planning of a large-scale river basin as a unit of water resources system is having a high priority in the economic development of a region. This has resulted in an urgent need for accurate and efficient management of the water resources for its conservation and use. System engineering provides methodologies for studying and analyzing various aspects of a system and its response to various parameters by using optimization and simulation techniques. Often these aspects are very complex with different objectives, scopes, scales and timing considerations. In such cases there is usually no unique model for the solution of the problems. A set of linked models may be nested in these cases in such a fashion that outputs of one model are inputs to another or two models are run in tandem. The answer to how the model links should be arranged is problem specific, but such use of nested models may be often quite useful.

In India, as per the National Water Development Agency (NWDA) guidelines, water can be transferred from a river basin to another, only when the exporting basin is surplus in its surface water resources at 75% water year dependability. An assessment of the annual water balance of each concerned river basin is carried out for determining whether a river basin is surplus or deficit in its water resources (surface and ground waters) in comparison to basin's annual future water demands. Here, the meaning of the *water balance* is a comparison between annual water availability and annual water demands of a river basin, and differs from the conventional meaning of water balance. Annual water demands are calculated for different purposes like municipal, irrigation, industrial, hydropower and salinity for the projection year of 2050 (with the expectation that population would hopefully be stabilized by that time) and then compared with the 75% and 50% water year dependable flows. The annual availability of water consists of two parts, viz., surface water and ground water. For the problem under study the annual water balance assessments indicate severe water deficit situation exists in the Upper Chambal basin. The Lower Chambal basin is marginally surplus in its surface water resources only due to a committed amount of import water it is receiving from the Upper Chambal basin. Therefore, water transfer options from Kalisindh and Parbati basins need to be considered in order to reduce the imbalance caused due to the inequitable distribution of water resources in comparison to water demands in the water deficit basins.

Yield model serves as an efficient preliminary screening model for reasonable reservoir designs with release reliabilities near targets. This study extends the yield model as available in the present form and presents *an improved general-purpose yield model* (IGPYM) applicable to a multiple reservoirs system consisting of single purpose and multipurpose reservoirs. The model is capable of considering more than two numbers of water uses, different reliabilities for each water use, allows deficit in annual yields during failure years, and redistribution of upstream regenerated flows in within the year periods. The model can be applied to both compatible and incompatible water purposes, and considers each purpose independently or in-group, depending on the total number of purposes to be considered in a reservoir. It is found that the model offers better flexibility in selecting reliabilities of water uses and deciding optimal yield failure fractions during failure years for different water uses. The model can act as a better screening tool in planning by providing outputs that can be very useful in improving the efficiency and accuracy of models such as dynamic programming and detailed simulation.

The results of the yield model are approximate and require refinement. Dynamic programming models are known to be efficient in resource allocation type of problem and in this work it is decided to adopt DP models to find import water requirements, fixation of design demands and for reservoir operation for all the reservoirs in the system. To consider water transfer in a system of reservoirs (sites), it is important to look into two aspects (a) excess water availability at a source (export) point and (b) annual water demands at both source (export) and destination (import) points. To cover both the aspects, initially it is assumed that at each reservoir all the known annual target water demands have to be met completely. The available water at a reservoir may not be sufficient to meet all its water demands and a DP model; namely, *procurement problem model* (PPM) is formulated for such cases to calculate the import of water required by each reservoir in a system facing shortage of water. The PPM assumes that unlimited water is available at the upper most exporting reservoir (starting point of the water transfer link) and hence all the annual target water demands can be met in the system. This assumption is not practical, but the model is successful in giving the annual target water export demands for all the water exporting reservoirs.

At this stage all the annual target water and energy demands are known for all the reservoirs in the system. Another DP model, namely, *controlled input model* (CIM) is formulated to fix the annual design demands for all the water needs that can be met with prescribed annual reliabilities. If the annual target water demands cannot be met, the model determines annual design water demands that can be met with prespecified annual reliabilities for each water need. The CIM also does reservoir operation. Annual yields for all the water needs are obtained at different reliabilities. A simulation model is developed to evaluate the anticipated performances of the system for the set of design and operating policy parameter values obtained through the application of the optimization models.

For the problem under study two alternative water transfer link proposals are studied. Link-I assumes that water will be exported from Patanpur to Mohanpura, Mohanpura to Kundaliya and Kundaliya to Gandhi Sagar; and Link-II assumes that the water transfer will be done from Patanpur to Mohanpura, Mohanpura to Kundaliya and

Kundaliya to Ranapratap Sagar. The IGPYM is applied to find (i) the maximum amount of water that can be exported with design reservoir capacities after meeting their respective annual target municipal water supply and irrigation demands at desired reliabilities; (ii) the maximum reliabilities that can be achieved for irrigation, water export and secondary energy generation; (iii) to know the annual amount of water the reservoirs are capable of supplying for each water use during a failure year; (iv) the maximum annual firm and secondary energy generations; (v) the trade-offs between different reservoir yields for known reservoir capacities; and (vi) the alternative reservoir capacities to derive the same annual municipal water supply, irrigation and energy benefits as obtained from the proposed reservoir capacities. Different cases are formulated depending on link alternatives, alternative reservoir capacities and alternative link canal capacities for the DP models. The PPM results present the amount of import water required for all the concerned reservoirs to meet their respective target demands completely and the CIM results present the design demands that can be met with specified reliabilities. Reservoir operation results using CIM show the achieved annual yield for each water use corresponding to different reliabilities by each reservoir in the system for all the cases. Testing of the reservoir operation results are done by simulation and the most promising cases under each link alternative are identified.

The developed models and their applications present a systems analysis application methodology for planning and operation of multipurpose multireservoirs, involved in inter basin water transfers. The results show that the Link-I is more promising compared to the Link-II with respect to meeting their respective demands. The proposed capacity of Kundaliya reservoir is high (around 350 MCM) and can be reduced substantially, by marginal increase in the proposed reservoir capacities at Patanpur and Mohanpura (11 MCM and 12 MCM, respectively).

# CONTENTS

**Title** **Page No.**

# LIST OF TABLES

# LIST OF FIGURES

## Chapter 5

*Single reservoir yield model*

$A_a$=area per unit active storage volume above Ao;

$A_o$=area at dead storage;

$D_t$ =a predetermined fraction of annual reservoir yield for the within year yield in period t;

$E0$ = average annual fixed evaporation volume loss due to dead storage;

$El^r$ = average annual volume loss rate per unit of active storage volume;

$El^t$ =evaporation loss in within year time t;

$El_j$ =evaporation loss in year j;

$I_j$ =annual inflows;

$Oy^{j,t}_{f,p}$ = reservoir yield during period t in year j;

$Oy^t_{f,p}$ =firm within year reservoir yield;

$Oy^t_{s,p}$ =secondary within year reservoir yield;

$Oy^{f,p}$ =firm annual reservoir yield;

$Oy^{s,p}$ =annual secondary reservoir yield;

$S_{j,t-1}$ = initial storage at the beginning of period t; in year j;

$S_{j,t}$ = final storage at the end of period t; in year j;

$S^w_{t-1}$ =initial storage at the beginning of within year period t;

$S^w_t$ =final storage at the end of within year period t;

$S^0_{j-1}$ = initial storage at the beginning of year j;

$S_j^0$ = final storage at the end of year j;

$S_{cr}^0$ = initial over year storage volume in the critical year;

$Sp_j$ = excess release (spill) in year j.

$Sp_{j,t}$ = excess release (spill) during period t in year j;

$Ya$ = total active storage capacity;

$Y^0$ =active over year reservoir capacity;

$Y^w$ =within year reservoir capacity;

$\beta_t$ = ratio of the inflow in period t of the critical year of record to the total inflow in that year;

$\gamma_t$ =the fraction of the annual evaporation loss that occurs in period t; and

$\theta_{p,j}$ =failure fraction for the yield with reliability p in year j.

*Multisite Multireservoir Yield Model*

i = a reservoir site;

j =a year;

t= a within year period;

k= a reservoir amongst the set of m contributing reservoirs upstream of reservoir i;

p =the exceedence probabilities to be considered;

$B_i^f$ =returns from annual firm $(E_i)$ energy for reservoir i;

$B_i^s$ = returns from annual secondary $(\overline{E}_i)$ energy for reservoir i;

$C_f$ =conversion factor for computation of hydroelectric energy;

$e_i$ = hydropower plant efficiency for reservoir i;

$E_i$ =annual firm energy generation from reservoir i;

$\overline{E}_i$ = annual secondary energy generation from reservoir i;

$El_i^r$ = average annual evaporation volume loss rate per unit of active storage volume for reservoir i;

$El^{i,t}$ = evaporation volume loss from reservoir i in period t;

$El_{i,j}$ = annual evaporation volume loss from reservoir i in year j;

$E0_i$ = average annual fixed evaporation volume loss due to dead storage for reservoir i;

$h_{i,t}$ = number of hours for generation of energy for reservoir i in time t;

$H_i$ = hydropower plant capacity for reservoir i;

$Ha_{i,t}$ = productive storage head for reservoir i in period t;

$I_{i,j}$ = inflow to reservoir i in year j;

$K_{i,t}$ = a predetermined fraction of annual irrigation yield from reservoir i for the within year yield in period t;

$Oy_{f,p}^{i,t}$ = within year firm yield at time t from reservoir i;

$Oy_{s,p}^{i,t}$ = within year secondary yield at time t from reservoir i;

$Oy_i^{f,p}$ = annual firm yield from reservoir i;

$Oy_i^{s,p}$ = annual secondary yield from reservoir i;

$Oy_{f,p}^{k,t}$ = within year firm yield at time t from upstream reservoir k;

$Oy_{s,p}^{k,t}$ = within year secondary yield at time t from upstream reservoir k;

$S_{i,j-1}^0$ = initial over year storage at the beginning of year j in reservoir i;

$S_{i,j}^0$ = final over year storage at the end of year j in reservoir i;

$S_{i,cr}^0$ = initial over year storage volume in the critical year for reservoir i;

$Sp_{k,j}$=annual spill from upstream reservoir k in year j;

$Sp_{i,j}$ = annual spill from reservoir i in year j;

$Ya_i$=total active storage capacity for reservoir i;

$Y_i^0$=over year storage capacity for reservoir i;

$\alpha_{i,t}$ =hydropower plant factor for reservoir i in period t;

$\beta_{i,t}$= ratio of the inflow in period t of the critical year of record in reservoir i to the total inflow in that year;

$\gamma_{i,t}$ =fraction of annual evaporation volume loss from reservoir i in period t;

$\delta_k^f$ =fraction of firm yield coming as regenerated flow from upstream reservoir k;

$\delta_k^s$ =fractions of secondary yield coming as regenerated flow from upstream reservoir k; and

$\eta_{i,t}$ =percentage fraction of annual firm energy target for reservoir i in period t.

### *Additional and Changed Variables in IGPYM*

$D_{i,t}^P$ = proportion of annual priority yield for reservoir i;

$D_{i,t}^S$ =proportion of annual second yield for reservoir i;

$D_{i,t}$ =proportion of annual total yield for reservoir i;

$El_i^a$=average annual evaporation volume loss rate per unit of active storage volume for reservoir i;

$\mathrm{Im}_{i,j}^k$ =annual water import to reservoir i in year j from reservoir k;

$\mathrm{Im}_k^{i,t}$ =water import to reservoir i in within year time t from reservoir k;

$OFy_i^t$=firm water yield from reservoir i in time t;

$OSy_i^t$=secondary water yield from reservoir i in time t;

$OFy_i$=firm annual water yield from reservoir i;

$OSy_i$=secondary annual water yield from reservoir i;

$OFEy_i^t$=part of the firm water yield at time t; from reservoir i; which is actually used for firm power generation;

$OSEy_i^t$=part of the secondary water yield at time t from reservoir i; which is used for secondary energy generation;

$Oy_i^{P,p1}$= annual priority yield of reservoir i with reliability p1;

$Oy_i^{S,p2}$ = annual second yield of reservoir i with reliability p2;

$Oy_{P,p1}^{k,t}$=within year priority yield with annual reliability p1 at time t from upstream reservoir k;

$Oy_{S,p2}^{k,t}$=within year second yield with annual reliability p2 at time t from upstream reservoir k;

$Oy_{P,p1}^{i,t}$=within year priority yield with annual reliability p1 at time t from reservoir i;

$Oy_{S,p2}^{i,t}$=within year second yield with annual reliability p2 at time t from reservoir i;

$SSWB_i^{75D}$ =annual surplus surface water balance at 75% annual dependability;

$\alpha_i$=desired ratio of priority yield to second yield for reservoir i;

$\theta_{p1,j}$ = failure fraction of priority yield with reliability p1; to be made available during failure years; and

$\theta_{p2,j}$ = failure fraction of second yield with reliability p2; to be made available during failure years.

## Chapter 6

*Dynamic Programming Models*

$CDD_{r,p}$ =*penalty for not being able to meet the demand for purpose p at r stages to go;*

$CTR_r$ =penalty for import or water transfer at r stages to go;

$CSR_r$ = penalty for reservoir storage at r stages to go;

$CSP_r$ =penalty for reservoir spill at r stages to go;

$D_{r,p}$ =target water demand for purpose p to be met from reservoir at r stages to go;

$El_r$ =reservoir evaporation losses in r stages to go;

$g_r(S_r, O_r)$ =return function for r stages to go;

$I_r$ =total inflow to reservoir at r stages to go;

$\bar{I}_r$ = local inflow to reservoir from surrounding area in r stages to go;

$\mathrm{ISPILL}_r$ =spill from inflow at r stages to go;

N = total number of stages to go;

$O_r$ = import of water required (a decision variable) to reservoir to meet demands without failure at r stages to go in PPM;

$O_r$ =amount of water to be used from reservoir inflow (a decision variable) to meet the demands at r stages to go in CIM;

$P_r$ =precipitation directly upon reservoir in r stages to go;

r = number of stages to go; such that r = 1;2;-------;N;

$S_r$ =reservoir storage at the beginning of r stages to go;

$S_{r-1}$ = reservoir storage at the end of r stages to go;

$\mathrm{SSPILL}_r$ =spill from storage at r stages to go;

$TSP_r$ =spill from reservoir at r stages to go;

$Ya =$ live capacity of reservoir;

$Y\max_r$ = storage capacity up to full reservoir level in r stages to go;

$Y\min_r$ = storage capacity up to minimum draw down level (MDDL) of reservoir in r stages to go;

$\alpha_p$ = coefficient for demand revision for purpose p; lying between 0 and 1; and

$\alpha_p D_{r,p}$ = design water demand (revised water target) for purpose p; or the actual water release from reservoir excluding reservoir spill for purpose p at r stages to go.

## Chapter 7

### *Simulation Model*

$A_{i,t}$ = surface area of reservoir i in time t;

$C_f$ = conversion factor for computation of hydroelectric energy;

$CC_i$ = water transfer link canal capacity from reservoir i;

$DE_{i,t}$ = energy demand from reservoir i in time t;

$DPW_{i,t}$ = volume of water required to generate target energy from reservoir i in time t;

$DWS_{i,t}$ = demand of domestic water supply from reservoir i in time t;

$DIR_{i,t}$ = irrigation demand from reservoir i in time t;

$DEX_{il,t}$ = demand for water export from reservoir i to a lower reservoir il in time t.

$DWS_i$ = annual demand for domestic water supply from reservoir i;

$DIR_i$ = annual demand for irrigation from reservoir i;

$DEX_{il}$ = annual demand for water export from reservoir i to a lower reservoir il;

$D_{i,t}^{WS}$ = fraction of annual target domestic water supply yield from reservoir i in period t;

$D_{i,t}^{IR}$ = fraction of annual target irrigation yield from reservoir i in period t;

$D_{il,t}^{EX}$ = fraction of annual target water export yield from reservoir i to a lower reservoir il in period t;

$e_i$ = hydropower plant efficiency for reservoir i;

$ev_{i,t}$ = average rate of evaporation from reservoir i in time t;

$El_{i,t}$ = evaporation at reservoir i in time t;

$h_{i,t}$ = number of hours for generation of energy for reservoir i in time t;

$H_i$ = hydropower plant capacity for reservoir i;

$Ha_{i,t}$ = productive storage head for reservoir i in period t;

$I_{i,t}$ = inflow to reservoir i in time t;

$\bar{I}_{i,t}$ = local inflow to reservoir i from surrounding area in time t;

NERi = number of water exporting reservoirs to reservoir i;

NUR$_i$ = number of upstream reservoirs above reservoir i;

$NIR_i$ = number of water importing reservoirs from reservoir i;

$OE_{i,t}$ = energy generated from reservoir i in time t;

$OEX_{iu,t}$ = water exported from an upper reservoir iu to reservoir i in time t;

$OEX_{il,t}$ = water export yield from reservoir i to a lower reservoir il in time t;

$OEX_{il,t}^{T}$ = total water export including additional water export from reservoir i to a lower reservoir il in time t;

$OIR_{iu,t}$ = volume of water released for irrigation from an upstream reservoir iu upstream of reservoir i in time t;

$OIR_{i,t}$ = irrigation yield from reservoir i in time t;

$OPM_{i,t}$ = part of the water from irrigation and water export yields from reservoir i in time t that is not used for energy generation;

$OPP_{iu,t}$ = volume of additional water released for energy generation over and above that from irrigation and water export released (i.e., volume of water used only for energy generation), from an upstream reservoir iu upstream of reservoir i in time t;

$OPP_{i,t}$ = volume of water used for energy generation from reservoir i in time t, over and above that from irrigation and water export yields;

$OPW_{i,t}$ = volume of water used to generate energy from reservoir i in time t;

$OWS_{iu,t}$ = volume of water released for domestic water supply from an upstream reservoir iu upstream of reservoir i in time t;

$OWS_{i,t}$ = domestic water supply yield from reservoir i in time t;

$Oy_{i,t}$ = total water yields in volume, excluding additional water export ($Sp_{i,t}^{AEX}$) from reservoir i in time t;

$Oy_{i,t}^{T}$ = total water yields in volume, including additional water export from reservoir i in time t

$P_{i,t}$ = precipitation directly upon reservoir i in time t;

$R_{i,t}$ = regenerated flows coming from water uses of upstream reservoirs to reservoir i in time t;

$S_{i,t}$ = final storage at the end of time t for reservoir i;

$S_{i,t-1}$ = initial storage at the beginning of time t for reservoir i;

$Sp_{i,t}$ = spill from reservoir i in time t;

$Sp_{iu,t}$ = spill from an upstream reservoir iu entering to reservoir i in time t;

$Sp_{i,t}^{AEX}$ = additional water export over and above water export demand, if excess water is available and canal capacity permits, at time t from reservoir i;

$TL_{iu,t}$ = water transfer loss from reservoir iu to i;

$Y\max_i$ = gross storage capacity of reservoir i;

$\alpha_{i,t}$ = hydropower plant factor for reservoir i in period t;

$\delta_{WS}^{iu}$ = fraction of domestic water supply yield from an upstream reservoir iu coming as regenerated flow to reservoir i;

$\delta_{IR}^{iu}$ = fraction of irrigation yield from an upstream reservoir iu coming as regenerated flow to reservoir i;

$\delta_{PW}^{iu}$ = fraction of the additional volume of water used for energy generation over and above that from irrigation and water export released from an upstream reservoir iu coming as regenerated flow to reservoir i; and

$\eta_{i,t}$ = fraction of annual firm energy target for reservoir i in period t.

## Chapter 8

### *Additional Constraint for Reservoirs Exporting Water*

$NER_i$ = number of water exporting reservoirs to reservoir i; and

$SSWB_i^{75D}$ = surplus surface water balance at 75% water year dependability of the catchments area of reservoir i.

## Chapter 9

### *Nash-Sutcliffe Efficiency*

$Oy_{mean}^{SIM}$ = mean yield obtained by simulation, and

$Oy_t^{SIM}$ = yield obtained by simulation in period t,

$Oy_t^{CIM}$ = yield obtained by the CIM in period t,

n = number of periods, and

t = time period considered in both the CIM and simulation model.

*Chapter 1*

# INTRODUCTION

## 1.1 PROLOGUE

The constantly increasing population, water demands for various basic and developmental purposes have forced engineers and planners to contemplate and propose more comprehensive, complex and ambitious plans for water resources systems. The development, conservation and efficient use of water forms one of the main elements in the development planning. The water resources are limited considering the future demands. In India, the rainfall is mostly confined to the monsoon season and is unevenly distributed both in space and time even during the monsoon season. As a result, frequent droughts are experienced and nearly one third of the country is drought prone. In the monsoon, flood waters that otherwise run waste into the sea can be conserved in various storage reservoirs and can be utilized for beneficial purposes during non-monsoon periods. If the water availability and requirements of various river basins are assessed realistically, then planning can be done to transfer water from water surplus basins to basins that are deficit in water. Inter basin water transfers through inter-linking of rivers is viewed as an approach to correct the natural imbalance due to inequitable distribution of water resources.

Integrated planning for water resources systems that may comprise of multiple and multipurpose reservoirs, is generally a complex task. However the huge investments involved and great potential for efficient utilization through improved systems design necessitate a comprehensive planning program. The reservoir analysis problem can be stated as: how large the reservoir storage needs to be to provide for a given demand with an acceptable level of reliability? This problem is known as determination of reservoir storage capacity. Other variations in the stated problem are possible, such as determining reservoir release for a given storage capacity. In all the cases the basic problem remains unaltered. The relationship between inflow characteristics, reservoir storage capacity, reservoir release, and the reliability of reservoir operations must be found. River/reservoir system management practices and associated modeling and analysis methods involve allocating storage capacity and stream flow between multiple uses and users; minimizing the risks and consequences of water shortages and flooding; optimizing the beneficial use of water, energy and land resources; and minimizing adverse environmental impacts. Different problem structures and conflicting reservoir purposes require complex mathematical descriptions. The decision variables, objective functions, and constraints vary for different types of reservoir problems. Their correct formulation is required to address trade-offs between conservation and non-conservation purposes. The systems analysis approach is being consistently employed to handle these problems for providing an improved basis in decision-making.

## 1.2 BACKGROUND OF INTER BASIN WATER TRANSFER IN INDIA

Suggestions for a national water grid for transferring surplus water available in some regions to water-deficit areas have been made from time to time. The following section highlights the earlier proposals and attempts in India for inter linking of rivers.

### 1.2.1 National Water Grid By Late Dr. K. L. Rao

A note on the National Water Grid was prepared by the Central Water & Power Commission (around 1972) and three possible alignments for the Ganga-Cauvery link along with other links were brought out. Further studies were made by late Dr. K. L. Rao who advocated one of the alignments for the Ganga-Cauvery link along with a few other links including the Brahmaputra-Ganga Link. The 2640 km long Ganga-Cauvery link essentially envisaged the withdrawal of 1680 cumec of the flood flows of the Ganga near Patna for about 150 days in a year and pumping about 1400 cumec of this water over a head of 549 m for transfer to the

Peninsular region and utilizing the remaining 280 cumec in the Ganga basin itself. The proposal envisaged utilization of 2.59 million ham of Ganga water to bring under irrigation an additional area of 4 million ha. Dr. Rao had also proposed a few additional links like (a) Brahmaputra-Ganga link to transfer 1800 to 3000 cumec with a lift of 12 to 15 m, (b) link transferring 300 cumec of Mahanadi water southwards, (c) canal from the Narmada to Gujarat and Western Rajasthan with a lift of 275 m and (d) Links from rivers of the Western Ghats towards east. Dr. Rao had estimated his proposals to cost about Rs. 12,500 crores. Very roughly at 1995 prices the Ganga–Cauvery link alone would amount to about Rs. 70,000 crores (capital cost). The annual costs including cost of power would be around Rs. 30,000 per hectare. The present NWDA proposals for inter linking river between Ganga and Cauvery at present prices would cost only around Rs. 15,000 per hectare annually. The proposals examined by the Central Water Commission were found to be grossly under-estimated. It was also observed that the scheme would require large blocks of power (5000 to 7000 MW) for lifting water. It will also have no flood control benefits. Therefore, the proposal was not pursued as such.

### 1.2.2 Garland Canal By Captain Dastur

Captain Dastur had put forward his proposal for Garland Canal which mainly consists of two canals, viz. (i) A 4200 km long, 300 m wide Himalayan Canal at a constant bed level between 335 m and 457 m above mean sea level aligned along the southern slopes of the Himalayas running from the Ravi in the west to the Brahmaputra in the east and beyond. The Himalayan river water stored in 50 integrated lakes to be created by cutting the hill slopes of the Himalayas to the same level as the bed of the canal, and another 40 lakes beyond Brahmaputra will feed it. The proposal envisaged a storage capacity of 24.7 million ham to control and distribute 61.7 million ham of water, (ii) 9300 km long, 300 m wide Central and Southern Garland Canal at a constant elevation of between 244 m and 305 m above the mean sea level. This Garland Canal was proposed to have about 200 integrated lakes having a storage capacity of 49.7 million ham to control and distribute 86.4 million ham. The Garland canals were proposed to be inter-connected at two points (Delhi and Patna) by 5 numbers of 3.7 m diameter pipelines for transfer of water. Captain Dastur estimated that all the surplus waters in the country will be utilized to irrigate 219 million ham. About 16.8 million volunteers were expected to complete the work in 3 to 4 years. The cost estimated by Captain Dastur (around 1974) was Rs. 24095 crores.

The proposal was examined by two committees comprising experts from Central Water Commission, State Governments and Professors from IIT and University of Roorkee who were of the opinion that the proposal was technically unsound and economically prohibitive. Preliminary studies carried out by Central Water Commission (around 1976) indicated that the cost of the Dastur proposal was about Rs. 12 million crores. The scheme was therefore given up.

### 1.2.3 Establishment of National Water Development Agency (NWDA)

The Ministry of Water Resources (then known as Ministry of Irrigation) in the year 1980 formulated a National Perspective Plan for Water Resources Development by transferring water from surplus basins to deficit basins/regions by inter-linking of rivers. The National Perspective Plan has two main components, i.e., the Himalayan Rivers Development and Peninsular Rivers Development. The National Water Development Agency (NWDA) was set up as a society in 1982 to carry out detailed studies and detailed survey and investigations, to prepare feasibility reports of the links envisaged under the National Perspective Plan. NWDA, after carrying out studies, identified 30 links for preparation of feasibility reports and has already prepared feasibility reports of 6 such links. The study got momentum due to a recent Supreme Court verdict directing the Government of India to inter-link all the major rivers in India for inter basin transfers of water. This entails construction of large river linking projects, which warrants sound investigation, careful planning and huge expenditure. A faulty implementation of these projects may be more harmful than doing nothing at all.

The studies for most of these river linkings are at their initial stages. It is felt that the application of system analysis techniques will help in better planning of these Herculean task. The proposed Parbati-Kalisindh-Chambal link under the peninsular rivers development plan is considered for this study.

The basins Parbati and Kalisindh, from where water is proposed to be transferred to the Chambal river, are sub-basins of the Chambal basin. The Chambal basin itself is a sub-basin of Yamuna basin, which again is a sub-basin of Ganga basin. The Ganga basin is a sub-basin of Ganga-Brahmaputra-Meghna system. To avoid confusions in the use of the words 'basin' and 'sub-basin', all the basins/sub-basins in the system are considered as independent unit and referred only as basin.

## 1.3 AN OVERVIEW OF THE CHAMBAL BASIN

### 1.3.1 River System

The Chambal river is a principal tributary of the Yamuna river, and rises in the Vindhyan range near Mhow in the Indore district in the state of Madhya Pradesh (India) at an elevation of 854 m at north latitude of 22°28′ and east longitude of 75°40′ and flows in a generally northerly direction for a length of 320 km up to the Madhya Pradesh-Rajasthan border. In this reach, the Chamal, the Siwana and the Retam join the river from the left and the Shipra and Chhoti Kalisindh from the right. The river, then, enters Rajasthan, after flowing for a length of 38 km turns to the right, and takes a northeasterly course. At 480 km from the source, it receives a major tributary from the right near the village of Laban, the Kalisindh, and 22 km below another tributary, the Kural from the left. The river continues to flow in a northeasterly direction for a further distance of 40 km, when it's other major right bank tributary, the Parbati, near the village of Pali, joins it. The river, then, forms the common boundary between Madhya Pradesh and Rajasthan for a length of 251 km. The Banas, a major left bank tributary, joins the Chambal in this reach, near the village of Rameshwar. The river, thereafter, forms the common boundary between Madhya Pradesh and Uttar Pradesh for 117 km and flows in a northeasterly direction up to the village of Pinahat. It gradually bears right and flows in a southeasterly direction to enter Uttar Pradesh, north west of the village of Chakarnagar. After flowing for 46 km in Uttar Pradesh, the Chambal outfalls into the Yamuna, south east of the village of Sahon in the Etawah district.

From the source down to its junction with the Yamuna, the Chambal has a total fall of 732 m, of which about 244 m is in the first few km and 122 m in a distance of about 100 km from Chourasigarh fort to Kota city. For the rest of its course, the river passes through flat fertile areas in the Malwa Plateau and later in the Gangetic plains. The total length of the river from the head to its confluence with the Yamuna is 960 km, of which 320 km are in Madhya Pradesh, 226 km in Rajasthan, 251 km form the common boundary between Madhya Pradesh and Rajasthan, 117 km form the common boundary between Madhya Pradesh and Uttar Pradesh and the balance of 46 km are in Uttar Pradesh.

### 1.3.2 History of Chambal Valley Development

The implementation of the Chambal valley development project was taken up in three stages. The first stage comprised of:

- Construction of Gandhi Sagar (GS) dam, 65 m high masonry dam with a gross storage capacity of 8449 MCM and live storage capacity of 7617 MCM and an installed capacity of 115 MW with firm power of 80 MW at 60 percent load factor.
- Construction of Kota barrage 37.3 m high earthen dam in river portion with a masonry and concrete spilling surplus capacity of 7.5 lakh cusec.
- Two canal systems taking off from the two flanks of Kota barrage with a total of 379.79 km of canal systems.

The first stage was completed in 1960.

The second stage consisted of construction of Ranapratap Sagar (RPS), a 55 m high masonry dam with a gross capacity of 2899 MCM and live storage of 1567 MCM and a power house with installed capacity of 172 MW and firm power of 90 MW at 60 percent load factor. This stage was completed in 1967.

Third stage of construction of 44.8 m high Jawahar Sagar (JS) dam, a concrete dam with installed capacity of 99 MW and firm power of 60 MW at 60 percent load factor was completed in 1972. Its gross storage capacity was 370 MCM in 1972.

## 1.4 THE STUDY PROPOSAL

For any inter basin water transfer project, the assessment of the water resources of the concerned basins are necessary to know the status of a basin as water surplus or water deficit in comparison to the basin's future water demands. The study proposes to asses the water resources potential of the concerned basins and to develop a methodology for planning and management of various aspects of water resources system related to inter basin water transfer. Linear programming, dynamic programming and simulation models are proposed to be used. It is proposed to develop a screening model to screen various possible interlinking alternatives. When water demands at a reservoir are known, in case of shortage it is necessary to find out that, how much additional water is required to meet the water demands completely at different time periods. This additional water may be considered as an import requirement at that reservoir. But knowing only the import water requirement is not sufficient. The candidate reservoir/reservoirs that would supply this import water requirement (export) may not be capable of doing so after meeting their own water demands. This study proposes to develop a methodology to evaluate the import water requirement at a reservoir likely to face water shortage, the water exports that a reservoir can make after meeting its own water needs up to the maximum possible extent, and the effect of these imports and exports on the system as a whole in terms of meeting various water demands with different reliabilities.

### 1.4.1 Objectives of the Study

The objectives of the present study are stated as under:

(1) To assess the water resources potential of the Upper Chambal, Lower Chambal, Kalisindh, and Parbati river basins, and of the catchment areas up to the proposed dam sites, in comparison to meeting their respective future water demands.

(2) To present a system analysis based methodology for inter basin water transfers, such as

I. To select/develop and adopt a more generalized preliminary screening optimization model and its solution strategy suitable for adequately representing system characteristics and estimating response of any reservoir system under consideration as follows:

   a) to allow water import to any reservoir and export from any reservoir in the system,

   b) to incorporate reliability criterion in reservoir yields for different water uses,

   c) to identify the maximum possible fraction of an annual reservoir yield that can be made available during failure years with target release reliability, and

   d) to find the trade-offs between different reservoir yields.

II. To apply optimization models and develop methodology to further analyze and refine the results of the screening model, and to find

   a) import of water required by each water importing reservoir in the system,

b) annual and monthly design demands including water exports by each reservoir in the system, and

c) annual reservoir yields corresponding to different reliabilities.

III. To apply simulation to test the results of optimization models.

(3) To study the proposed Parbati-Kalisindh-Chambal water transfer links by applying the above techniques and methodology.

### 1.4.2 The Approach and Methodology

Water resources planning and management is broadly concerned with the accurate assessment, identification and development of different water resources systems. The careful planning for allocation of water resources to different developmental activities has become extremely important to meet the ever-increasing demand of water supply, hydropower, and irrigation etc. It emphasizes the need for planning and development of river basin water resources, which is a complex and difficult task, and creates numerous social, economical, environmental and engineering problems. Most of these difficulties are due to variable inflows and large number of possible alternatives. Optimal planning of a large-scale river basin as a unit of water resources system is having a high priority in the economic development of a region. This has resulted in an urgent need for accurate and efficient management of the water resources for its conservation and use. System engineering provides methodologies for studying and analyzing various aspects of a system and its response to various parameters by using optimization and simulation techniques. Often these aspects are very complex with different objectives, scopes, scales and timing considerations. In such cases there is usually no unique model for the solution of the problems. A set of linked models may be nested in these cases in such a fashion that outputs of one model are inputs to another or two models are run in tandem. The answer to how the model links should be arranged is problem specific, but such use of nested models may be often quite useful.

The following sections discuss the approach and methodology for assessment of the water resources and the use of linear and dynamic optimization and simulation techniques as nested models to solve the inter basin water transfer planning and operation problem.

#### 1.4.2.1 Water balance study (WBS)

In India, as per the National Water Development Agency (NWDA) guidelines, water can be transferred from a river basin to another, only when the exporting basin is surplus in its surface water resources at 75% water year dependability. An assessment of the annual water balance of each concerned river basin is carried out for determining whether a river basin is surplus or deficit in its water resources (surface and ground waters) in comparison to basin's annual water demands. Here, the water balance meant a comparison between annual water availability and annual water demands of a river basin, and differs from the conventional meaning of water balance. The water balance study is data intensive. The Chambal basin is declared as "classified", by the Ministry of Water Resources, Govt. of India. Even after sincere efforts, the monthly flow data at all the concerned gauge sites for a long duration could not be collected. The observed flows at all the gauge sites for the available years data are almost negligible during non-monsoon period. Naturally a water balance study on monthly basis will show water deficiency in the concerned basins during non-monsoon months. As water transfer will take place through reservoirs only, and reservoirs have the capability to conserve water for non-monsoon months, the water balance is done on yearly basis in this study. In water balance study, annual water demands are estimated for different purposes like municipal, irrigation, industrial, hydropower and salinity for the projection year of 2050 (with the expectation that population would hopefully be stabilized by that time) and then compared with the 75% and 50% water year dependable flows. The annual availability of water consists of two parts, viz., surface water and ground water. If surplus water exists at a site with surface water at 75% water year dependability after meeting all the demands, then the excess amount can be exported.

For carrying out water balance study, the guidelines framed by the NWDA are followed. Since the main objective of this study is to offer a methodology for inter basin water transfers using the system analysis techniques, the guidelines framed by the NWDA are almost as such adopted.

#### 1.4.2.2 Preliminary screening optimization model

For design of any system, an initial guess regarding the size of the system's design variables is required. These estimates can be obtained through the application of simple linear programming models. Yield model serves as an efficient preliminary screening model for reasonable reservoir designs with release reliabilities near targets. A reservoir yield model for multireservoir multiyield using linear programming, available in literature is further extended and improved and termed as *improved general-purpose yield model* (IGPYM). The IGPYM considers: (i) more than two numbers of water uses, both compatible and incompatible, (ii) different reliabilities for each water use, (iii) allows water imports and exports and (iv) redistribution of upstream regenerated flows in within the year periods. In order to have more flexibility in model application, two new terms, i.e., the priority yield and second yield are introduced in this work by replacing previously defined firm yield and secondary yield, respectively. The firm yield is that yield, which the reservoir will always be able to provide and that larger yields are not firm in the sense that they cannot be always met. In probabilistic terms, the firm yield has the maximum possible reliability, i.e., no failure years, and is given by, n/(n+1), in an n year record by using the Weibull plotting position formula. All yields in addition to the firm yield having reliability less than the firm yields are secondary yields. The new yields termed as the priority and second are the yields which have no restrictions on release reliabilities in the possible range of annual reliabilities given by 1/(n+1) to n/(n+1). Here, the planner can prefix or obtain from model results, the reliabilities of both these yields. Either of the two yields or both may be used partially or fully for a single purpose or multi purpose water use. The objective function may be to maximize annual yields, or return from the yields, or to minimize reservoir capacity.

#### 1.4.2.3 Dynamic programming (DP) optimization model

The results of the yield model are approximate and require refinement. Dynamic programming models are known to be efficient in resource allocation type of problem and in this work it is decided to adopt DP models to find import water requirements, fixation of design water demands and for reservoir operation for all the reservoirs in the system.

To consider water transfer in a system of reservoirs (sites), it is important to look into two aspects (a) excess water availability at a source (export) point and (b) annual water demands at both source (export) and destination (import) points. To cover both the aspects, initially it is assumed that at each reservoir all the known annual target water demands have to be met completely. In case the available water at a reservoir is not sufficient to meet all its demands, it is required to formulate a DP model (termed as PPM) to calculate the import of water required at the site. The objective at the importing reservoir is to minimize penalties (cost) assigned to water import, increase in the resulting reservoir end storage and reservoir spill. Water import penalty values are so selected that they encourage water transfer when excess water is available at the source point (water exporting reservoir) and discourage otherwise. The penalty for increase in the reservoir end storage and reservoir spill are so selected that an importing reservoir is ready to accommodate in its storage high flows during monsoon periods and conserve water for non-monsoon periods. The PPM assumes that unlimited water is available at the upper most exporting reservoir (starting point of the water transfer link) and hence all the annual water demands can be met. This assumption is not practical, but the model is successful in giving the annual target water export demands for all the water exporting reservoirs.

At this stage all the annual target water and energy demands are known for all the reservoirs in the system. Another DP model (termed as CIM) is formulated to fix the annual design demands for all the water needs that can be met with prescribed reliabilities. Like the PPM, the objective for all the water importing, exporting and reservoirs non-participant in the transfer links, is to minimize the penalties (cost) assigned to increase in the resulting reservoir end storage, reservoir spill and for not meeting the target demands. The penalty for storage and spill are selected similar to the PPM. The penalty for not meeting the water demands are so selected that priority water demands are met first. If the annual target water demands cannot be met, the model revises these target water demands and gives annual design water demands that can be met with prespecified reliabilities for each water use.

### 1.4.2.4 Reservoir operation and simulation

The CIM also does reservoir operation, where monthly design demands obtained in planning stage are fed as input to the model. The model determines the portion of the design demands for each water use that can be fully met in each time period. These model releases for each water use in each time period are considered as reservoir releases for the corresponding water use in that time period. If there is any spill in a period, and if the link canal capacity allows to transfer a part or total volume of this spill along with the water export release, then this additional volume is considered as an additional water export, and is added as an import to the importing reservoir to maximize the utilization of water. Annual yields for all the water uses are obtained for different reliabilities. A simulation model is used to test the results of the DP model.

## 1.5 OUTCOMES OF THE STUDY

The optimization and simulation models developed in this study are applied to the five reservoirs system in the Chambal Basin in India, to study the Parbati-Kalisindh-Chambal water transfer proposal involving two alternative links. Three proposed reservoirs, namely, Patanpur (PAT) in Parbati river, Mohanpura (MOH) in Newaz river and Kundaliya (KUN) in Kalisindh river are proposed to transfer surplus waters of Parbati and Kalisindh basins either to GS reservoir in Upper Chambal basin (Link-I) or to RPS reservoir in Lower Chambal basin (Link-II) after supplying their respective water demands for domestic and irrigation purposes. The Newaz river is a tributary of Kalisindh river. This study presents a methodology for planning of inter basin water transfers, based on system analysis techniques.

Assessments of the water resources on an annual basis of the concerned basins are carried out in comparison to the basin's future (2050 AD) water demands, following the method of water balance framed by National Water Development Agency (NWDA). These assessments indicate severe water deficit situation in the Upper Chambal basin. The Lower Chambal basin is marginally surplus in its water resources due to the committed amount of import water it is receiving from the Upper Chambal basin and would have been deficit in its surface water resources in the absence of import water it is receiving from Upper Chambal basin. Therefore, water transfer options from Kalisindh and Parbati basins need to be considered in order to reduce the imbalance caused due to the inequitable distribution of water resources in comparison to water demands either to Upper Chambal basin or to Lower Chambal basin. If the water transfer can be made to Lower Chambal basin, then the export load from Upper Chambal to Lower Chambal basin can be reduced.

This study extends the yield model as available in the present form and presents *an improved general-purpose yield model* (IGPYM) applicable to a multiple reservoir system consisting of single purpose and multipurpose reservoirs. The model is capable of considering more than two numbers of water uses by introducing priority and second yields, different annual reliabilities of release for each water use, allows deficit in annual yields during failure years, and redistribution of upstream regenerated flows in within the year periods. The model can be applied to both compatible and incompatible water purposes, and considers each purpose independently or in-group, depending on the total number of purposes to be considered in a reservoir. It is found that the model offers better flexibility in selecting reliabilities of water uses and deciding optimal yield failure fractions during failure years for different water uses. That is, at a given reservoir, if the desired reliabilities of both the priority and second yields are less than the maximum possible reliability given by n/(n+1), with or without complete yield failure for any yield (priority or second) during failure years, the system is capable of supplying the same annual yields with desired reliabilities from reduced reservoir capacity, or higher annual yields with the given reservoir capacity. The model can act as a better screening tool in planning by providing outputs that can be very useful in improving the efficiency and accuracy of models such as dynamic programming and detailed simulation.

In this study two dynamic programming models, namely, *procurement problem model* (PPM) and *controlled input model* (CIM) are formulated. The PPM calculates amount of import water requirement at a reservoir to meet its water demands. The CIM estimates water demands that a reservoir can meet with specified reliabilities, and also amount of water it can export to other sites. The objective of the work is to present a realistic and efficient dynamic programming modeling approach for reservoir planning and operation, related to a multipurpose, multi site reservoir system. The combined application of PPM and CIM can be very useful for planning inter basin water transfer projects. The PPM can be applied for reservoir planning only, whereas CIM is useful to both reservoir planning and operation. The

CIM has the potential of simulation where releases from reservoir for different purposes are done optimally.

Reservoir operation results determine the annual yield achieved for each water use corresponding to different reliabilities at each reservoir in the system for all the cases. Testing of the reservoir operation results are done by simulation.

The developed models and their applications present a systems analysis application methodology for planning and operation of multipurpose multireservoirs, involved in inter basin water transfers. The results show that the transfer links connecting reservoirs Patanpur, Mohanpura, Kundaliya and Gandhi Sagar in sequence is more promising with respect to meeting the water demands. The proposed capacity of Kundaliya reservoir is high and can be reduced substantially at the cost of marginal increase in the proposed capacities at Patanpur and Mohanpura reservoirs.

## 1.6 CHAPTER WISE SCHEME OF THE THESIS REPORT

The Chapter wise scheme devised to report the research work is given below:

### Chapter 2

A review of the literature pertaining to this study, such as inter basin transfers of water in India, system analysis techniques, single and multireservoir operation models using deterministic and stochastic linear programming, dynamic programming, yield models, simulation, other miscellaneous approaches and mixed models, is presented in this chapter. Literature review is carried out by referring to the prestigious national and international journals, textbooks, thesis reports and conference proceedings. A brief description of the reported research work of different researchers is presented in chronological order as far as possible.

### Chapter 3

This chapter presents a description of the Chambal basin, the river system, the configuration and basic information of reservoirs system and the water transfer proposal in the context of the present study.

### Chapter 4

This chapter provides an assessment of the available water resources on an annual basis in comparison to future water demands in the concerned basins with the help of water balance studies. Status of the each basin as 'water surplus' or 'water deficit' is obtained.

### Chapter 5

This chapter describes the basic concepts of the yield model, its development and extension to multireservoir systems, the need to improve the available form of the model for general purpose application with better flexibility and the improved general purpose yield model (IGPYM) developed in this work. Comparison of the IGPYM with the earlier available yield models is done to show its advantages over them.

### Chapter 6

This chapter deals with the formulation and development of the dynamic programming based optimization models, namely, the procurement problem model (PPM) and the controlled input model (CIM). The purpose of the models, their working principles and the data requirements are discussed.

### Chapter 7

A simulation model, which allows water transfer between reservoirs and to be used for evaluating the anticipated performances of the system for the set of design and operating policy parameter values obtained through the application of the optimization models is described in this chapter.

### Chapter 8

The applications of the developed models for reservoir planning are presented in this chapter. The methodology and the sequences of steps to be followed are discussed. Different cases are formulated for the applications of the IGPYM, PPM and CIM.

### Chapter 9

This chapter discusses the reservoir operations using the CIM. The consequences in terms of meeting water demands for different water needs at different reliabilities are evaluated for each case. The simulation model described in Chapter 7 is used to evaluate the anticipated performances of the system.

### Chapter 10

The analysis of results and conclusions of this study are reported in this chapter. The presentation in this chapter begins with an overview of this study and a summary of the accomplished work. The subsequent sections discuss the findings of study and inferences drawn from the analysis of results. Finally the conclusions of this study with reference to the modeling approach employed and its application to the Chambal river basin system are reported. Some suggestions are made at the end of this chapter to outline the scope for further related studies.

*Chapter 2*

# LITERATURE REVIEW

## 2.1 INTRODUCTION

Fresh water is scarce and getting scarcer. The constantly increasing water demands for various basic and developmental purposes have forced engineers and planners to contemplate and propose more comprehensive, complex and ambitious plans for water resources systems. Applications of the systems approach and use of system analysis techniques and models to real life systems have improved our understanding of such systems, and contributed to improve the system design, management and operation. Loucks (1992) discussed the role of water resources system models in planning. The major challenges faced by the water resources system planners and managers, the information they need to meet these challenges and the role analysts have in helping to provide this information, have been discussed.

Water transfers are a common component of many regional water systems and are being increasingly considered for meeting growing water demands and for managing the impacts of drought. Water transfer can take many forms and can serve a number of different purposes in the planning and operation of water resource systems. However, to be successful, water transfers must be carefully integrated with traditional water supply augmentation and demand management measures. This integration requires increased cooperation among different water use sectors and resolution of numerous technical and institutional issues, including impacts to third parties. Lund and Israel (2003) identifies the many forms that water transfers can take, some of the benefits they can generate, and the difficulties and constraints, which must be overcome in their implementation.

Inter basin transfer of water resources is not a new concept. Quite a number of such projects have been implemented in the USA, Canada, Mexico, Sri Lanka, China and Russia.

In India, the Western Yamuna Canal and the Agra Canal built in Mughal times are good examples of inter basin water transfer. The Kurnool Cudappa canal (1860-70) and Periyar Vaigai (1896) are also important examples of this concept. During the last century, and the present, the Rajasthan Canal, the Parambikulam-Aliyar, the Telugu Ganga and the Sardar Sarovar Projects have either been completed or are nearing completion.

Suggestions for inter basin water transfer in India to create a balance between surplus and deficit basins have been made from time to time since long; but two proposals put forward in the seventies viz.: (1) Garland Canal by Captain Dinshaw J. Dastur (1977) and (2) National Water Grid by Dr. K. L. Rao (1979) gained considerable attention. Both these proposals had been examined by the Central Water Commission (CWC) and expert academicians and found to be not worthwhile to be pursued further due to economic non-viability and other reasons.

The Ministry of Water Resources (then known as Ministry of Irrigation) in the year 1980 formulated a National Perspective Plan for Water Resources development by transferring water from surplus basins to deficit basins/regions by inter-linking of rivers. The National Perspective Plan has two main components, i.e., the Himalayan Rivers Development and Peninsular Rivers Development. The National Water Development Agency (NWDA) was set up as a society under the societies Registration Act, 1860 in 1982 to carry out the detailed studies and detailed survey and investigations and to prepare feasibility reports of the links under the National Perspective Plan. NWDA has, after carrying out studies, identified 30 links for preparation of feasibility reports and has completed feasibility reports of 6 such links.

Recently the Supreme Court of India has directed the Government of India to inter-link all the major rivers in India for inter basin transfer of water. This entails construction of large river linking projects, which warrants sound investigation, careful planning and huge expenditure. A faulty implementation of these projects may be more harmful than doing nothing at all.

## 2.2 INTER BASIN WATER TRANSFER IN INDIA

The issue of inter basin water transfer through linking of rivers in India has received much discussion and debate. People are divided into two camps. The pro-linking camp says it will solve the drought and flood problem in India, not to speak of water shortages, the anti-linking camp is of the firm opinion that not only is such a grandiose plan totally untenable, it will mess up the delicate environmental balance to a level from which it will be difficult to recover. The evidence cited by both the camps is impressive with studies, reports, environmental impact assessments, which incidentally come out with diametrically opposite answers. Proponents of river linking point to the numerous potential benefits of the project-enhanced food production, reliable municipal and industrial water supply, flood control, reduction of drought, huge amounts of hydro electricity generation, and creation of long stretches of navigable waterways among the major benefits. Critics point to the fact that playing with nature on such a grand scale can only amount to suicidal folly.

Biswas (1983) stated that large-scale mass transfer of water has been a controversial topic during the last two decades. Instead of taking entrenched and dogmatic views on the topic, each case should be considered on its merits and decisions should be taken accordingly. Attempts should be made to identify and evaluate secondary and tertiary benefits and costs, which are often neglected. Furthermore, feasibility studies should not concentrate on engineering and economic factors only; social and environmental costs should also be considered. Even more important is the fundamental question of whether such costly alternatives are necessary and whether the extra water required cannot be obtained by improving the existing water management process.

Abu-Zeid (1983) discussed the major water transfer projects in Egypt with its impact on agriculture, environment, siltation in the lake, downstream degradation of the Aswan Dam, effects of loss of silt on agriculture, fisheries, public health, land reclamation, canal system, etc.

In Japan, Interregional Water Transfer (IWT) has been carried out since ancient times and has become increasingly important in recent years although the IWT projects that have been carried out so far or are now being considered are all relatively small in scale. Okamoto (1983) observed that, Japan being an island country, the water transfer distances are shorter and yearly volumes of water transferred are smaller than those of IWT projects in many other countries. However, it can be said with some confidence that the IWT projects in Japan, though smaller in scale, face similar problems-technological, socio-economic, institutional and environmental-that need to be solved, and are also similar in terms of complexity. It seems that the problem of direct technology transfer does not so much depend on the scale of a project itself but rather on the political system (democratic or centrally planned), the state of economic development, and existing natural conditions.

According to Greer (1983) the most important fundamental lesson of the Texas Water Plan is the need for balanced planning of the proposed transfer scheme. Planners must ask themselves if environmental systems are being studied with the same detail as are economic and engineering systems, if all relevant studies are well co-ordinated, and if balanced emphasis is being given to all aspects of potential development. Planning must be based on projected population, economic levels, and water needs at thirty, forty, or fifty years in the future for an undertaking of this magnitude. If such considerations are not taken into account, then the lessons that have been learned in the United States and elsewhere over the last decade will be needlessly repeated.

In China the south-to-north water transfer is a gigantic project involving a human transformation of the environment (Dakang 1983). It will have a tremendous impact not only on the natural environment but also on the social environment and the productive activities of society as well. Hence, extreme precaution is needed in the fields of water conservancy, agriculture, soil science, geology, biology, environmental protection, hydrology, geography and economics. Topics concerning the impact of south-to-north water transfer on the natural environment were: control of secondary salinization in irrigated areas; the effect of water transfer on climate in irrigated areas and surrounding districts; the effect of water transfer on hydrogeological conditions; and the effect of downstream water transfer on the estuary and seacoast of the Chang Jiang as well as on the environment of lake waters and on aquatic life ecology along the transfer route. Additional topics were the evaluation and evolution of water quality; the rational utilization of land after water transfer; and cropping patterns and prediction of benefits from increases in agricultural production.

In reference to China's long-distance water transfer proposals Nickum (1983) stated that there are considerable short-term benefits which would accrue to detailed socioeconomic institutional studies of water management deficiencies on the North China Plain, followed by the targeting of funds and manpower towards solving the technical, funding and motivational problems, especially, but not exclusively, at the secondary and tertiary system levels. In light of the implicitly high social rate of discount given in current national financial and investment policies, a marshalling of resources in these directions would likely yield far more benefit than a near-term commitment to a long-distance water transfer scheme. The nature of water rights and interprovincial relations must be considered as well in making plans for future water resource development. All of this work is an essential prerequisite to making a realistic assessment of the likely deleterious impact of the introduction of new water via a mass transfer and to drawing up the institutional reforms necessary to mitigate such harmful side-effects, most notably the spread of secondary salinization due to excess application and improper drainage.

Herrmann (1983) observed that so far as the environmental impacts of large interregional water transfer is considered, no intensive modelling with validation by actual data has been done. A helpful tool for the authorities when analysing regional environmental impact (impact caused by interregional water transfer) may be some sort of economic optimization technique. The components of the computational framework may include models of the cause-effect relationships between different hydraulic engineering measures and their environmental impacts, and models of the relationship between environmental goals and the minimum cost of accomplishing them as optimization models.

Rao and Vijay (1991) made a study of Godavari-Cauvery river link. Jain (1993) made a study of the proposed Kalisindh-Chambal river link (India) by simulation technique. The objective was to verify whether the target water demands for the proposed reservoirs can be met with target reliabilities, and to know how far the project targets can be planned by simulation studies.

Transaction cost has been a frequent topic in theoretical and practical discussions of water transfers. However, the risk or probability that a transfer effort will be unsuccessful should also have a significant effect on the decision by potential water purchasers to seek water transfers in lieu of seeking water by conventional means (source capacity expansion or water conservation). Lund (1993) examined the importance of the uncertainty of transfer completion is analytically under a decision theory framework and discussed some implications of uncertain transactions completion for water transfer policy. He commented that, seeking water transfers becomes more attractive to potential water purchasers if the probability of a successful transfer is increased, if more of the transfer costs for water transfers are increased after a transfer has been approved, and if the costs of delaying implementation of alternative water supplies are small.

The 1991 and 1992 California Drought Emergency Water Banks were the first large water transfer programs in the U.S.A. in which the state sponsored Water Banks have drawn widespread attention, there have been a great number of water transfers and exchanges taking place in California independently of the state. This non-state transfers illustrate well the widespread applicability of transfers in managing water resource systems, as well as the multiple mechanisms available for effecting water transfers. Israel and Lund (1995) focuses on California's recent experiences with water transfers, and offer a series of potential lessons for federal, state, and local managers for integrating water transfers in regional water resource systems.

Shao et al. (2003) presented a review of interbasin water transfer projects in China and recent developments in the feasibility study of the South-to-North water transfer project involving the Yangtze River and the Yellow River basins. In large countries with sharp temporal and spatial variation in water resources, interbasin water transfer projects seem to be an ultimate solution to ease water shortage and secure a balanced economic development among different regions. However, they observed that such projects are prone to problems and controversies, and may challenge the established basin management, legal system and policy making procedure which are taken for granted until such projects are put under consideration. The impacts of the project on the water law, policy-making procedures, existing basin management method, as well as on the natural environment are also discussed.

India's scheme of interlinking its rivers for transferring water from 'water surplus' to 'water deficit' basins is fraught with substantive and serious impacts and implications. In order to appraise them appropriately, it is necessary to understand various aspects of interlinking such as its concept, technology and economics. Also, as there is major commonality of technology components such as dams and barrages for both interlinking of rivers and basin-wise water resources development for multipurpose benefits, it will be necessary to distinguish between the two. It is rational to consider the former as an additionality to the latter, so that impacts and implications of interlinking are correctly appraised (Prasad, 2003).

The methodology currently adopted for planning inter basin water transfer in India requires introduction of appropriate improvements for more realistic appraisal of the pertinent issues. Sharma and Sarma (2003) presented a critical study on basic approach to inter basin water transfer in India with special reference to the Brahmaputra basin. They discussed the technical, social and legal issues and point out some studies, application of modeling technique and engineering tools for in-depth scientific analysis as a precursor to water transfer.

While issues related to water attract considerable attention in India, very little quantitative information is available on water budget. There are two reasons for this lacuna; the dearth of information on hydrological variables, and the absence of an easily accessible quantitative framework to put these variables in perspective. Shankar et al. (2003) assembled a framework to address both issues. At its core is a hydrological routing model; the basic data needed for implementing the framework are a digital elevation model and data on precipitation and evapotranspiration. They demonstrated the viability of the framework by applying it to the hydrology of the Mandovi river in Goa. The model output mimics the observed discharge well.

Verma (2003) commented that before linking of rivers, there is a need to develop and manage land and water resources on watershed basis strictly following watershed development and management principles, in river basins. Development of watersheds in river basins before linking rivers will control floods, flow of silt and damage of lands and increase irrigated area, efficiency and life of the irrigation projects.

Ganguly (2003) discussed different issues related to inter basin water transfer. The issues include: (i) rehabilitation of the project affected persons; (ii) sedimentation of reservoirs; (iii) water logging of agricultural land; (iv) submergence of mineral deposits and archaeological monuments/shrines; (v) aquatic life; (vi) submergence of rare species of flora and fauna; (vii) health impact; (viii) water quality; (ix) impact on climate; (x) reservoir induced seismicity; (xi) environmental impact during construction; (xii) obstruction to cross-country drainage due to excavation of large link channels across the general slope of the country; (xiii) eutrophication (high biological productivity resulting from increased input of nutrients or organic matter into aquatic systems) in reservoirs; (xiv) change in ground water table; (xv) impact on society and wild life due to introduction of canals cutting across social communication as well as wild life movement paths; (xvi) impact due to lower flows in existing rivers and channels on river regime, water quality and ecology; (xvii) pricing of water; (xviii) constitutional provisions; and (xix) terrain capability.

Rao (2003) discussed some of the issues related to inter basin water transfer, viz., political response, gigantism, performance of irrigation projects, river basin as unit for planning and management and political consensus; and suggests principles, strategy and the agenda for the Task Force, responsible for investigating and implementing the river linking projects.

Sarma and Srivastava (2003) presented a system analysis modeling approach for planning and operation of reservoirs, involved in inter basin water transfer projects and demonstrated the approach by applying it to the Parbati-Kalisindh-Chambal water transfer link involving five-reservoirs, proposed by National Water Development Agency (NWDA), India.

Singh and Gosain (2003) presented a study on the problems of transboundary watercourses. The study is divided into three sections. The first section surveys the basic philosophies behind the international water sharing laws and work done by the prominent international organizations in this arena. This is supplemented by a critical analysis of the Helsinki Convention (1992) and the UN Convention (1997). The second section provides an insight into the provisions of the Indian Constitution pertaining to the interstate river water disputes followed by a detailed analysis of the relevant Parliamentary legislations and the follow up measures including the enactment of Interstate Water Disputes Act, 1956 and the River Boards Act, 1956. The final section suggests ways and means to help resolve the conflicts pertaining to interstate rivers in India, which is consistent with the Indian Constitutional provisions as well as the philosophy and spirit of the international water sharing laws.

Due to huge volumes of water transfer involved, the inter basin water transfer projects planned in India will require large financial and other resources and will be among the biggest water resources development schemes ever undertaken in the world. In view of high stakes involved, it is important that a risk analysis of this scheme is carried out to identify the weak spots. Jain and Singh (2003) presented a preliminary qualitative risk analysis of the peninsular component of inter basin water transfer proposal. The analysis include: risk of insufficient water, risk due to natural hazards, environmental impacts of the proposed projects, risk due to law and order, risk due to social and political reasons and other issues.

Chander (2003) gave a framework for evaluating inter basin water transfer projects and suggested five criteria. He identified the database required for each of these criteria and suggested that the data be used in a simulation model to determine the impact of transfer for various hydrologic regimes. An interdisciplinary panel can then use these results to develop consensus regarding the size and route of the transfer.

Bhavanishankar and Raman (2003) gave an alternative proposal that should derive the same benefit as proposed linking of rivers in India, with least disturbance to ecology and environment.

Other notable literatures in the field of inter-basin water transfers are Yevjevich (2001), Feldman (2001), and Knapp et al. (2003).

## 2.3 WATER RESOURCES SYSTEM ANALYSIS LITERATURE

System analysis techniques have been used successfully in the management and operation of complex reservoir systems. The complexities of a multipurpose multiple reservoir system generally require release decisions to be made by an optimization or simulation model. The choice of methods depends on the characteristics of the system being considered, on the availability of data, and on the objectives and constraints specified. Most of the optimization models are based on some type of mathematical programming technique. In general, the available methods can be classified as follows (Yeh, 2003): linear programming; network flow; quadratic programming; dynamic programming; nonlinear programming; mixed integer linear programming; interior point method; and simulation. During the past decade, major advances in the development of software tools (solvers) are witnessed for solving large-scale linear and nonlinear optimization problems. Most of the solvers are available commercially and are user friendly. Accompanied by the drastic increase in computational power it is now possible to solve large-scale optimization problems on a desktop PC within reasonable execution time. Table 2.1 shows the web sites of the 10 popular solvers.

Developments in the area of application of numerical methods have started since late forties. Dantzig did the break through by developing the simplex method for solving the linear programming in 1947. Works done by Kuhn and Tucker in 1951 on the necessary and sufficient conditions for optimal solution of nonlinear problems, and enunciation of principle of optimality by Bellman for solving the dynamic programming in 1957 are the landmarks in the field of systems analysis. Numerous techniques for application of systems analysis in the field of water resources planning and management have been reported since the early work reported by Dorfman (1962). Hence, the literature available in this area is voluminous.

**Table 2.1** Commercially available solvers

| Solver | Web Site | Type of problems |
|---|---|---|
| CONOPT | www.conopt.com | NLP |
| CPLEX | www.ilog.com/products/cplex | LP, MILP |
| DICOPT | egon.cheme.cmu.edu/Group/ResearchAreas.html | MINLP |
| GRG2 | www.solver.com | LP, NLP |
| LINGO | www.lindo.com | LP, MILP, NLP, MINLP |
| MINOS | www.sbsi-sol-optimize.com | LP, NLP |
| OSL | www-3.ibm.com/software/data/bi/osl | LP, MILP |
| PCx | www.softwareshop.anl.gov/pcx.html | LP |
| SNOPT | www.sbsi-sol-optimize.com | LP, NLP |
| XPRESS | www.dashoptimization.com | LP, MILP |

Note: LP- linear programming; MILP- mixed integer linear programming; NLP- nonlinear programming; MINLP- mixed integer nonlinear programming.

Reviews of the systems analysis techniques and their applications have been presented and published. Loucks and Falkson (1970) reviewed and compared three techniques, namely, DP, policy iteration and LP for the stochastic reservoir operation model incorporating first-order Markov chains. Stedinger et al. (1983) reviewed and compared LP based deterministic, implicitly stochastic and explicitly stochastic reservoir screening models. Yakowitz (1982) presented a review of application of dynamic programming to water resources systems. Stedinger (1984) compared the capacities and operating policies resulting from the original LDR model, LDR-based model of Loucks (1970), and simulation using the standard operation policies (SOP) and the minimum failure frequency policy. Loucks et al. (1985) reviewed some important short comings of management and policy models and argue for improved human-computer model interaction and communication, which can lead to more effective model use, which in turn should facilitate the exploration, analysis and synthesis of alternative designs, plans and policies by those directly involved in the planning, management, or policy making process. Yeh (1985) has provided a comprehensive state-of-the art review of theories and applications of systems analysis techniques of the reservoir problems. A set of conclusion and recommendations was also provided. Simonovic (1992) has provided a short review of reservoir management and operation models. Wurbs (1993) presented a comparison of models from a general overview perspective. Dandy et al. (1997) presented a review and comparison of simulation, network linear programming, full optimization LP model and the LP yield model for estimating the safe yield of the Canberra water supply system consisting of four reservoirs. Yeh (2003) reviewed the algorithms developed for optimizing the operations of water resources systems. The algorithms reviewed include linear programming, network flow, quadratic programming, dynamic programming, nonlinear programming, mixed integer linear programming, interior point method, and simulation. Labadie (2004) assess the state-of-the-art in optimization of reservoir system management and operations and consider future directions for additional research and application. Optimization methods designed to prevail over the high-dimensional, dynamic, nonlinear, and stochastic characteristics of reservoir systems are scrutinized, as well as extensions into multiobjective optimization. Application of heuristic programming methods using evolutionary and genetic algorithms are described, along with application of neural networks and fuzzy rule-based systems for inferring reservoir system operating rules. A more detailed account of the methodologies and techniques is available in comprehensive texts and edited volumes (Maass et al., 1962; Hufschmidt and Fiering, 1966; Hall and Dracup, 1970; Ladson, 1970; James and Lee, 1971; Haimes, 1977; Major, 1977; Cohon, 1978; Major and Lenton, 1979; Loucks et al., 1981; Goodman, 1984; Helweg, 1985; Chaturvedi and Rogers, 1985; Jewell, 1986; Chaturvedi, 1987; Labadie and Fontane, 1989; Karamouz, 1990; Datta, 1993; Hiller and Lieberman, 1995; Wurbs, 1996; Biswas 1997; and ReVelle, 1999).

Application of the techniques to real life problems related to rivers in India is reported in doctoral works carried out in India, e.g., Srivastava, 1976; Ranvir Singh, 1981; Bhatia, 1984; Kohistani, 1995; Sadeghian, 1995; Sunita Devi, 1997; Mishra, 1998; Waikar, 1998; Talukdar, 1999; Kothari, 1999; Dahe, 2001; Chaudhury, 2003; Jena, 2004; Deepti Rani, 2004; Patil, 2004; and Awchi, 2004.

### 2.3.1 Linear Programming Applications

Although there is a difficulty in formulating LP models due to non-linear functions of reservoir problems, still LP has been one of the most widely used techniques for solving these problems. The essential advantages of LP include the following (Mujumdar and Narulkar, 1993; Yeh, 1985; Yeh, 2003): it can accommodate relatively high dimensionality with comparative ease; universal optima are obtained; no initial policy is needed; and standard computer codes are readily available. LP models also include chance-constrained LP, stochastic LP, and stochastic programming with recourse. LP has been used extensively to optimize reservoir management and operation. For a nonlinear objective function, a Taylor series expansion can be used to perform linearization, and solutions are obtained by iteration.

Dorfman (1962) initiated the application of LP technique in reservoir system planning problems. The early work on stochastic LP model reported in literature was by Manne (1962). He evaluated the value of flood control storage for hydroelectric and water supply purposes taking inflows as random variable and assuming it to be a Markov process. Thomas and Watermeyer (1962) extended Manne's work applying the same technique for solving stochastic reservoir operation problem. Loucks (1968) developed a stochastic LP model for a single reservoir. A first-order Markov chain described the net flows for each time period and transition probabilities of inflows were estimated from historical inflows. The stochastic model was applied to Fibger lakes within the Osevego river basin. He pointed out the dimensionality problem associated with this type of model in real situations, which can easily exceed several thousands of constraints.

ReVelle et al. (1969) initiated the application of chance-constrained LP to reservoir system optimization. He proposed the linear decision rules (LDR) that relate releases to storage and decision parameters. ReVelle and Kirby (1970) modified the original LDR to include evaporation losses using linearized storage-area curves and projected storage. They also used the objective of minimizing the probability of violating the minimum flow constraint. Loucks (1970) pointed out that the reservoir operation rules discussed by Young (1967) were fundamentally different than the original LDR. He proposed the 'linear release rule' relating the release to storage, inflow, and decision parameter, which resulted in less conservative results compared to the original LDR. Jores et al. (1971) applied the original LDR, chance-constrained LP, synthetic streamflow generation and simulation in modeling the multiple source water supply system for Baltimore. The objective was to minimize the pumping costs of the backup supply. Nayak and Arora (1971) applied a modification of the original LDR, which replaced the usual initial storage with a net initial storage consisting of initial storage plus upstream reservoir releases scheduled for that period, to a multireservoir system of four reservoirs. Eisel (1972) developed a chance-constrained model based on LDR originally proposed by Bryant (1961). The resulting nonlinear separable convex programming problem was solved by the piece-wise linear approximation method of separable programming. Lot of works were reported based on LDR during seventies and early eighties, e.g., Eastman and ReVelle (1973); Lane (1973); Curry et al. (1973); Loucks and Dorfman (1975); ReVelle and Gundelach (1975); Gundelach and ReVelle (1975); Houck (1979); Jores et al. (1981); and Houck and Datta (1981). Stedinger (1984) compared the capacities and operating policies resulting from the original LDR model, Loucks (1970) LDR-based model, and simulation using the standard operation policies (SOP) and the minimum failure frequency policy. He found that the original LDR performed poorly when estimated capacities were compared to what was actually required during simulation. The capacities required by Loucks' LDR model were found to be more reasonable and roughly equal to those required with SOP. Similar results were obtained when operating policy performance was compared.

Cohon and Marks (1973) presented a case study of a river system in which development is to be planned according to national and regional objectives. A linear screening model for finding the best set of development alternatives was introduced and a brief discussion on methods for handling more than one objective in such models was presented. Benefit transformation curves were derived from a multiple objective linear programming model by Thampapillai and Siden (1979). These transformation curves were used to assess the relationship between objectives. The model consists of a weighted objective function, which can be parametized. Procedures were suggested to narrow the search for an efficient management strategy on the transformation curve. However, the validity of the transformation curve depends on how non commensurables are valued and so different methods of valuation were presented and used.

Hogan et al. (1981) discussed some important conceptual problems concerning the application of chance-constrained programming (CCP) to risky practical decision problems by comparing CCP to stochastic programming with recourse (SPR). Datta and Houck (1984) developed a real-time reservoir operation model based on a chance-constraint formulation assuming a particular form of linear decision rule. Simulation of actual operation using this model for a reservoir was carried out to demonstrate the feasibility and efficiency of this approach. Changchit and Terrell (1989) presented an application of chance-constrained goal programming methodology to a system of multipurpose reservoirs, and demonstrated the methodology by applying it to a three-reservoir system in Oklahoma. The model uses a time period of month. Afshar et al. (1991) presented a mixed integer linear optimization model for river basin development for irrigated agriculture in the planning and design phases. The model is a chance-constrained optimization model that considers the interaction between the capacities of the storage and delivery system and the land and crop allocation. The model is capable of integrating all decision variables in the design phase, thus accounting directly for any interdependency between the design variables. The model was applied to an existing reservoir on the Zayandeh Road river in Iran. Solution of the model provides the optimum extent of the land development for irrigation, cropping pattern, reservoir and canal capacities, as well as the necessary linear decision rule parameters.

Chaturvedi and Srivastava (1981) presented a sequential iterative modeling process where deterministic LP models and simulation are combined together to obtain alternative optimal planning, considering six major reservoirs for the Narmada river basin in India. Two types of LP models were used. Simulation model continued screening on the basis of information obtained from LP models to find a near optimal solutions. Deterministic linear programming models, viz., linear programming deterministic continuous (LPDC) and linear programming deterministic discontinuous (LPDD), were employed for screening, followed by simulation to decide the alternative combinations and capacities of these six major projects. The LPDC model regulated the mean monthly flows where as the LPDD model used wet and dry years in order to deviate from regulating mean monthly flows.

Yazicigil et al. (1983) developed and tested a linear based optimization model, which is easily modifiable, flexible and which allows sensitivity analysis and experimentation with new operating guidelines to be used by reservoir system operators to improve daily, real time operations and to evolve better long term operating guidelines. The four multipurpose reservoirs in the Green Valley Basin were used as case study. Tao and Lennox (1991) formulated a reservoir system operation problem by successive linear programming and applied it to the operation of the High Aswan Dam (HAD) in the Nile river basin. Afzal et al. (1992) developed a linear programming model to optimize the use of different quality water by alternative irrigation. The model described a method of allocating land and water to different crops wherever low rainfall, limited quantity, and different quality waters are the basic parameters governing the irrigation system. Mohan and Raipure (1992) developed a linear multi-objective programming model and used the constraint technique to derive the optimal releases for various purposes from a system of five reservoirs in India. Trade-off analysis between conflicting objectives of irrigation and hydropower was carried out. Crawley and Dandy (1993) used the linear programming technique for identification of optimum monthly operation policies for the Adelaide headwork's system in Australia. They developed model with the objective function to minimize the pumping costs while ensuring system reliability by maintaining minimum target levels in the reservoirs. Mohan et al. (1998) presented a linear programming model for irrigation planning under stochastic inflows with reference to a tank irrigation system in South India. The model has been developed to determine optimal cropping pattern under different levels of dependable inflows. Suitable statistical distributions have been fitted for inflows into the reservoir for each month. This model maximizes net benefits and derives both optimal storages and releases for various inflow scenarios. The different rule curves derived from the model can be used for operation during normal water availability, water shortages and during the excess flow conditions.

The general formulation of integer linear programming (ILP) is identical to the LP formulation with the exception that decision variables are integers. If only some of the decision variables are required to be integers and the others can be any real numbers, the formulation becomes mixed integer linear programming (MILP). Major and Lenton (1979) demonstrated the application of a system of three models in an integrated way for the planning of Rio Colorado basin in Argentina. A mixed integer linear programming screening model, for finding the most promising configurations, a simulation model to evaluate the hydrologic reliability of these configurations, and a sequencing model to schedule the configuration of projects in four time periods are presented. Helm et al. (1984) presented a procedure for the analysis of time phasing of reservoir system development based on the multiple reservoir stochastic model of Curry et al. (1973). The objective of the mixed integer continuous LP formulation was to select the reservoir sizing, timing, and to establish operating policies such that the total cost associated with the system of linked reservoirs is minimized. Due to the resulting problem size and its general structure, Bender's decomposition was applied and the procedure is illustrated using a numerical example for three interconnected reservoirs. Malek-Mohammadi (1998) presented an integrated optimization model for planning irrigation systems considering surface reservoir capacity, ground water and spring withdrawal, delivery system capacities, land to be developed for irrigation, and cropping pattern. The system is optimized by means of a chance-constrained optimization model using mixed integer LP to maximize the net benefit associated with the development. The linear release rule proposed by Loucks (1970) was employed to determine the reservoir capacity. Srinivasan et al. (1999) presented a mixed-integer linear programming model for reservoir performance optimization. They improved the mixed-integer formulation of Moy et al. (1986) for a more complete representation of the resiliency criteria. The improvement achieved with the modified model is demonstrated using the same example as presented with the original model. Tu et al. (2003) develops a mixed integer linear programming (MILP) model that considers simultaneously both the traditional reservoir rule curves and the hedging rules to manage and operate a multipurpose, multireservoir system. During normal periods of operation, when inflows are plentiful, this optimization model efficiently distributes the available stored water from different reservoirs to meet the planned demands imposed by competing users. However, during periods of drought, or when anticipating a drought, the planned demands cannot be fully met, and a water shortage occurs. By considering the hedging rules along with the rule curves, guidelines are provided for reservoir releases. To minimize the impact of drought, the hedging rules effectively reduce the ongoing water supply to balance with the target storage requirement. The MILP model is applied to a multireservoir system in the southern region of Taiwan, where the results obtained demonstrate the applicability and utility of the model.

### 2.3.2 Reservoir Yield Model

Loucks et al. (1981) developed the yield model which is a implicitly stochastic LP model that incorporates several approximations to reduce the size of the constraint set needed to describe reservoir system operation and to capture the desired reliability target releases. A basic problem with the implicitly stochastic models is that many periods may need to be included in a model if an adequate distribution of unregulated natural stream flows is to result. This can be avoided in part by designing for the 'critical period' of record (Hall et al. 1969). Loucks et al. (1981) demonstrated that in several cases the yield model provides a reasonable estimate of the distribution of reservoir capacity requirements obtained with the sequent peak algorithm.

Palmer et al. (1982) developed simulation and LP models to determine the yield of the Potomac and Patuxent river basins when operated jointly with the Potomac river. The yield of each of the five reservoirs in the system was determined using simulation models. Simulation and linear programming models were developed to determine the yield of the reservoir system when operated jointly with the Potomac river. The models indicate that the yield, which results from the proper joint operation of the system, is significantly greater than the yield of the individual components of the system.

Stedinger et al. (1983) reviewed and compared deterministic, implicitly stochastic, and explicitly stochastic reservoir screening models. The models were applied to a three-reservoir water supply problem and results were compared with simulation. They concluded that (1) simple screening models that can identify potentially efficient system designs are highly desirable, (2) purely deterministic screening models based on historical mean monthly flows do not provide sufficient reservoir capacity to achieve target reliabilities, (3) use of most critical flows in a record leads to larger reservoir capacities and higher system reliabilities, (4) the explicitly storage models, linear decision rule, chance-constrained formulation of ReVelle et al. (1969) and Loucks (1970) overestimated reservoir capacity and generated operating policies that failed to utilize available water and storage space efficiently, and (5) the yield model of Loucks et al. (1981) produced reasonable reservoir designs with release reliabilities near targets.

Lall and Miller (1988) presented an optimization model in the spirit of the yield model for selecting and sizing potential reservoirs on a river basin. Decomposing the problem into simulation and optimization components derived a compact, nonlinear formulation. Reservoir capacities are determined using a modified sequent peak algorithm to simulate monthly reservoir operation. Simulation is also employed to determine optimal sizes for hydropower generations at each site.

Lall (1995) developed a yield model for selecting between candidate surface-water reservoirs and ground water development. A hybrid simulation-optimization strategy is used to consider monthly operation of the reservoir and aquifer system. A modified sequent peak algorithm is used for reservoir sizing, and a unit response matrix approach is used to model the ground water subsystem. Example applications are presented with data from the Jordan river basin in Utah.

Dandy et al. (1997) made a comparison of simulation, network linear programming, full optimization LP model and the LP yield model for estimating the safe yield of the Canberra water supply system consisting of four reservoirs. They pointed out that, although a simulation model will accurately assess the system yield for an assumed set of operating rules, it will not assess the maximum yield that can be achieved by adopting the best possible set of operating rules for the system. The optimization models can be said to use the optimal operating rules for the system in order to obtain the maximum yield in a single run, without the need for an iterative procedure as in case of simulation models. They however pointed out that, if the system yield with a specified reliability needs to be determined, there is considerably more difficulty in using the optimization and yield models.

Sinha et al. (1999a) presented a nonlinear optimization model for selecting and sizing potential reservoir sites on river basins. The model improves the work of Lall and Miller (1988) and Lall (1995) by replacing the modified sequent peak algorithm for sizing reservoirs with a behavior analysis algorithm that allows operation of the reservoir system with realistic operating policies. The approach of evaluating derivatives by divided differences is replaced by automatic differentiation. The model is developed in the context of Par, Auranga, Ambica, and Purna river basins in India.

Sinha et al. (1999b) presented a yield model for selecting and sizing potential reservoirs and hydroplants on a river basin. A linked simulation-optimization framework is used for formulation. Sizing of reservoirs and hydroplants, and evaluation of objective function and constraints and their derivatives are done as a part of simulation. For sizing reservoirs, a new sequent trough algorithm is used. Derivatives are evaluated using automatic differentiation. The resulting formulation is applied to Par, Auranga, Ambica, and Purna river basins in India. The annual yield reliability is considered as a decision variable. In this linked simulation-optimization formulation, mass equations and the decision variables, like release and storage, are not explicitly considered but are satisfied implicitly through the simulation.

Schwarz (2000) presented a multiobjective analysis to size reservoir and identify non-inferior system operating rules that mitigate the impacts of consumptive operations for the river Potomac. The marginal impacts of consumptive use are offset by adding reservoir storage to the system, balancing technical efficiency, economic efficiency, and equity. Parametric operating rules to size augmentation storage are developed as a multiobjective extension of firm yield analysis (Loucks et al. 1981) applied to forecast-based operation of a multireservoir system. Critical period analysis is used to identify the reservoir storage volume and system operating rules that efficiently mitigate critical period consumptive use impacts under design conditions. The critical period analysis of system rule is developed as a multiobjective extension of traditional storage yield analysis for a multireservoir system operated with real-time forecasts. Examples drawn from Maryland's river Potomac consumptive regulation illustrates how operational definitions of equity and reliability offer a normative framework to manage risk-based approximation within a permitted riparian regulatory system.

Mariam (2000) adopted implicit stochastic yield model based on linear programming for planning optimal annual yield of proposed Morand reservoir in Narmada basin in India, and work out optimal allocations of land and water resources, using crop planning model, to develop cropping patterns for the annual reservoir yields that can be obtained from the reservoir for different degree of annual project dependability. He opined that the yield model provides a reasonably acceptable estimate of the annual reservoir yield for planning of the project.

Dahe and Srivastava (2000) have demonstrated the use of yield model for assessment of annual yield of Upper Narmada irrigation reservoir with specified reliability and the extent of availability of irrigation supply during failure years. Such an assessment can assist the planners to decide upon the irrigation policies regarding the area to be brought under irrigation with sustainable cropping pattern and to reduce the damages due to the likely shortages in supply during failure years.

Dahe (2001) has made an optimization approach employing the implicit stochastic yield model based on linear programming addresses issue of assessment and optimal utilization of annual yield for system of reservoirs. Basic yield model is extended to develop yield model for multi-reservoir system to achieve the desired annual reliabilities for irrigation and power generation and incorporate an allowable deficit in annual irrigation target. The study was carried out for 25 major irrigation reservoirs in Narmada basin in India for optimal planning of the river basin projects.

Dahe and Srivastava (2002) have extended the basic yield model and presented a multiple-yield model for multiple-reservoir system consisting of single purpose and multipurpose reservoirs with an objective to achieve pre-specified reliabilities for irrigation and energy generation and to incorporate an allowable deficit in annual irrigation target. The yield model is applied to a system of eight reservoirs in the upper basin of the Narmada river. They have opined that this model can act as a better screening tool in planning by providing outputs that can be very useful in improving the efficiency and accuracy of detailed analysis methods such as simulation.

### 2.3.3 Dynamic Programming Applications in Reservoir Planning and Operation

Dynamic programming (DP), a method first introduced by Bellman (1957), is an optimization procedure for solving multistage decision process. The popularity and success of DP can be attributed to the fact that the nonlinear and stochastic features that characterize a large number of water resources systems can be translated into a DP formulation. It has a wide variety of applications in engineering and economic decision problems (Yakowitz, 1982; and Yeh, 1985). The key features of DP algorithm which result in its successful application in various fields in general and water resources in particular are that, a complex multistage problem is decomposed into a series of simple sub problems that are solved recursively one at a time and nonlinear problems as well as problems involving stochastic variables may be readily accommodated in the general frame work of dynamic programming.

The well known 'curse of dimensionality' is the major limitation in the use of dynamic programming (Bellman and Dreyfus, 1962). The computational requirement for DP increases exponentially with each additional state variable and multiplicatively with each additional discrete class. Chow et al. (1975) discussed the computational requirement of discrete dynamic programming applied to multireservoir problems.

#### 2.3.3.1 Single reservoir planning and operation with dynamic programming

Young (1967) and Hall et al. (1968) were first to study the problem of finding optimal operating rules for a single reservoir using dynamic programming. Hall et al. (1969) modified their earlier method by incorporating additional factors like firm water and peak energy constraints, energy pricing and flood control etc. Bhaskar And Whitlatch, Jr. (1980) analysed a single multipurpose reservoir using a backward looking dynamic programming.

In Karamouz and Houck (1982), an algorithm to generate monthly reservoir operating rules had been proposed and tested in 48 cases. The algorithm was easy to use, and each component of the algorithm (deterministic dynamic programming, multiple regression and simulation) was relatively simple. Further, in another study by Karamouz and Houck (1987) to generate monthly reservoir operating rules, both deterministic (namely DPR) and stochastic (namely SDP) dynamic programming models have been used. Based on the results, it was concluded that SDP model performed better for small reservoirs and DPR model for large reservoirs. An efficient algorithm for real-time monthly operation of a multipurpose reservoir was presented by Mohammadi and Marino (1984a). The model was a combination of LP (used for month-by-month optimization) and DP (used for annual optimization) and was applied to Poisom reservoir of the California Central Valley Project.

Mujumdar and Ramesh (1997) developed a real time reservoir operation model for irrigation of multiple crops using deterministic dynamic programming. The reservoir storage, soil moistures of individual crops and a crop production measure constituted the state space. The model was applied to the Malprabha reservoir in Karnataka (India).

The application of stochastic dynamic programming is well suited for sequential decision process and has been widely reported in literature for single reservoir operation (Little, 1955; Butcher, 1971; Dudley and Burt, 1973; Su and Deininger, 1974; Buras, 1985; Vedula and Mujumdar, 1992; Mujumdar and Vedula, 1992; Karamouz and Houck, 1987; Vedula and Mohan, 1990; and Talukdar, 1999).

#### 2.3.3.2 Multireservoir planning and operation with dynamic programming

Ever since Bellman (1957) introduced dynamic programming, a wide variety of engineering and economic decision problems have been solved using this technique. The dynamic programming is particularly favored in water resource systems planning and management because of the ease with which multistage problems are handled by the DP algorithm.

##### 2.3.3.2.1 *Deterministic dynamic programming applications*

The computational requirements for DP increases exponentially with each additional state variable and multiplicatively with each additional discrete class. As the number of reservoirs increase, the problem may become unmanageable even on a state-of-the-art computer. Hall and Shepherd (1967) were the first to use dynamic programming for multireservoir problems. Chow et al. (1975) gave a discussion on the computational requirement for the discrete dynamic programming applied to multireservoir problems. In spite of this very serious limitation, dynamic programming and its various forms have been extensively applied to multireservoir planning and operation problems, mainly because of the multistage and nonlinear nature of such problems. Many modified DP algorithms have been specially developed for multireservoir problem to reduce computational requirements. Bellman and Dreyfus (1962) introduced the principle of successive approximation. Larson (1968a, 1968b) developed dynamic programming with successive approximation (DPSA) algorithm, which decomposes a problem of several state variables into a number of single state variable problems. A nominal initial trajectory of state variables was assumed initially and the corresponding decision variables were determined. Only one state variable was then optimized over the time horizon by a one dimensional DP solution assuming all other state variables to be fixed at their initial values. This variable was then held fixed and next variable was selected for optimization. The procedure was repeated till no further improvement in the objective function was possible. Larson (1968a, 1968b) demonstrated the algorithm with a hypothetical four-reservoir problem. This hypothetical problem was ideally formulated and has been used by many researchers for demonstrating many algorithms developed subsequently. Larson and Korsak (1970) presented the DPSA method in detail and worked out an illustrative example. Trott and Yeh (1971) applied the technique of successive approximations whereby one-dimensional DP solves a high dimensional problem. They applied it to solve a problem involving multireservoir systems.

Heidari et al. (1971) modified the Larson's incremental dynamic programming algorithm to incorporate fixed time steps and named it as discrete differential dynamic programming (DDDP). They solved the same problem as that of Larson (1968a, 1968b). Since then, DDDP has become a popular technique for reservoir operation. Fults and Hancock (1972) applied the DDDP technique to a five-reservoir problem of CVP system in

California, USA for an operation on daily basis. Later on Fults et al. (1976) applied the same technique in the same system for operation of nine reservoirs on monthly basis. In both the cases, only the major storage reservoirs were analyzed for maximization of power generation.

Yeh and Trott (1972) determined firm water output from the first operation of a six-reservoir system. The original forward DP had six state and decision variables and was solved by successive approximation. Trott and Yeh (1973) used dynamic programming with successive approximation (DPSA) technique to get optimal return for a specific set of reservoir sizes from the system of reservoirs. A modified gradient technique is then used to determine the set of reservoir sizes, which maximize the net benefits, subject to the imposed constraints.

Becker and Yeh (1974) developed an optimization algorithm for the real time monthly operation of a large-scale water resources system. The procedure makes use of the best features of LP and DP in that LP serves for month-to-month optimization (nonlinearities being accounted for by an iterating technique), and DP is used for the selection of an optimal release policy through the specified number of months. The algorithm requires deterministic forecasts or estimates of monthly stream flows, consistent with real time operation.

Yeh et al. (1979) developed an optimization algorithm for real-time hourly reservoir operation of a Central Valley Project (CVP). The process has two phases, phase I includes linearization by a unique iteration procedure and solution by linear programming (LP). The output is the initial feasible policy used as input to phase II for DPSA algorithm. Phase II optimization maximizes the daily power generation by the system.

Giles and Wunderlich (1981) described a weekly planning model for planning and operational studies of the TVA reservoir system. The model simulates the operation of a multipurpose, multireservoir system by weekly time steps over planning periods of up to one year. It evaluates an objective function that consists of the weighted sum of five cost functions (navigation, flood control, power generation, recreation and water quality). DPSA is used to find the storage and release sequences, which minimize the objective function over the selected planning period. Limitation of DPSA procedure was its dependence on the initial schedule and that it does not guarantee a global optimum, but solutions found were always better than the initial policy.

All DP algorithms discussed so far require the state space to be discretised. For practical real life problems, however, the discretisation poses a serious computational problem and in many cases some important information may be sacrificed unintentionally in order to arrive at a discretisation scheme that makes the problem computationally tractable. Developments were therefore made in DP algorithms to eliminate discretization. The differential dynamic programming (DDP) for unconstrained problems introduced by Jacobson and Myne (1970) is an important milestone in the development of the DP algorithm that eliminates discretisation of state space. A detailed treatment on methodology and computational aspects of DDP technique has been given by Dreyfus and Law (1977) and Murray (1978). Yakowitz and Rutherford (1984) have solved an optimal control problem with as many 40 state variables. An extensive review on the development and applications of DDP has been presented by Yakowitz (1988).

The major disadvantage of DDP was that it couldn't handle constraints on the state space or decision variables explicitly. It has however, served as a major motivation towards the development of constraints differential dynamic programming (CDDP). The CDDP is an improvement of DDP to incorporate constraints on the state and decision space. Murray and Yakowitz (1979) modified the DDP algorithm to CDDP to accommodate constraints. They illustrated the efficiency of the algorithm with the help of hypothetical four-reservoir problem of Larson (1968a, 1968b). They also enlarged the problem of a ten-reservoir and computed the optimal policy. Comparing the solutions with those of DDDP showed the superiority of

CDDP. Yakowitz (1986) suggested a modified algorithm for CDDP, which has been proved to converge to a global optimum quadratically. In spite of many attractive features of the technique, no single attempt of application of the technique to any real life case study has been reported so far.

Howson and Sancho (1975) developed a new algorithm for the solution of multi-state dynamic programming problems, referred to as the progressive optimality algorithm (POA). It is a method of successive approximation using a general two-stage solution. The algorithm is computationally efficient and has minimal storage requirements. A description of the algorithm is given including a proof of convergence. Performance characteristic for a trial problem are also summarized. Turgeon (1981a) applied POA to a problem of weekly hydro scheduling with NLP as the optimization routine. He developed a technique to accommodate the time delays between the reservoirs. POA has been extensively analyzed and applied by Marino and Loaiciga (1983). They applied it to a hydropower problem of Northern CVP system with an adaptive model to forecast the inflows. Quadratic programming and LP were used for optimization depending on alternative formulations and operating conditions. They proposed a modification in POA technique for a faster solution. Marino and Loaiciga (1985a, 1985b) applied the sequential dynamic decomposition algorithm to obtain optimal reservoir operation policies of the northern portion of the Central Valley Project, USA. Zessler and Shamir (1989) applied POA to a regional supply system with eight reservoirs and seven pumping stations. They reported that the algorithm convergences to the optimum from initial solution. The global optimum however, is guaranteed only under certain conditions; otherwise a local optimum may be reached.

Chara and Pant (1984) proposed successive variation approach (SVA). Work done by Chara (1982) was reported in this paper. Any initial feasible policy convergences to the optimal one with little computational efforts with this approach. Examples have been worked out for linear and nonlinear performance criteria. Three examples have been taken from the literature to facilitate comparison with DDDP and CDDP approach.

Lumped to discrete programming approach (LDPA) developed by Bhatia (1984) was a successive approximation technique used in multireservoir operation.

Ozden (1984) proposed the binary state dynamic programming (BSDP) approach and applied it to the standard four-reservoir problem of Larson (1968a, 1968b), and to a case study of a planning problem of four-reservoir system in Turkey. He showed that the algorithm is computationally less expensive than the DDDP technique.

Moncada et al. (1994) developed an implicit dynamic programming formulation, wherein, the end-of-year storage was treated as a fuzzy goal and all other objectives were treated as fuzzy constraint. The resulting reservoir operations were evaluated in a simulation model.

Ferrero et al. (1998) used a new dynamic programming based algorithm for the long-term hydrothermal scheduling of multireservoir systems. The proposed algorithm has smaller storage and computing time requirement than the dynamic programming-successive approximation method. The operation of an example multireservoir system is simulated indicating that the proposed method leads to lower operation costs than those of the successive approximation method.

Chandramouli and Raman (2001) developed a dynamic programming based neural network model for optimal multireservoir operation. Multireservoir operating rules were derived using feed forward neural network from the results of three state variable's dynamic programming algorithm. Parambikulam Aliyar Project system was used for the study.

A dynamic programming based neural network model has been developed by Chandramouli et al. (2002). A modified dynamic programming algorithm with three state variables and four decision variables was proposed. The operating policies were derived from the three state variable dynamic programming algorithm using a neural network. The new dynamic programming neural network model gives a very good performance for the multireservoir system case study considered.

Kumar and Baliarsingh (2003) proposed a new algorithm, Folded DP, for optimal operation of multireservoirs, which is an iterative process but initial trial trajectory is not required to start with. So, the number of iterations is independent of the initial condition. The developed algorithm is applied to a hypothetical four-reservoir system of Larson (1968a, 1968b). They concluded that although there is no guarantee of reaching at the global optimum, but the inconvenience of obtaining the initial trajectory could be avoided.

Sarma and Srivastava (2003) presented two dynamic programming models, namely, procurement problem model (PPM) and controlled input model (CIM) for inter basin water transfer projects. The PPM calculates amount of import water requirements for a reservoir. The CIM estimates water demands that a reservoir can meet, and also amount of water it can export to other reservoirs. The models were applied to a system of five-reservoirs in the Chambal basin in India, where water is to be transferred from three proposed reservoirs to two existing reservoirs. Two alternative water transfer proposals were studied. The objective was to present a realistic and efficient dynamic programming modeling approach for planning and operation of multipurpose multireservoir system.

#### 2.3.3.2.2 *Stochastic dynamic programming (SDP) applications*

The system parameters like inflows, demands, storages, releases etc. are highly time dependent and stochastic in nature. That is why, for determination of the optimal operating policy of a reservoir, deterministic models which use average or critical values of inputs like stream flow are usually optimistic and hence even for the preliminary identification of different project designs and operating policies prior to a detail simulation study, these deterministic models are of limited use (Loucks et al., 1981).

Stochastic dynamic programming formulations in multireservoir problems become quite complex computationally even when one hydrologic variable is incorporated in the model. So, applications of SDP for multireservoir problems are found to be less in number. The implicit stochastic approach in DP formulation was first introduced by Young (1967), in a single reservoir-planning problem. However, McKercher (1975) was the first to extend the Young's (1967) algorithm to planning and operation problem of a multireservoir hydroelectric system. Another classic example of implicit SDP is by Gal (1979). He used the policy iteration method, which starts with an assumption of polynomials to represent the expected cost of operation of the system. This cost function and the corresponding coefficients of the polynomials were optimized iteratively to achieve the minimum expected cost.

From computational point of view, explicit stochastic DP approach is too much expensive as the two stochastic variables are added to the space state and the problem become difficult to be solved even for a system with only few reservoirs.

Schweig and Cole (1968) was the first to use explicit stochastic DP approach to a multireservoir problem. They adapt the Little (1955) model to a system of one lake and one aquifer with course discretisation of state space and concluded the SDP solution is computationally difficult for multireservoir problems.

The aggregation-disaggregation of reservoirs and one-at-a-time successive decomposition are the algorithms, which have been commonly introduced in SDP models in multireservoir systems. This aggregation-disaggregation of reservoirs was applied by Arvanitidis and Rosing (1970) in a valley on the basis of potential energy of unit volume of storage or inflows. Once the aggregation was achieved, the problem of determining minimum expected cost of hydrosystem operation was solved through a SDP with potential energy and inflow of previous month as state variable. Turgeon (1980) extended this approach for the solution of a hydropower system in two different ways. In one approach, the expected optimal weekly energy was achieved through a valley wise aggregation of reservoirs and one-at-a-time successive decomposition. In the second approach, he converted the problem into a two variable SDP model by aggregating all reservoirs of the system, except one, to achieve the same objective. Later, he demonstrated (Turgeon, 1981b) a procedure similar to the second approach for reservoirs in series configuration. The aggregation-disaggregation approach was also used by Tai and Goulter (1987) for a three reservoir system in Lauri river, Canada. They took the advantage of high cross correlation in aggregating the reservoirs and disaggregating the releases. Valdes et al. (1992) applied this approach in a monthly energy generation problem. Release policies of each reservoir and daily releases were determined by disaggregating the aggregated monthly releases.

Arun Kumar and Yeh (1973) first used the one-at-a-time decomposition approach. The approach consists of fixing a stationary policy for all reservoirs except one, to be analyzed and solved a SDP for that reservoir to get a stationary solution. Further an approach similar to DPSA was adopted to achieve an optimal solution. Arun Kumar and Chon (1978) developed the theoretical basis for solution of a problem of reservoirs configured in series on the same one-at-a-time decomposition approach. Using same approach Braga et al. (1991) analyzed a hydropower system. They propose an offline analysis to establish the value of stored water in terms of future generation of power and used it in an outline SDP analysis.

Paundyal et al. (1990) presented a model of long term operational aspects of a multiunit hydropower system for maximizing firm energy and expected annual energy. An incremental DP algorithm was first used with the objective of maximizing firm energy from the system. In second step, SDP which incorporates the uncertainties inherent in the stream flow series, has been used to derive long term joint operation policy of the system of reservoirs in the configuration selected from the first step.

Ponnambalam and Adams (1996) considered optimization of a multi-reservoir and multipurpose system using dynamic programming with stochastic approach. Perera and Codner (1998) took the help of two factors to improve the computational efficiency of stochastic DP model during operation of an urban water supply reservoir system. They assumed strong cross correlation of system flow among the various sites and used a corridor approach.

### 2.3.4 Combined Models

From computational point of view, derivation of optimal operating policy for multireservoir cases is always found to be expensive. This necessitates the use of a combination of two or more algorithms. In earlier stages, the multireservoir problem was decomposed to a master and a number of sub problems, which were then solved one after another in an iterative fashion to achieve an optimal configuration or an operating policy. Hall and Shepherd (1967) and Hall and Dracup (1970) used such type of approach by LP-DP combination. In another approach, different algorithms were used for different individual aspects of a problem and the results are then integrated through an interaction between the algorithms. One algorithm may solve for multiple optimal solutions and the other may select the best among these solutions. Hall and Shepherd (1967), Hall et al. (1968), and Takeuchi and Moureau (1974) applied this LP-DP combination for multireservoir case under deterministic environment. Becker and Yeh (1974) used the LP-DP combination for a real time operation of CVP system, USA. Becker et al. (1976) used the same monthly model of Becker and Yeh (1974) and developed daily and hourly model for the CVP system. The monthly model output was used as an input to the daily model and the output of the daily model was used as an input to the hourly model. Later Yeh (1979) and Yeh et al. (1979) used this combined LP-DP model for real time operation of multireservoir problems. Yeh and Becker (1982) used a LP-DP combined approach for a multiobjective study of the CVP system, USA. They used the same Becker and Yeh (1974) algorithm to find the operating policy for five different objectives of the system. The trade-off of different objectives was derived using constraint method of multiobjective analysis. It appears that the combined applications of LP-DP models are very popular and lots of reported works are available in literatures, e.g., Gablinger and Loucks (1970); Marino and Mohammadi (1983a); Mohammadi and Marino (1984a); Mohammadi and Marino (1984b); Vedula and Mohan (1990); Srivastava and Patel (1992); and Sarma and Srivastava (2003).

Simulation is a modeling technique that approximates the behavior of a system on the computer, representing all the characteristics of the system by mathematical relationships. It is an effective tool for studying the management of a complex water resource system, for it can incorporate the experience and judgment of the planner or designer into the model. Various practitioners successfully have used simulation models. However, in recent years, a tendency has been developed toward incorporating an optimization scheme into a simulation model to perform a certain degree of optimization. It has become quite common to have a few optimization routines nested in a simulation model. Jacoby and Loucks (1972) proposed the combined use of optimization and simulation models. This paper reports on an investigation of the use of analytical optimization models to screen a set of possible plans and to select a small number worthy of simulation analysis. Deterministic and stochastic LP screening models were developed and applied for the planning of Delware river basin system. Chaturvedi and Srivastava (1981) analyzed six major reservoirs of Narmada basin in India using deterministic LP with simulation model. Palmer et al. (1982) developed simulation and LP models to determine the yield of a reservoir system when operated jointly with the Potomac river. Dudley (1988) used an optimization model to develop release rules for reservoir management when all users share equally in releases, and simulation was used to generate an historical time sequence of announced releases. These announce releases become a state variable in a farm management model which optimizes farm area to irrigate. Kuo et al.

(1990) used a simulation-DP combined approach for development of a real time operation model for Tanshui river reservoirs, Taiwan. This consist of a 10-day streamflow forecast model, a rule curve based simulation model and a DP optimization model. After getting the initial feasible operating policy by using the simulation model, the DP base optimization model was then used to determine an improved operating policy. Srivastava and Patel (1992) used optimization (LP and DP)-simulation models for the systems analysis of the Karjan irrigation reservoir project in India. A model based on SDP formulation, which considers risk explicitly, was developed by Jain et al. (1992). The objective of the model was to maximize the reservoir storage at the end of flood season while ensuring that the risk of the overflow is within acceptable limit. The model was applied to the Dharoi multipurpose reservoir of the Sabarmati river in Gujarat (India) and its performance was tested by simulation. Other notable works involving simulation techniques are Wurbs (1996), Pretto et al. (1997), Wurbs (1997), Ravi Kumar and Venugopal (1998), and Belaineh et al. (1999).

Roefs and Guitron (1975) compared three models, namely linear programming, dynamic programming and policy iteration; on the basis of computational efforts. They concluded that the SDP model was the preferred algorithm. Grygier and Stedinger (1985) have examined successive LP, optimal control and LP-DP algorithm to optimize the operation of a multireservoir hydro system. Karamouz and Houck (1987) tested and compared two algorithms of reservoir operating rules by deterministic and stochastic optimization for a single reservoir. The deterministic model comprises deterministic dynamic programming, regression analysis and simulation, while the stochastic model was a stochastic DP. The SDP model described streamflows with a discrete lag one Markov process. The authors concluded that SDP model performed better for small reservoirs (capacity of 20% of the mean annual flow), but for larger reservoirs (capacity exceeding 50% of mean annual flow) deterministic model performed better. Kohistani (1995) used linear programming, dynamic programming and simulation as nested link models to solve the integrated planning and operation of four reservoirs in India.

Harboe (1992) presented six applications of multiobjective decision making techniques for finding optimal or satisfying operating rules for reservoir systems. The examples include situations with hydropower vs. irrigation supply, flood control vs. low flow augmentation, selection of an operating rule, low-flow vs. reliability, and low-flow and recreation vs. water quality. The techniques applied include the constraint method, compromise programming, goal programming, Tchebycheff approach (max-min), Consensus, and ELECTRE I and II.

Vogel and Stedinger (1988) examined the variability of required storage capacity estimates based on 20-year and 80-year stream flow records. An autoregressive AR(1)-lognormal model was 'fit' to historical flow sequences generated with four different stochastic stream flow records: AR(1) lognormal, AR(1) normal, AR(1) gamma, and an AR-moving-average (1,1) lognormal model. Vedula and Mohan (1990) developed a real time operational methodology for the Bhadra reservoir in the state of Karnataka (India). The algorithm has three phases of operation. The first phase determines the optimal release policy for a given initial storage and inflow using SDP. Second phase constitute the flow forecasting using ARIMA model and in the last phase a real time simulation model was developed. In the SDP model, the inflows were assumed to follow a discrete Markov process. Yang et al. (1995) presents different operation techniques for real time reservoir regulation on the basis of two hydrological models and two optimization methods: the first-order autoregressive (AR) model, the GR3 conceptual rainfall-runoff model, the stretched-thread (ST) method, and dynamic programming (DP). With these elements, three reservoir operation techniques can be designed by combining one hydrological model with one optimization method, namely GR3 with ST, AR with ST, and AR with stochastic DP. The study confirms the value of simple optimization methods such as ST and the applicability of scenarios methods in real-time reservoir operation.

### 2.3.5 Other Miscellaneous Techniques and Approaches

Colorni and Fronza (1976) explored the possibility of applying reliability programming to determine monthly contract volumes to be released by a reservoir. The reliabilities are considered as extra decision variables and are not fixed a priority as in case of chance-constrained programming. The optimal operation results from a compromise between profit and risk. Simonovic and Marino (1980) presented an application of reliability programming to a multipurpose reservoir. The approach allows the reliabilities to be considered as decision variables, and explicitly considered the trade-off between benefits and risk. It was pointed out that the computational requirements might limit the applicability of the algorithm to higher dimensional problems. Hashimoto et al. (1982) discussed three criteria for evaluating the possible performance of water resource systems. These measures describe how likely system is to fail (reliability), how quickly it recovers from failure (resiliency), and how severe the consequences of failure may be (vulnerability). These criteria can be used to assist in the evaluation and selection of alternative design and operating policies for a wide variety of water resource projects. They have illustrated the use of these criteria with the performance of a water supply reservoir. Rangarajan et al. (1999) proposed a reliability-programming model, which incorporates a four-step simulation algorithm to derive the loss function, which is a relationship between the reliability and its associated economic losses. The performance of the model was demonstrated through a case study.

Simonovic and Savic (1989) presented the potential benefits of 'expert systems' in the area of reservoir management and operations and illustrated with an example of an engineering expert system for reservoir analysis. Loucks (1995) reviewed the needs and opportunities in developing and implementing decision support system (DSS). The paper stressed the information needs of the decision making process that motivate the development of DSSs. The focus of the paper is on the process of the successful DSS development and implementation. An approach and some guidelines are outlined for the development of DSSs. The approach emphasizes and requires considerable interaction and feedback is required throughout the entire DSS building, testing and evaluation (debugging), and implementation process. The paper concludes by identifying some research needs and opportunities affecting DSS development and its effective use.

Genetic algorithm (GA), an approach based on genetics was first introduced in water resources systems by Esat and Hall (1994). They applied GA technique for operating rule determination of a four-reservoir problem, which maximizes the benefits from power generation, irrigation and water supply subject to some physical constraints. Later, Fahmy et al. (1994), Oliveira and Loucks (1997) and Wardlaw and Sharif (1999) applied GA to different reservoir operation problems. Every author agreed on the point that GA has a distinct advantage and it has potential as an alternative to SDP. Raman and Chandramouli (1996) used neural network approach with dynamic programming and derived operating policy of Aliyar reservoir in Tamilnadu. Further, Chandramouli and Raman (2001), and Chandramouli et al. (2002) have extended the dynamic programming based neural network model to derive operating policy for multireservoir system. Saad et al. (1994) used it for a disaggregation procedure to derive the operating rules for hydroelectric power system. The procedure to apply GA to optimize operation rules has been proposed and applied by Tung et al. (2003) to the LiYuTan reservoir in Taiwan. The first step of the procedure is to predefine the shape of boundary curves of operation zones according to reservoir storage routing. Then relatively fewer variables are used to describe the curves. They concluded that the proposed procedure utilizing GA to optimize the operation zones with predefined shape can provide better and realistic outcomes through limited iterations.

The application of the fuzzy rule based modeling in reservoir operation is relatively new and only few applications are reported in literature. Russell and Campbell (1996) proposed its application to find out reservoir operating rule by applying this to a single purpose hydroelectric project and concluded that although it is a promising approach but it suffers from the curse of dimensionality. It can supplement the conventional optimization techniques but cannot probably be a replacement. Shrestha et al. (1996) also used the fuzzy rule based modeling in reservoir operation. They constructed the model to derive operation rules for the Tenkiller Lake in Oklahoma. Fontane et al. (1997) have addressed the imprecise and noncommensurable objectives for reservoir operation through fuzzy dynamic programming using an implicit stochastic approach. Fuzzy membership functions for evaluating the achievement of a linguistically described operational goal and linguistically described constraints are estimated from surveys of decision makers. Summary statistics of the membership function values for optimal operation provide easily interpreted measures of degree of satisfaction among diverge objectives. An example application to the proposed Grey Mountain Reservoir on the Cache la Poudre River in northern Colorado was presented. Panigrahi and Mujumdar (2000) propose a complete approach for long-term storage/transfer/distribution system management and developed fuzzy rule based model for the operation of a single purpose reservoir. The paper presented by Tilmant et al. (2002a) compares reservoir-operating policies obtained from fuzzy and nonfuzzy explicit stochastic dynamic programming. Despite major differences in the mathematical representation of operating objectives and/or constraints it was shown that both formulations yield similar measures of system performance. Faye et al. (2003) implemented an adaptation procedure of weighting parameters of the minimization criteria based on fuzzy logic. Fuzzy logic is shown to be very adequate when it comes to apprehend finely the stakes in presence in the long-term management.

*Chapter-3*

# THE BASIN, RIVER SYSTEM AND THE WATER TRANSFER PROPOSAL

## 3.1 INTRODUCTION

The Chambal river basin, located in western India, is considered for the present study with the objective of planning water transfer from its water surplus sub-basins, if any, to the water deficit sub-basins. The Chambal basin can be divided into five major sub-basins, namely, Upper Chambal, Lower Chambal, Parbati, Kalisindh and Banas. The term "sub-basin" requires referring the parent basin. The above-mentioned basins are sub-basins of Chambal basin, the Chambal basin is a sub-basin of Yamuna basin, the Yamuna basin is a sub-basin of Ganga basin, and the Ganga basin is a sub-basin of Ganga-Brahmaputra-Meghna system. To avoid confusion, all the basins/sub-basins are simply referred as "basin". The study area does not cover the Banas basin and hence this basin is not described in detail. The index map of Chambal basin is given in Fig. 3.1.

The Chambal basin is declared as "classified", by the Ministry of Water Resources, Govt. of India. The permission to present the flow data in Chambal basin could not be obtained.

## 3.2 THE RIVER SYSTEM

The Chambal river is a principal tributary of the Yamuna river; rises in the Vindhyan range near Mhow of Indore district in Madhya Pradesh at an elevation of 854 m. The Chambal river falls into Yamuna river near village Sahon of Etawah district. The total length of the river from its origin to its confluence with Yamuna river is 960 km, out of which it runs 325 km

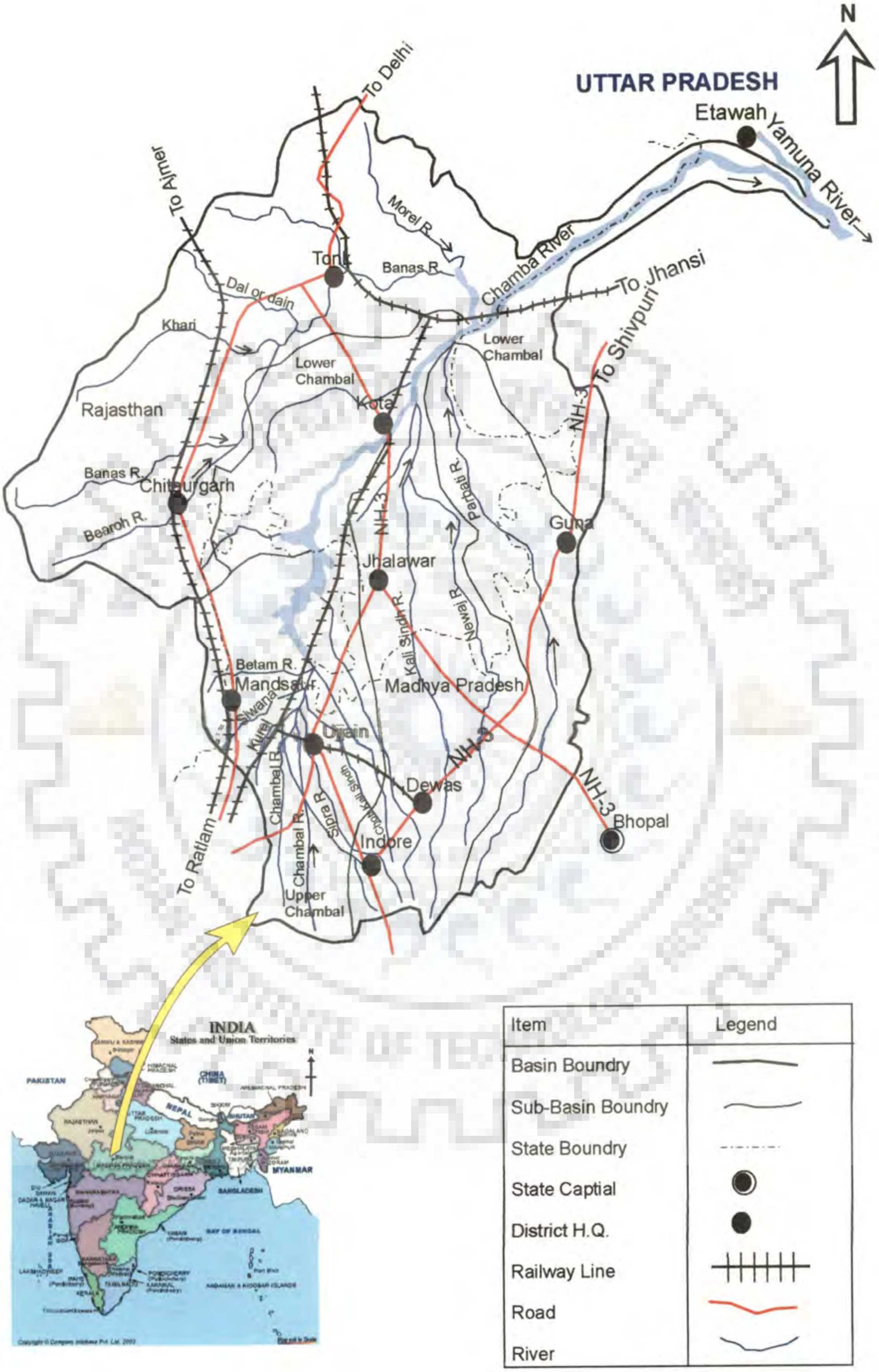

**Figure 3.1** Index map of Chambal basin

through a gorge. The major tributaries that join Chambal are Malini, Sipra, Chhoti Kalisindh, Parbati, Sivani, Kural, Kalisindh, Ratan, Ghambhir, Cham and Banas.

The Kalisindh river is a principal tributary of the Chambal river. It originates from Vindhyachal ranges at an elevation of about 610 m from Barziri hill near Bagli in Dewas district and joins the Chambal river in the Kota district of Rajasthan. The Kalisindh river traverses a near northerly course for its total length of 351 km till it joins the Chambal river. The Kalisindh river flows through a length of 180 km in Madhya Pradesh through Dewas and Shajapur districts and the remaining 171 km of its length through Jhalawar and Kota districts of Rajasthan. The river is joined by a number of tributaries, the more important of which are Lakhundar, Ahu and Parwan. The Kalisindh basin lies between north latitudes $22^{o}34^{/}$ to $25^{o}32^{/}$ and the east longitudes $75^{o}39^{/}$ to $77^{o}07^{/}$. The districts falling in the Kalisindh basin are Dewas, Ujjain, Shajapur, Rajgarh, Sehore, Guna Mandsaur in Madhya Pradesh and Jhalawar, Kota and Chittaurgarh in Rajasthan.

The Parbati river is the third largest tributary of the chambal river passing through Madhya Pradesh and Rajasthan. It originates at the Vindhyachal ranges (609 m) near Ashta in the Sehore district of Madhya Pradesh and joins the Chambal river in the Kota district of Rajasthan. Initially for a length of 162 km in Madhya Pradesh, the river traverses a northeasterly course and in the balance 60 km in northwesterly course. The river then forms common boundary between Madhya Pradesh and Rajasthan for the next 50 km before entering the Kota district of Rajasthan. It then traverses about 107 km before joining the Chambal river. The total length of the river is 436 km. The important tributaries of the Parbati river are Papnaus, Ajnal, Sewan, Paru, Utawali, Baraparwa, Mawal, Tem, Bhader, Gochi, Sukh, Chopan, Negri, Bethli, Upreni, Dubral, Andheri, Baran, Kosam, Ahelil and Sukni. The Parbati basin lies between the north latitudes $22^{0}46'$ to $25^{0}52'$ and the east longitudes $76^{0}19'$ to $77^{0}25'$. It has a fern leaf shape. The districts covered by the basin are Sehore, Bhopal, Vidisha, Shajapur, Rajgarh, Guna, Shivpuri and Morena in Madhya Pradesh and Kota and Jhalawar in Rajasthan.

The Banas river rises from the eastern flank of the Aravali mountain ranges at an altitude of about 895 m, near the Kumbalgarh fort in the Udaipur district. It flows in an easterly direction passing through north of the Chittorgarh district and enters the Bhilwara district near the village Duriya. Then the river flows in a north to northeast direction in the Jahajpur tehsil and subsequently enters the Tonk district at Nagdia. From this point, it takes a serpentine course and flows through Sawai Madhopur district before joining the Chambal river. The total length of the Banas river is 550 km and the average bed slope of the river is 1 in 763.

## 3.3 BASIN DESCRIPTION

The Chambal basin extents over an area of about 135971 sq km covering parts of Madhya Pradesh, Rajasthan and Uttar Pradesh. The basin is situated between the east longitude of $73^0 20'$ to $79^0 15'$ and the north latitude of $22^0 27'$ to $27^0 20'$. The state-wise and district-wise break up of the Chambal basin is presented in Table 3.1.

### 3.3.1 Topography and Physiography

The Chambal basin consists of Vindhyan and Aravali ranges, Malwa plateau, Umatwara plateau hills. The Banas basin comprises Aravali ranges covering Udaipur, Chittorgarh and Bhilwara districts.

**Table 3.1** District wise break up of Chambal basin

| State | District | Area falling in the basin | |
|---|---|---|---|
| | | (Sq km) | (%) |
| Madhya Pradesh | Mandsaur | 9457.83 | 6.96 |
| | Sehore | 3330.00 | 2.45 |
| | Morena | 6677.61 | 4.91 |
| | Shajapur | 6178.00 | 4.54 |
| | Dewas | 3131.00 | 2.30 |
| | Rajgarh | 6117.26 | 4.50 |
| | Ujjain | 6116.07 | 4.50 |
| | Guna | 5338.20 | 3.93 |
| | Ratlam | 2935.52 | 2.16 |
| | Dhar | 1653.23 | 1.22 |
| | Indore | 2862.75 | 2.11 |
| | Bhind | 279.74 | 0.21 |
| | Shivpuri | 2013.81 | 1.48 |
| | Vidisha | 382.00 | 0.28 |
| | Bhopal | 646.00 | 0.48 |
| Sub total | | 57119.02 | 42.00 |
| Uttar Pradesh | Agra | 409.12 | 0.30 |
| | Etawah | 235.53 | 0.17 |
| Sub total | | 644.65 | 0.47 |
| Rajasthan | Chittorgarh | 8621.89 | 6.34 |
| | Jhalawar | 6322.16 | 4.65 |
| | Kota | 12219.33 | 8.99 |
| | Bharatpur | 772.24 | 0.57 |
| | Sawai Madhopur | 6501.54 | 4.78 |
| | Bundi | 5550.00 | 4.08 |
| | Tonk | 7220.00 | 5.31 |
| | Bhilwara | 10455.00 | 7.69 |
| | Ajmer | 5710.96 | 4.20 |
| | Jaipur | 7291.30 | 5.36 |
| | Udaipur | 7543.40 | 5.55 |
| Sub total | | 78207.82 | 57.52 |
| Grand Total | | 135971.49 | 100.00 |

The Upper Chambal basin consists of the Vindhyan ranges in south, i.e., in upper reaches and the Malwa plateu in middle and lower reaches. The upper reaches of the catchment are located in widely undulating plateu with low flat-topped hills spread intermittently. The general elevation of the catchment varies from 580 m to 400 m.

The Lower Chambal basin is bounded on the north by the ridge separating it from the Yamuna basin, on the east by ridge separating it from the Sindh basin, on the south by the Vindhyan ranges and on the west by the Aravali hills. The basin has a range of Kota lime stone and sand stone hills in Rajasthan.

The Kalisindh basin is dominantly plain and cascades towards the north interspersed by two hill ranges, viz., Mukandwara and Ratibar. The basin is bounded in south by the great Vindhyan ranges from where most of the southern tributaries of the Yamuna originate. The upper reaches of the basin fall in physiographic section named as Malkidesh soaning in the altitude ranges of 450 m to 600 m followed by Umatwara plateau which covers Ujjain, part of Shajapur and Rajgarh districts with an average altitude of 300 m to 450 m. Northern parts of Shajapur,Rajgarh, Guna and Southern parts of Jhalawar districts form Jhalawar plateau having average elevation of 150 m to 300 m. In the basin, slopes are gentle from south to north. In northern portion of the basin the Harawati plains stretches in wide belts from Bhawani Mandi in the west almost up to Asnawar in the east and from Bahani in south to Itawa in north and bounded on the northern, eastern and southern sides by the Mukandwara hills.

The Parbati basin comprised of upland, eastern ranges, western ranges, valley portion and Harawati plains of Kota and Morena districts. The upland areas are either plain rolling land or gently rolling series of mounds and valleys and cover parts of the Sehore, Bhopal, Shajapur and Vidisha districts in Madhya Prasesh. The eastern ranges are well defined and continuous. These separate the high level land of the Sindh basin. The western ranges separate high-level land of the Kalisindh basin.

### 3.3.2 Geology

The geological formation of the basin shows a coexistence of most ancient Precambrian rocks to most recent alluvium belonging to the Bhilwara Supergroup, Aravalli Supergroup, Delhi Supergroup, Vindhyan Supergroup, volcanic fissure eruptions called the Deccan Traps and alluvium and wind blown sand. The main quarries include limestone, sandstone and marble rock in the basin.

The Bhilwara Supergroup, consisting of Bundelkhand gneisses and the banded gneissic complex, and the Aravalli Supergroup are exposed towards north and northwest. Deccan Traps and alluvium lie towards east and northeast.

Major part of the catchment of the Upper Chambal basin is covered by Deccan Traps belonging to Cretaceous to Tertiary consisting of fissure lava flows of varying thickness. Sedimentary rocks like limestone occur in the basin. Recently formed alluviums consisting of laterite are also found in the basin. The depth of water table in the Upper Chambal basin varies from less than 2 m to 18 m depending on topographical conditions. The fluctuation in water table varies from 0.67 m to 9 m.

The main geological rock formations in the Lower Chambal basin consist of Aravalli Supergroup, Vindhyans and Deccan traps. The middle reach of the basin has Pleistocene sand alluvium soils, blown sand, kankar, carbonate beds and evaporite deposits of recent age. The Great Boundary Fault in Rajasthan separates Metamorphics of the Aravalli and Vindhyan Supergroups belonging to Precambrian age. The Chambal river has carved its course along this fault. The Aravallis consist of basal quartzite, shale, conglomerates and composite gneisses and slates. The Vindhyans consist of basement rocks, over which the Samuri, Kaimur, Rewa and Bhander group lies. The Upper Vindhyans consist of thick series of sedimentary rocks comprising of sandstones, limestones and slates. Kota limestones and sandstones are the main rocks in this basin. The Delhi Supergroup overlies the Aravallis. The famous marble of Makrana belongs to the Ralio group of the Delhi Supergroup. The depth of water table below ground levels in the Lower Chambal basin varies from 1.0 m to 27.50 m.

The upper reaches of the Kalisindh basin have Deccan traps as the main rock belonging to Upper Cretaceous to Lower Tertiary age. Volcanic activity in the form of fissure eruptions of tholeutic magma marked the close of the Mesozoic Era in the Lower Cretaceous age. The Traps of varying thickness are at times inter bedded with fossiliferous intertrappen beds.

The upper reach of the Parbati basin (mostly in Madhya Pradesh) has Deccan traps as the main rock. The northern portion of the basin (in Rajasthan) has the rocks of Vindhyan formation. The Upper Vindhyan and Lower Vindhyan formations belong to the Proterozoic age. The former comprises of the Bhander, Rewa and Kaimur series and the later of the Samuri series. Kota limestone and sandstone are the main rocks found in the Rajasthan portion of the basin. The depth of water table in the Parbati basin varies from 1.5 m to 28.0 m and the ground water fluctuation ranges from 4 m to 15 m.

### 3.4 CLIMATE

In a year, four distinct seasons occur in the basin. They are (i) the cold weather, (ii) the hot weather, (iii) the southwest monsoon and (iv) the post monsoon. The cold weather season commences in December and continues till the end of February. The season is characterized by its bright cloudless days and nights. The hot weather starts in March and continues up to middle of June. The season is generally dry. The southwest monsoon sets in middle of June and withdraws by the first week of October. During this season, the weather is somewhat sultry and oppressive. In the post monsoon, a few thunderstorms occur, especially in October. Thereafter, the weather clears up and dry pleasant weather prevails throughout the basin.

### 3.4.1 Rainfall

The basin receives rainfall from southwest monsoon extending from June to September. Some light showers are received off and on during the winter months also. The maximum and minimum annual rainfall in the basin varies from 356 mm to 1270 mm. The basin lies between isohyets of 400 mm and 1400 mm as per the Indian Meteorological Department (IMD) Atlas. The average monthly rainfall for the basin is given in Table 3.2.

### 3.4.2 Temperature

The basin experiences high temperatures in summer and fairly low temperatures in winter. In the month of January, the mean temperature over the basin is between 15°C and 20°C. In April, the mean temperature varies from 27.5°C to 32.5°C. In the month of July too, it ranges between 27.5°C and 32.5°C. In the month of October, the basin experiences temperatures between 25°C and 27.5°C. The basin-wise mean monthly temperature has been given in Table3.3.

### 3.4.3 Relative Humidity

The relative humidity indicates an annual average relative humidity of about 51.58 percent at Udaipur in Banas basin, 53.13 percent in Indore in Upper Chambal basin, 50.46 percent in Sheopur in Lower Chambal basin, 48.8 percent at Jhalawar in Kalisindh basin and 51.25 percent at Guna in Pabati basin. Average monthly values indicate that a minimum value of about 20.0 percent to 29.5 percent occurs in the month of April and a maximum value of about 78 percent to 84 percent occurs in the month of August in the Chambal basin. The mean relative humidity of some selected observatories are presented in Table 3.3.

**Table 3.2** Normal monthly evapotranspiration and rainfall in Chambal basin

| Month | Banas | | Upper Chambal | | Lower Chambal | | Kalisindh | | Parbati | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $Et_o$ (mm) | Rainfall (mm) | $Et_o$ (mm) | Rainfall (mm) | $Et_o$ (mm) | Rainfall (mm) | $Et_o$ (mm) | Rainfall (mm) | $Et_o$ (mm) | Rainfall (mm) |
| Jan | 59.33 | 9.00 | 85.60 | 7.10 | 61.60 | 8.80 | 66.60 | 20.00 | 66.90 | 13.70 |
| Feb | 78.50 | 4.40 | 106.60 | 3.10 | 80.30 | 3.90 | 86.80 | 8.50 | 86.90 | 3.10 |
| Mar | 125.30 | 3.50 | 157.60 | 2.80 | 131.40 | 5.00 | 136.30 | 11.40 | 136.40 | 4.20 |
| Apr | 158.30 | 2.60 | 205.46 | 3.30 | 166.90 | 4.90 | 174.00 | 4.50 | 171.80 | 4.00 |
| May | 204.40 | 4.60 | 233.30 | 12.70 | 225.00 | 7.40 | 228.00 | 13.50 | 229.90 | 5.70 |
| Jun | 178.70 | 87.00 | 199.60 | 133.60 | 210.30 | 78.50 | 210.80 | 130.10 | 213.50 | 111.20 |
| Jul | 119.50 | 197.30 | 123.70 | 300.20 | 138.60 | 308.60 | 131.30 | 388.50 | 110.80 | 356.60 |
| Aug | 102.30 | 206.90 | 107.90 | 231.90 | 120.60 | 267.90 | 111.40 | 382.40 | 125.80 | 326.70 |
| Sep | 115.30 | 120.40 | 116.90 | 173.70 | 133.30 | 32.20 | 118.50 | 213.70 | 129.60 | 163.50 |
| Oct | 112.30 | 16.10 | 163.10 | 33.00 | 122.40 | 15.20 | 114.30 | 23.50 | 118.20 | 18.20 |
| Nov | 70.90 | 5.70 | 91.90 | 21.10 | 75.40 | 6.20 | 74.00 | 14.50 | 75.00 | 10.20 |
| Dec | 55.20 | 2.50 | 77.70 | 6.60 | 58.30 | 2.90 | 59.40 | 9.20 | 60.70 | 5.00 |
| Total | 1381.20 | 666.00 | 1669.36 | 929.10 | 1524.10 | 741.50 | 1511.40 | 1219.80 | 1525.50 | 1022.10 |

**Table 3.3** Climate data of Chambal basin

| Station | Climate data | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Udaipur (Banas) | Mean temperature (°C) | 16.00 | 18.65 | 23.70 | 28.10 | 31.75 | 30.60 | 27.30 | 26.10 | 26.50 | 18.90 | 11.00 | 8.30 |
| | Wind velocity (Km/hr) (At 2 m height) | 1.83 | 2.15 | 2.98 | 3.91 | 5.22 | 6.14 | 5.22 | 3.90 | 3.07 | 1.90 | 1.24 | 1.24 |
| | Relative humidity (%) | 53.00 | 42.00 | 33.50 | 29.50 | 31.50 | 55.50 | 74.00 | 78.00 | 70.50 | 52.00 | 48.00 | 51.50 |
| | Mean cloud cover (Octa) | 1.03 | 0.73 | 1.13 | 1.13 | 0.90 | 2.88 | 5.48 | 5.75 | 3.20 | 1.40 | 0.65 | 0.95 |
| Indore (Upper Chambal) | Mean temperature (°C) | 17.85 | 19.95 | 24.50 | 29.05 | 32.35 | 30.05 | 26.05 | 25.10 | 25.15 | 24.15 | 20.45 | 18.30 |
| | Wind velocity (Km/hr) (At 2 m height) | 8.10 | 7.90 | 7.50 | 8.30 | 10.90 | 13.30 | 11.50 | 9.80 | 7.70 | 5.90 | 5.90 | 6.10 |
| | Relative humidity (%) | 47.00 | 46.50 | 24.00 | 24.50 | 31.00 | 60.00 | 80.00 | 82.50 | 73.50 | 51.00 | 43.00 | 43.50 |
| | Mean cloud cover (Octa) | 1.42 | 1.02 | 1.37 | 1.40 | 1.37 | 3.85 | 5.70 | 5.77 | 4.52 | 2.05 | 1.10 | 1.25 |
| Sheopur (Lower Chambal) | Mean temperature (°C) | 16.15 | 19.15 | 25.10 | 30.05 | 34.60 | 34.50 | 29.85 | 28.00 | 28.00 | 25.65 | 20.20 | 17.20 |
| | Wind velocity (Km/hr) (At 2 m height) | 4.16 | 3.93 | 4.93 | 5.54 | 7.32 | 7.86 | 6.39 | 5.08 | 4.70 | 3.77 | 3.16 | 3.08 |
| | Relative humidity (%) | 56.00 | 41.50 | 30.00 | 20.00 | 21.50 | 43.50 | 73.50 | 83.00 | 74.00 | 58.00 | 48.50 | 56.00 |
| | Mean cloud cover (Octa) | 1.85 | 1.33 | 1.58 | 1.53 | 1.33 | 3.43 | 5.83 | 5.73 | 3.70 | 1.73 | 0.68 | 1.35 |
| Guna (Parbati) | Mean temperature (°C) | 16.50 | 19.00 | 24.00 | 29.15 | 33.65 | 32.55 | 27.55 | 26.30 | 26.40 | 24.50 | 19.80 | 17.00 |
| | Wind velocity (Km/hr) (At 2 m height) | 4.40 | 5.10 | 5.90 | 7.40 | 10.40 | 13.00 | 12.00 | 10.40 | 7.40 | 3.90 | 2.90 | 3.30 |
| | Relative humidity (%) | 52.00 | 42.50 | 30.00 | 21.00 | 23.50 | 54.00 | 79.00 | 84.00 | 78.00 | 53.00 | 47.00 | 51.00 |
| | Mean cloud cover (Octa) | 1.60 | 1.20 | 1.20 | 1.20 | 1.40 | 3.30 | 5.60 | 5.80 | 3.70 | 1.40 | 0.80 | 1.10 |
| Jhalawar (Kalisindh) | Mean temperature (°C) | 17.25 | 19.90 | 25.15 | 30.30 | 34.65 | 33.30 | 28.60 | 27.35 | 27.55 | 25.90 | 21.00 | 18.05 |
| | Wind velocity (Km/hr) (At 2 m height) | 3.60 | 4.10 | 4.90 | 6.00 | 9.00 | 11.50 | 9.60 | 7.80 | 5.80 | 2.90 | 2.10 | 2.60 |
| | Relative humidity (%) | 50.00 | 39.00 | 27.00 | 21.50 | 29.00 | 50.50 | 75.00 | 79.00 | 71.50 | 48.50 | 45.00 | 49.50 |
| | Mean cloud cover (Octa) | 1.35 | 0.83 | 1.03 | 0.98 | 1.10 | 2.45 | 4.45 | 3.00 | 3.00 | 1.30 | 0.70 | 0.93 |

### 3.4.4 Evapotranspiration

The normal monthly evapotranspiration in the basin is presented in Table 3.2. The average annual evapotranspiration varies from 1380 mm to 1555 mm in the basin. The evapotranspiration is maximum during the month of May, mostly averaging more than 200 mm. The evapotranspiration reduces to around 100 mm to 120 mm in months of July to October and reduces further in winter months to its minimum value throughout the basin.

### 3.4.5 Wind Velocity

The mean monthly wind velocities observed at various stations is presented in Table3.3. The wind velocity in the basin ranges from 2 km/hr to 4.5 km/hr in the months of October to February. The wind velocity gradually increases thereafter and becomes maximum during pre-monsoon period. The wind velocities are roughly 8 km/hr to 12 km/hr during the monsoon period.

## 3.5 SOILS AND LAND USE

### 3.5.1 Soils

Detailed soil survey and investigations are not carried out in the Chambal basin. Based on broad reconnaissance survey conducted by state agricultural department, the soils of the basin can be classified as deep medium black soils, non brown soils, alluvial soils of recent origin, yellowish brown soils, red loams, brown soils of saline phase and hilly soils.

Black soils have primarily developed from basaltic trap and are predominantly clayey in texture. The soil depth varies widely from shallow to very deep. They swell on wetting and shrink on drying owing to predominance of montmorillonitic type of clay mineral. These soils are found in parts of Kota, Bundi, Chittorgarh and Bhilwara districts of Rajasthan and Shivpuri,Guna and Mandsor district of Madhya Pradesh.

Alluvial soils are clayey loam to clay, sub angular to angular blocky in structure, non-calcareous and moderately to poorly drained. These soils are found in parts of Sawai Madhopur and Bharatpur districts of Rajasthan, and Bhind, Morena and Mandsour districts of Madhya Pradesh.

Red loams found in Chittorgarh are shallow to moderately deep, sandy loam to loam in texture, non-calcareous and well drained. The pH and EC values are 8.0 and 3.2 mmhos/cm, respectively.

Yellowish brown soils found in parts of Bhilwara, Sawai Madhopur, Ajmer and Udaipur are loamy to clayey loam in texture, non-calcareous and moderately well drained. The pH and EC values are 8.3 and 1.4 mmhos/cm, respectively.

Hilly soils are found along the hill range of Aravalli ranges. These are shallow, gravelly loam grayish brown to reddish brown in colour, non-calcareous and moderately well drained. The pH and EC are 7.6 and 0.66 mmhos/cm, respectively.

Desert calcareous brown soils are found in some parts of western Rajasthan. These are deep, sandy or loamy sand to sandy loam in texture, yellowish brown, granular, calcareous and well drained with pH and EC values of 8.10 and 1.2 mmhos/cm, respectively.

The principal soil types found in various districts lying in the basin are presented in Table 3.4.

**Table 3.4** Soils in Chambal basin

| State | District | Type of soil |
|---|---|---|
| Madhya Pradesh | Indore | Medium black |
| | Ujjain | Medium black |
| | Ratlam | Medium black and mixed red and black |
| | Mandsour | Medium black and mixed red and black |
| | Morena | Medium black |
| | Bhind | Medium black |
| | Dewas | Medium black |
| | Shajapur | Medium black |
| | Rajgarh | Medium black |
| | Guna | Medium black and mixed red and black |
| | Shivpuri | Medium black and mixed red and black |
| | Vidisha | Medium black |
| | Dhar | Medium black |
| | Sehore | Medium black |
| Rajasthan | Chittorgarh | Red and yellow and mixed red and black |
| | Kota | Medium black, mixed red and black and alluvial |
| | Bundi | Medium black, mixed red and black and alluvial |
| | Sawai Madhopur | Red and yellow and medium black |
| | Udaipur | Red and yellow |
| | Jhalawar | Medium black |
| | Tonk | Alluvial |
| | Bhilwara | Red and yellow and mixed red and black |
| | Jaipur | Alluvial |
| | Bharatpur | Red and yellow medium black and alluvial |
| | Ajmer | Mixed red and black and gray brown |
| Uttar Pradesh | Agra | Medium black and alluvial |
| | Etawah | Alluvial and saline |

### 3.5.2 Land Use

The total geographical area of the Chambal basin is 135971 sq km. The annual land use figures for all the basins for the year of maximum cultivable area from the available years data has been presented in the Table 3.5. The cultivable area is considered as the total of the areas falling under culturable wasteland, land under miscellaneous crops and trees, current fallows, other fallows and net area sown. The land use particulars of the Chambal basin is calculated by adding the land use particulars of each basin for the year of maximum culturable area.

**Table 3.5** Land use particulars in Chambal Basin

| Basin | Banas | Upper Chambal | Lower Chambal | Kalisindh | Parbati |
|---|---|---|---|---|---|
| Year of maximum culturable area | 1976-77 | 1982-83 | 1976-77 | 1982-83 | 1992-93 |
| **(A) Unculturable land** | | | | | |
| 1. Forest area | 297.45 | 116.95 | 616.21 | 270.79 | 318.54 |
| 2. Land put to non agricultural use | 263.82 | 147.56 | 138.77 | 135.85 | 84.11 |
| 3. Barren and unculturable land | 672.63 | 111.53 | 408.99 | 168.43 | 107.85 |
| 4. Permanent pasture and other grazing land | 471.37 | 208.50 | 130.40 | 233.37 | 101.43 |
| **Sub total (A)** | **1705.27** | **584.54** | **1294.40** | **808.45** | **611.93** |
| **(B) Culturable land** | | | | | |
| 5. Land under misc. crops and trees | 1.14 | 0.48 | 19.64 | 1.76 | 0.79 |
| 6. Culturable waste land | 698.20 | 109.69 | 272.69 | 144.79 | 81.37 |
| 7. Other fallow | 236.26 | 17.06 | 55.21 | 33.43 | 23.37 |
| 8. Current fallow | 204.29 | 9.77 | 60.61 | 24.34 | 19.76 |
| 9. Net area sown | 1956.99 | 1553.27 | 765.27 | 1453.42 | 848.88 |
| **Sub total (B)** | **3096.88** | **1690.26** | **1173.40** | **1657.74** | **974.17** |
| 10. Area sown more than once | 507.99 | 532.23 | 136.50 | 334.50 | 168.96 |
| 11. Gross area sown (Item 9 + Item 10) | 2464.98 | 2085.49 | 901.77 | 1787.91 | 1017.84 |
| **12. Geographical area** (Sub total A + Sub total B) | **4802.15** | **2274.80** | **2467.80** | **2466.18** | **1586.10** |

Note: For the year of maximum culturable area of each basin. Unit-1000 ha.

### 3.5.3 Land Holdings

The number and size of land holdings of different districts of the basin have been calculated on pro rata basis. About 70 percent of land holding is 4 ha and above. Table 3.6 presents land-holding particulars for Chambal basin.

**Table 3.6** Existing Land holding particulars in Chambal basin

| Size of land holdings | Holdings | | Land holding area | |
|---|---|---|---|---|
| | Number | (%) | (ha) | (%) |
| Up to 1 ha | 1299138 | 46.11 | 309280 | 4.31 |
| 1 ha to 2 ha | 463009 | 16.43 | 666108 | 9.28 |
| 2 ha to 4 ha | 500273 | 17.76 | 1334774 | 18.59 |
| 4 ha to 10 ha | 421506 | 14.96 | 2557011 | 35.62 |
| Above 10 ha | 133197 | 4.74 | 2311762 | 32.20 |
| Total | 2817123 | 100.00<br>(14% of total population of 19757393) | 7178935 | 100.00<br>(53% of total geographic area of 135971 sq km) |

## 3.6 REGIONAL ECONOMY

### 3.6.1 Population

The population of the Upper Chambal, Lower Chambal, Kalisindh and Parbati basins are assessed, based on the population of block (sub district) and area of each block falling in the basin. The block level population is summed to derive the basin population. The total population of the four basins based on 1991 census was 12141154, of which 8684438 was rural and 3456716 was urban. The density of population was 143 persons per sq km as per

1991 census. The total, rural and urban population statistics of the basins is presented in Table 3.7.

**Table 3.7** Population statistics in Upper Chambal, Lower Chambal, Kalisindh and Parbati basins

| Census Year | Type | Population | | | |
|---|---|---|---|---|---|
| | | Upper Chambal | Lower Chambal | Kalisindh | Parbati |
| 1971 | Total | 2649421 | 1596364 | 1994478 | 1258484 |
| | Rural | 1732721 | 1297304 | 1803008 | 1046292 |
| | Urban | 916700 | 299060 | 191470 | 212192 |
| 1981 | Total | 3348713 | 2097952 | 2525833 | 1634455 |
| | Rural | 2075801 | 1628160 | 2236606 | 1321812 |
| | Urban | 1272912 | 469792 | 289227 | 312643 |
| 1991 | Total | 4171075 | 2777654 | 3195678 | 1996747 |
| | Rural | 2368080 | 2030556 | 2704449 | 1581353 |
| | Urban | 1802995 | 747098 | 491229 | 415394 |

### 3.6.2 Forest

The area covered by the forest is 1546746 ha, which is 11.38% of the total area of the basin, as compared to national average of 22 percent. Large forest area lies in Guna, Sheopur, Mandsour, Dhar, Bhind and Indore in Madhya Pradesh and Kota, Jhalawar, Bundi districts of Rajasthan state. These forests can be classified as dry scrub, tropical throne type and subsidry edapic type. Important forest products are wax, timber, firewood, charcoal, gum, tendu leaves, bamboo, honey and herbs.

### 3.6.3 Agriculture and Animal Husbandry

Out of the total culturable area of 8452780 ha of the basin, net area sown is 6486755 ha and gross area sown is 8150693 ha, respectively. The culturable area is 62.17% of the total geographical area of the basin. Agriculture in the catchment is mostly rain fed. The principal crop grown in the basin is wheat. The other crops are paddy, maize, gram, jowar, bajra, barley, groundnut, pulses, cotton, vegetables and sugarcane.

Most of the farmers depend on cattle for agriculture operations. The live stock population in the basin is not available for a commom year. For Banas basin data of year 1977, for Upper Chambal basin data of 1982, for Lower Chambal basin data of 1977, for Kalisindh basin data of 1983 of Madhya Pradesh portion and data of 1972 for Rajasthan portion and for Parbati basin the data of 1995 of Madhya Pradesh portion and data of 1992 of Rajasthan portion is available. The live stock population data are presented in Table 3.8.

**Table 3.8** Live stock populations in Chambal basin

| State | Basin | | | | |
|---|---|---|---|---|---|
| | Upper Chambal | Lower Chambal | Kalisindh | Parbati | Banas |
| Madhya Pradesh | 2432.90<br>(1982) | 851.248<br>(1977) | 1738.41<br>(1983) | 1019.17<br>(1995) | 90.72<br>(1977) |
| Rajasthan | 260.54<br>(1982) | 1931.983<br>(1977) | 1252.02<br>(1972) | 598.00<br>(1992) | 8654.11<br>(1977) |
| Uttar Pradesh | - | 116.708<br>(1977) | - | - | - |

Note: Figures in brackets indicate census year. Unit: Thousand.

### 3.6.4 Power

There are three hydel projects located in the Chambal catchment, viz., Gandhi Sagar (5x23 MW), Ranapratap Sagar (4x43 MW) and Jawahar Sagar (3x33 MW). One atomic power project (1220 MW) and one thermal power project (640 MW) are located in Kota. Nearly 80 percent of villages in the basin are electrified.

### 3.6.5 Mineral Wealth

The basin possesses a variety of mineral resources. Coper, lead, zink, silicon, mica, asbestos, clay lime, Kota stone are available in Kota and Jhalawar districts. Dolamite, marble, cement grade and limestone occur in the Chittorgarh and silica sand is found in Sapotra tehsils, respectively.

### 3.6.6 Industries

The basin has a number of large scale industries, important among them are related to textile, sugar, cement, paper card board, steel, synthetic fibre, cotton yarn, electric goods, chemicals, mica, bricks, gypsum and alkali salt located at Kota, Ujjain, Dewas, Jhalawar, Guna, Indore, Jaipur, Udaipur and other towns.

A gas based fertilizer plant is set up at Vijaypur in Guna district. Dewas is the only district in Madhya Pradesh which is industrialized for mainly textiles, dyeing, tanning and steel manufacturing units. In Rajasthan portion Kota district has a large number of medium scale industries, i.e., paper, wood, printing, leather, copper, tubes and rodes, chemicals etc. The famous Kota sarees are made in the small-scale sector of this region.

### 3.6.7 Communication

The region has a well-developed network of railways, national highway, state highway, district and village roads. National Highway number 12 connects Bhopal, Rajgarh, Jhalawar, Kota and National Highway number 8 connects Jaipur and Udaipur districts while National Highway number 3 connects Dholapur, Shivpuri, Morena, Guna, Shajapur district of Chambal basin.

The Delhi-Jaipur-Ahmedabad, Jaipur-Udaipur-Chittorgarh, Delhi-Kota-Ratlam-Mumbai, Delhi-Bhopal-Ujjain-Indore, Indore-Ujjain-Mumbai routes of Western and Central railway passes through the basin.

Air routes connect Bhopal, Indore, Kota, Jaipur and Udaipur.

## 3.7 THE WATER TRANSFER PROPOSAL

The objective of the study as mentioned in Section 1.4.1 is to present a systems analysis application methodology for inter basin water transfer projects and demonstration of the methodology by applying it to a river linking project. The Parbati-Kalisindh-Chambal link is one out of 30 links identified by the NWDA. This link in the Chambal basin is considered for application of the systems analysis methodology.

Gandhi Sagar (GS), Ranapratap Sagar (RPS) and Jawahar Sagar (JS) are the three existing reservoirs in Chambal river. The GS is in the Upper Chambal basin and the rest two are in the Lower Chambal basin. Three proposed reservoirs, namely, Patanpur (PAT) in Parbati river, Mohanpura (MOH) in Newaz river and Kundaliya (KUN) in Kalisindh river are proposed to transfer surplus waters of Parbati and Kalisindh basins either to Upper Chambal basin (Link-I) or to Lower Chambal basin (Link-II) after supplying their respective water demands for domestic and irrigation purposes. The Newaz river is a tributary of Kalisindh river. The JS dam is just a pick-up dam for producing hydropower. Its gross storage capacity is 370 MCM in 1972. Considering the fact that the JS dam is almost always full due to its very limited storage capacity and it is in the downstream/lower side of all the other concerned reservoirs, the JS dam is not incorporated in this study. For water transfer, two alternative links are considered; Alternative I (Link-I) assumes that water will be exported from PAT to MOH, MOH to KUN and KUN to GS, and Alternative II (Link-II) assumes that the water transfer will be done from PAT to MOH, MOH to KUN, and KUN to RPS. The line diagrams of these two alternatives are shown in Fig. 3.2.

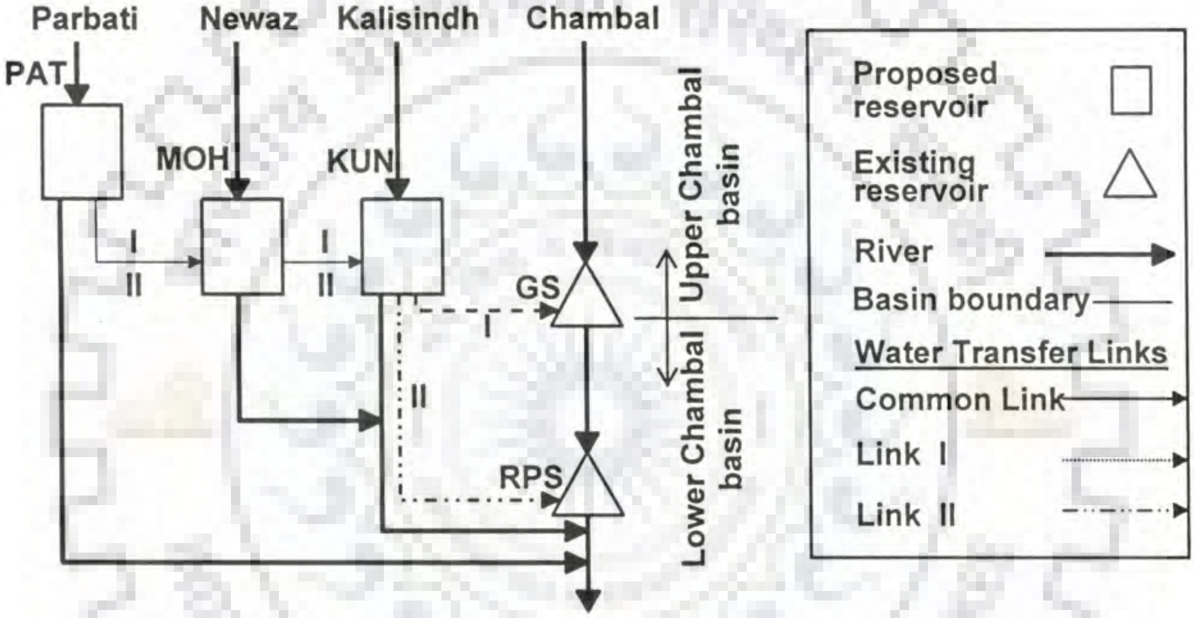

**Figure 3.2** Line diagram of the reservoir system

### 3.8 RESERVOIR PARAMETERS

The GS dam and the associated powerhouse was completed in 1960. It is a 65 m high masonry dam with an installed hydropower capacity of 115 MW with annual firm power of 80 MW at 60 percent load factor. The RPS, a 55 m high masonry dam, and a powerhouse with installed capacity of 172 MW and annual firm power of 90 MW at 60 percent load factor, was completed in 1967. The capacities of the GS and RPS reservoirs and the design capacities of the proposed reservoirs are presented in Table 3.9.

**Table 3.9** Design capacities of reservoirs in the system

| Reservoir | Status | Gross storage (MCM) | Live storage (MCM) | Dead storage (MCM) |
|---|---|---|---|---|
| Patanpur (PAT) | Proposed | 156 | 110 | 46 |
| Mohanpura (MOH) | Proposed | 140 | 122 | 18 |
| Kundaliya (KUN) | Proposed | 1275 | 1025 | 250 |
| Gandhi Sagar (GS) | Existing | 8449.34 | 7616.74 | 832.68 |
| Ranapratap Sagar (RPS) | Existing | 2898.68 | 1566.50 | 1332.20 |

The monthly net inflow records at reservoir sites are available for 17 years, starting from 1977 to 1993. The mean monthly flows at reservoir sites are presented in Fig. 3.3.

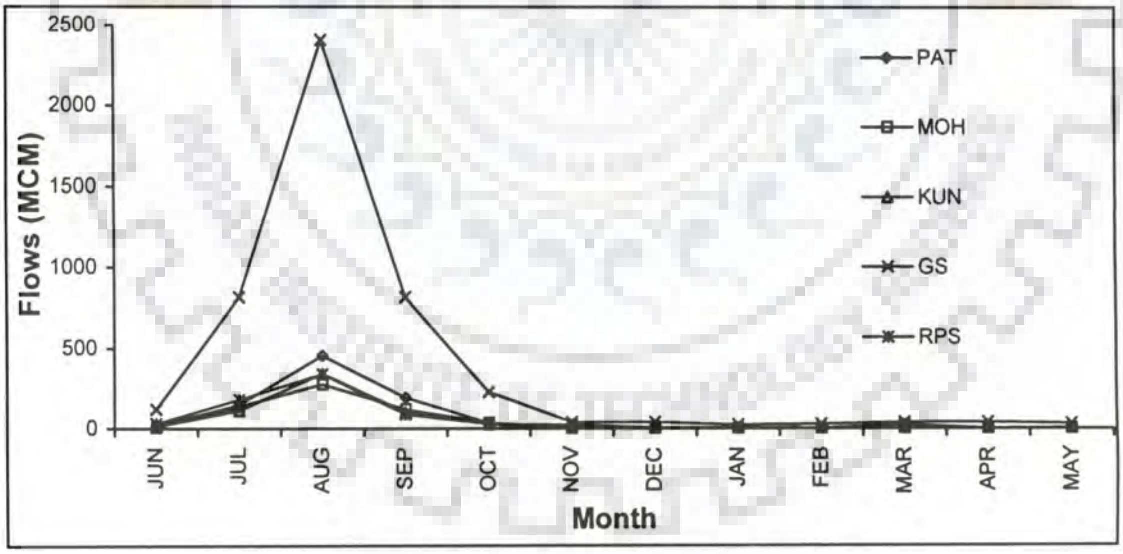

**Figure 3.3** Mean monthly flows at reservoir sites

The elevation-area-capacity data of the reservoirs as prepared by the NWDA are presented in Annexure-I. The storage-area curves and the storage-elevation curves of the reservoirs are presented in Annexure-II. The average monthly rates of evaporation losses as calculated by NWDA are given in Table 3.10. The values of the fraction of annual evaporation loss that occur in a period from reservoirs are presented in Fig. 3.4.

**Table 3.10** Average monthly rate of evaporation from reservoirs

| Month | Patanpur, Mohanpura and Kundaliya (m) | Gandhi Sagar and Ranapratap Sagar (m) |
|---|---|---|
| Jun | 0.2108 | 0.3 |
| Jul | 0.1313 | 0.15 |
| Aug | 0.1114 | 0.09 |
| Sep | 0.1185 | 0.12 |
| Oct | 0.1143 | 0.14 |
| Nov | 0.0740 | 0.11 |
| Dec | 0.0594 | 0.1 |
| Jan | 0.0666 | 0.1 |
| Feb | 0.0868 | 0.12 |
| Mar | 0.1363 | 0.22 |
| Apr | 0.1740 | 0.29 |
| May | 0.2280 | 0.38 |
| Total | 1.5114 | 2.12 |

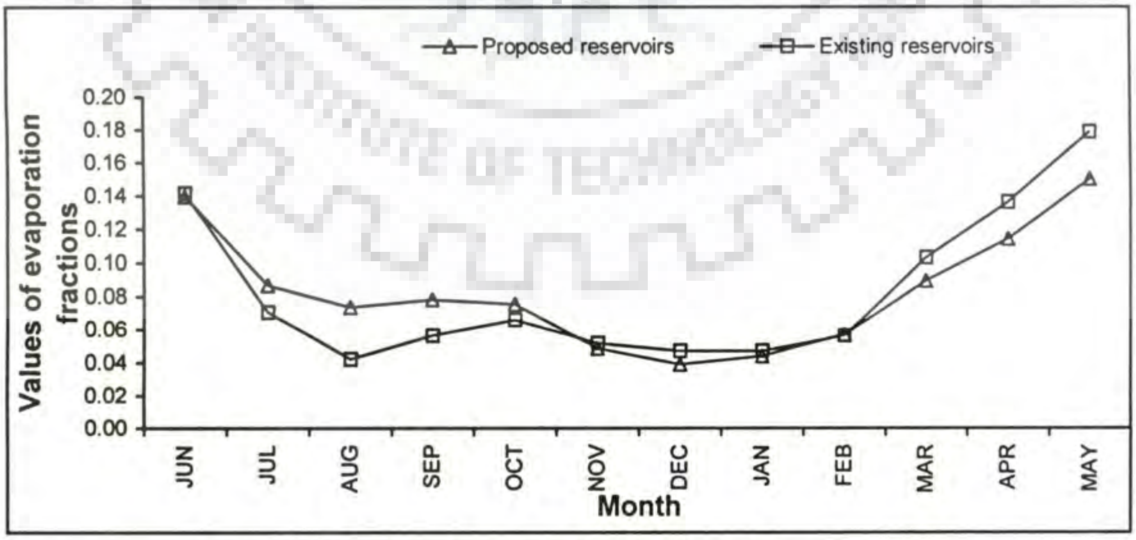

**Figure 3.4** Values of evaporation fractions from reservoirs

Reservoirs PAT, MOH and KUN have three purposes to serve, e.g., domestic water supply, irrigation and water export to other reservoirs. GS reservoir serves irrigation and power generation, and RPS reservoir is a single purpose hydropower reservoir. For GS reservoir, it is assumed that the irrigation water is also available for power generation. Table 3.11 shows the annual target water demands for domestic water supply and irrigation at these reservoirs.

**Table 3.11** Water demands for domestic water supply and irrigation from reservoirs

| Month | Patanpur (PAT) | | Mohanpura (MOH) | | Kundaliya (KUN) | | Gandhi Sagar (GS) |
|---|---|---|---|---|---|---|---|
| | WS | IRR | WS | IRR | WS | IRR | IRR |
| Jun | 0.25 | 9.59 | 0.25 | 9.87 | 0.60 | 21.91 | 109.63 |
| Jul | 0.25 | 21.92 | 0.25 | 22.56 | 0.60 | 50.08 | 556.58 |
| Aug | 0.25 | 15.07 | 0.25 | 15.51 | 0.60 | 34.43 | 1343.18 |
| Sep | 0.25 | 9.59 | 0.25 | 9.87 | 0.60 | 21.91 | 996.12 |
| Oct | 0.25 | 6.85 | 0.25 | 7.05 | 0.60 | 15.65 | 136.87 |
| Nov | 0.25 | 9.59 | 0.25 | 9.87 | 0.60 | 21.91 | 51.12 |
| Dec | 0.25 | 15.07 | 0.25 | 15.51 | 0.60 | 34.43 | 30.94 |
| Jan | 0.25 | 20.55 | 0.25 | 21.15 | 0.60 | 46.95 | 27.91 |
| Feb | 0.25 | 19.18 | 0.25 | 19.74 | 0.60 | 43.82 | 20.85 |
| Mar | 0.25 | 4.11 | 0.25 | 4.23 | 0.60 | 9.39 | 29.59 |
| Apr | 0.25 | 2.74 | 0.25 | 2.82 | 0.60 | 6.26 | 32.62 |
| May | 0.25 | 2.74 | 0.25 | 2.82 | 0.60 | 6.26 | 27.58 |
| Total | 3.00 | 137.00 | 3.00 | 141.00 | 7.20 | 313.00 | 3363.00 |

Note: WS-domestic water supply, IRR-irrigation. All values are in MCM.

# ASSESSMENTS OF WATER RESOURCES

## 4.1 INTRODUCTION

Water is a basic human need and a prime natural resource. It is hard to believe that this earth in which water seems to be the dominant element should ever face a shortage of water. According to UN estimates, the total amount of water on earth is around 1,4000 million km$^3$, which is enough to cover the earth with a water layer of a depth of 3,000 metres. However, oceans cover about three-fourths of the earth's surface and nearly 97 percent of earth's water is in oceans and seas. Fresh water constitutes a very small proportion (2.7 percent) of the total quantity of water available on the earth. Of this, 75.2 percent lies frozen in polar regions and a further 22.6 percent is present as groundwater, of which again a part lies too far underground to be used. Fortunately, a tiny fraction of the planet's water is renewed and made fresh by nature's solar-powered water cycle. This is available in lakes, rivers, atmosphere, moisture, soil and vegetation. What is effectively available for consumption and other uses is a small proportion of the quantity present in rivers, lakes and underground aquifers. Again, there are great variations in the availability of fresh water over space and time. The pressure on the availability of usable water is mounting because of the finite nature of the supply and the ever-increasing demand on it by a growing population aspiring to higher standards of living. It is most crucial for sustaining life and required in almost all the activities of man, i.e., domestic and industrial use, irrigation to meet the growing food and fiber needs, power generation, navigation and recreation etc. The development, conservation and use of water, therefore, forms one of the main elements in a country's development planning. The National Water Policy adopted by the Govt. of India in 1987 emphasized the need for inter basin transfer of water. It states that water should be made available to water short areas by transfer from other areas including transfer from one river basin to another based on National perspectives after taking into account requirements of the areas/basins.

Water balance study is carried out for basins to know their water demands and water availability to decide whether water is needed to be imported from other basins to meet the water demands, or whether the basin is capable of exporting water, if its availability is more than the demands. Water can be transferred from a river basin to another, only when the exporting basin is surplus (water availability at 75% water year dependability exceeds annual water demands in the basin) in its surface water resources as per NWDA guidelines. For determining whether a river basin is surplus or deficit in its surface water resources at 75% water year dependability in comparison to basin's annual water demands, an assessment of the annual water balance of each river basin is required. Here, the water balance meant a comparison between the river basin's annual water availability and annual water demands, and differs from the conventional meaning of water balance.

The objective of this water balance study is to find the status of the future water balance of the basins, which are involved as donor/recipient basins in the proposed inter basin water transfer proposal through the Parbati-Kalisindh-Chambal water transfer link. In order to develop broad understanding of water surplus and water deficit basins, water balance analysis is carried out for the Upper Chambal, Lower Chambal, Kalisindh and Parbati basins. The existing Gandhi Sagar reservoir is hosted by the Upper Chambal basin, Ranapratap Sagar and Jawahar Sagar reservoirs are hosted by the Lower Chambal basin and the proposed Kundaliya and Mohanpura reservoirs are hosted by the Kalisindh basin and the Parbati basin hosts the proposed Patanpur reservoir. The water balance study is done for the year 2050 AD, with the general expectation that the population will be hopefully stabilize by 2050 AD.

National Water Development Agency (NWDA) is working on the methodology (National Water Development Agency, 1991b) of 'water balance study' for more than twenty years, and has given complete guidelines for performing water balance of a river basin. Since the prime objective of this research work is to present a methodology for inter basin water transfers using system analysis techniques, the guidelines framed by the NWDA are not questioned and are followed as it is. The only difference is that the NWDA does not consider the ground water resources in estimating the 'water surplus' or 'water deficit' status of basins; in the present study, the ground water is considered as an additional resource for estimating the water balance. The ground water availability is taken as per the Central Ground Water Board guidelines (Central Ground Water Board, 1995). The NWDA has completed a water balance study on Chambal basin (National Water Development Agency, 1991a) in the year 1991. Since then some of the data are updated and some guidelines for calculating water demands are changed (like change in the calculation of irrigation requirements, addition of water requirement for environmental and ecological purposes and change in the calculation of regeneration of water from upstream uses). Hence an attempt is made in present work to reassess the water demands in the Chambal basin at sub-basin levels, whereas estimation of water resources here is reported directly from NWDA reports. Only the water balance study reports of the catchment areas of the proposed dam sites are comparatively new which follow the recent NWDA guidelines. So the results of these reports at proposed dam sites are directly incorporated.

In India, "water year" starts from either the month of June or July, depending on arrival of normal monsoon in a particular region. In Chambal basin, water year is considered to start in June. Any reference to a "year", means a water year, starting in the month of June and ending in the month of May.

The water balance study is data intensive. The Chambal basin is declared as "classified", by the Ministry of Water Resources, Govt. of India. Even after sincere efforts, the monthly flow data at all the concerned gauge sites could not be collected. The monthly flow data at the reservoir sites could be collected for the available 17 years, from 1977 to 1993. These monthly flow data show that flow is almost negligible during non-monsoon period. Naturally a water balance study on monthly basis will show water deficiency in the basins during non-monsoon months. As water transfer will be done through reservoirs only, and reservoirs have the capability to conserve water for non-monsoon months, the water balance is done on yearly basis in this study. The permission to present the flow data of Chambal basin could not be obtained.

## 4.2 SURFACE WATER ASSESSMENT

The surface water potential at each basin level is reported here as such from the water balance study (National Water Development Agency, 1991a) made by NWDA. The NWDA determined the surface water potential by obtaining rainfall-runoff relationship through regression analysis, and the same is explained below. The observed monthly discharge data at Gandhisagar dam site in Upper Chambal basin (covering the entire basin), Barod in Kalisindh basin (covering 99.2 percent of catchment area) and Khatoli in Parbati basin (covering 97.2 percent of catchment area) are considered to derive the virgin yield of these basins. The virgin yields are worked out by summing the observed flows with the utilizations at the upstream sites. The general practice adopted by NWDA in calculating virgin yield is to consider 97% of upstream utilizations through major and medium projects and full upstream utilization of minor projects; and same criteria is adopted as such in this study. As no gauge and discharge site represents the Lower Chambal basin fully, the virgin yield of the basin is derived by average coefficient of runoff for adjacent gauge and discharge site of Baranwada on the Banas, Gandhisagar on the Upper Chambal, Khatoli on the Parbati, Barod on Kalisindh and Bhind on Kunwari.

The monthly rainfall data of rain gauge stations, influencing the catchment of basin were used to obtain weighted monsoon rainfall (WMR) by Thiessen's Polygon method. A basin map showing locations of the raingauge stations is given in Annexure III (a). The number of raingauge stations used were 18 for Upper Chambal basin (Indore, Badnagar, Ujjain, Dewas, Agar, Khachrod, Salina, Jaora, Sitamau, Neemuch, Dhar, Mhow, Depalpur, Taraha, Mahidpur, Mandsaur, Manasa and Garoth); 18 for Lower Chambal basin (Garoth, Neemuch, Begun, Hindoli, Bindi, Kota, Naenwa, Indergarh, Itawah, Antah, Sawai Madhopur, Khander, Sheopur, Sabulgarh, Bijaipur, Shahabad, Shivpuri and Guna); 15 for Kalisindh basin (Sankatch, Ashta, Shajapur, Shujalpur, Sarangapur, Agar, Biaora, Khilchipur, Pirawah, Pachpachar, Aklera, Jhalawar, Sangod, Angach and Itawah, ); and 12 for Parbati basin (Ashta, Ichhawar, Sehore, Narsingarh, Chachaura, Guna, Sheopur, Aklera, Chhipabarod, Mangrol, Shahabad and Itawah).

Using the monsoon virgin yield and WMR, rainfall-runoff relationships were developed by NWDA using regression analysis and best-fit equation for each basin were derived. These monsoon rainfall-runoff relationships for the basins are reported in Annexure-III (b). $R^2$ values for the rainfall-runoff relationships are 0.833, 0.891, 0.787 and 0.771 for Upper Chambal, Lower Chambal, Kalisindh and Parbati basins, respectively. The weighted monsoon rainfall data were available for a common period of 1930 to 1982. This data was used to compute monsoon runoff and the annual yields were obtained by adding non-monsoon yields to monsoon yields and then water year dependable flows at 75% and 50% levels were determined. The 75 % water year dependable flows for Upper Chambal, Lower Chambal, Kalisindh and Parbati were found to be 3024.35 MCM, 5114.42 MCM, 5096.16

MCM and 4748.02 MCM, respectively. The 50 % water year dependable flows were 5489.22 MCM, 7464.70 MCM, 8667.91 MCM and 6406.89 MCM, respectively.

## 4.3 IMPORTS AND EXPORTS

For Upper Chambal basin, there is no import of water for irrigation use from outside the basin. However, the proposed Indore water supply scheme will draw 66.37 MCM of water per annum from the Narmada basin for water supply to Indore, Mhow and Rau. Beside this, a quantity of 4.42 MCM is also proposed to be diverted from the Choral project in Indore district of the Narmada basin to Chambal for water supply to the Indore city. The total annual import from the Narmada basin will thus be 71 MCM.

As per the project report of Gandhi Sagar reservoir prepared by the Madhya Pradesh state in respect of sharing of the Chambal water, 3947 MCM of water is committed from the Gandhi Sagar reservoir to meet the requirements of hydropower generations at Gandhi Sagar, Ranapratap Sagar and Jawahar Sagar reservoirs; and for irrigation use of the Kota barrage. The water requirement for hydropower at Gandhi Sagar is assessed to be 584 MCM. The balance downstream committed use (3363 MCM) is considered as the export from the Upper Chambal basin and import to the Lower Chambal basin. Also, 15.00 MCM of water of the Kunwari basin is proposed to be utilized to irrigate 3818 ha in the command of the Ambah branch canal in the Lower Chambal basin.

A quantity of 540 MCM of water from Lower Chambal basin is proposed to irrigate an area of 47.00 ha in Kota and Jhalawar districts of Rajasthan in Kalisindh basin. An area of 41710 ha in the Parbati basin in Kota district of Rajasthan and Morena district of Madhya Pradesh is covered under the Chambal Ayacut Development (phase-II) Project, utilizing 357.39 MCM of water. This is considered as import to Parbati basin and export from Lower Chambal basin. The import and export of water are presented in Table 4.1 (a) and Table 4.1 (b), respectively.

**Table 4.1(a)** Import into various basins in Chambal

| Recipient basin | Donor basin | Purpose | Volume (MCM) |
|---|---|---|---|
| Upper Chambal | (a) Narmada basin | Water supply | 66.37 |
| | (b) Narmada basin (Choral Project) | Water supply | 4.42 |
| | | | Total=71.00 |
| Lower Chambal | (a) Upper Chambal (Gandhi Sagar Dam) | Hydropower and Irrigation | **3363.00** |
| | (b) Kunwari basin | Irrigation | 15.00 |
| | | | Total=3378.00 |
| Kalisindh | Lower Chambal (Chambal canal system) | Irrigation | **540.00** |
| Parbati | Lower Chambal (Chambal canal system) | Irrigation | **357.39** |

**Table 4.1(b)** Export from various basins in Chambal

| Donor basin | Recipient basin | Purpose | Volume (MCM) |
|---|---|---|---|
| Upper Chambal | Lower Chambal | Hydropower and irrigation | **3363.00** |
| Lower Chambal | (a) Kalisindh | Irrigation | **540.00** |
| | (b) Parbati | Irrigation | **357.39** |
| | (c) Kunwari and Sindh | | |
| | • Existing | Irrigation | 1104.00 |
| | • Ongoing | Irrigation | 67.00 |
| | • Proposed | Irrigation | 568.47 |
| | (d) Uttangan | Irrigation | 370.00 |
| | | | Total=3006 |

## 4.4 ASSESSMENT OF GROUND WATER POTENTIAL

The methodology recommended by NWDA does not include ground water potential while assessing the total water resources in a basin. Huge capital and maintenance expenditures are involved in a inter basin water transfer project. Such projects are prone to legal and political conflicts. Other consequences, like environmental, ecological, land separation by canals are also involved. So, it is felt that before taking any decision regarding inter basin water transfer, the total available water in the concerned basins should be assessed, including ground water resources.

The Central Ground Water Board (CGWB) has presented the total annual replenishable ground water resources and annual existing gross draft for different states in India in a district-wise manner (*Ground Water Resources of India*, Ministry of Water Resources, Govt. of India, Faridabad, 1995). The CGWB has also given guide lines to keep separate a part of the (15%) total ground water for only drinking and industrial purpose. The remaining part may be used for irrigation purpose. The following paragraph discusses how the balance ground water resource for future use is calculated by following the CGWB guidelines.

The ground water potential, net draft and balance ground water potential for future use are worked out at basin level. The replenishable ground water resource from normal natural recharge and canal irrigation system and existing annual drafts are assessed on proportionate area basis from the district-wise data given in ground water statistics for Madhya Pradesh and Rajasthan published by Central Ground Water Board (CGWB) in the year 1995. The total replenishable ground water resources are calculated by adding the replenishable ground water resource from normal natural recharge and from canal irrigation system. Provision for domestic, industrial and other uses is kept as 15% of total replenishable ground water resource. Available ground water resources for irrigation is calculated by subtracting the water demarcated for use in domestic, industrial and other sectors from total replenishable ground water. Utilizable ground water resource for irrigation is considered as 90% of the replenishable ground water resources available for irrigation use. Net annual ground water draft is considered as 70% of the annual gross draft. Balance ground water resources for future irrigation use is calculated by subtracting net annual draft from annual available ground water resources for irrigation use.

The details for ground water resources assessed are given in Annexure-IV.

## 4.5 WATER NEEDS

Assessment of reasonable requirements of water in the foreseeable future for various purposes including domestic, irrigation, hydropower, industries and navigation is essential for planning of water resources management and development. The water needs are to be met either from surface flows or from ground water resources or from combination of both. Assessment of reasonable requirement of water by the end of 2050 AD under each category of water use has been attempted in the following paragraphs.

### 4.5.1 Domestic Water Needs

The requirements of water for domestic use in the rural and urban areas and for live stock population of the basins have been calculated by projecting the rural, urban and live stock populations to 2050 AD and considering per capita water requirement of 200 liters, 70 liters and 50 liters per capita per day for domestic urban, rural and live stock population categories, respectively. The available census data for the years 1971, 1981 and 1991are used for human population forecasting. The total human population and rural human population are projected to 2050 AD on the basis of the method recommended by the NWDA. The projected urban human population is then worked out by deducting projected rural population from the projected total population. The formula and rules given by NWDA for population projection are as follows:

$P_{2050} = P_{1991} (1+r)^n$

where

$P_{2050}$ = population in the year 2050 AD;

$P_{1991}$ = population in the year 1991;

r = annual compound rate of growth; and

n = number of years.

The annual compound growth rate is adopted on the following basis:

(i) The annual compound growth rate of 1981-91 decade shall be adopted when there is a decreasing trend in growth rate of population from 1971-81 decade to 1981-91 decade.

(ii) The annual compound growth rate shall be adopted as average of annual compound growth rate of 1971-81 decade and 1981-91 decade when the annual compound growth rate of population shows an increasing trend from 1971-81 decade to 1981-91 decade.

(iii) The annual compound growth rate is to be restricted to 2.5% for both total and rural population in both the above cases.

(iv) The live stock population shall be projected to 2050 AD on the basis of same formula as above, but considering an annual compound growth rate of 1%.

The live stock population is calculated considering a growth rate of 1% for all the basins as recommended by NWDA. The live stock populations for the years 1982 for Upper Chambal basin, 1977 for Lower Chambal basin and 1983 for Kalisindh basin are used for live stock population forecasting. For Parbati basin, data for the years 1995 for Madhya Pradesh state and 1992 for Rajasthan state is used.

The full water requirement of urban human population and 50% of rural human population is considered to be met from surface water resources and the water requirement of remaining 50% of rural human population and entire live stock population is considered to be met from ground water resources. The projected human and livestock populations for the year 2050 AD and the water requirements are presented in Table 4.2.

### 4.5.2 Irrigation Needs

For assessing the surface water need for irrigation, estimate has been made of the areas that can be brought under irrigation and the reasonable requirement for irrigation area. The area that can be brought under irrigation by surface water is taken to comprise of the area presently under irrigation from the existing major, medium and minor projects and the area that would be brought under irrigation from the ongoing and identified future major, medium and minor projects. The design annual irrigation and utilization for the existing and ongoing projects have been kept undisturbed while assessing annual irrigation water needs. Estimated annual surface irrigation water needs for all the basins for existing and ongoing projects are presented in Table 4.3.

**Table 4.2** Projected population and water requirement by the year 2050 AD

| Basin | Human population | | Live stock population | Water requirement (MCM) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Human | | Live stock | Total | From surface water | From ground water |
| | | | | Rural | Urban | | | | |
| Upper Chambal | Rural | 5232135 | 5313462 | 133.68 | 754.96 | 96.97 | 985.61 | 821.80 | 163.81 |
| | Urban | 10341880 | | | | | | | |
| | Total | 15574015 | | | | | | | |
| Lower Chambal | Rural | 7626348 | 5728724 | 194.85 | 512.63 | 104.55 | 812.03 | 610.06 | 201.98 |
| | Urban | 7022373 | | | | | | | |
| | Total | 14648721 | | | | | | | |
| Kalisindh | Rural | 8465326 | 6106646 | 216.29 | 338.77 | 111.45 | 666.51 | 446.92 | 219.60 |
| | Urban | 4640685 | | | | | | | |
| | Total | 13106008 | | | | | | | |
| Parbati | Rural | 4639328 | 2826630 | 118.53 | 145.24 | 51.59 | 315.36 | 204.51 | 110.86 |
| | Urban | 1989583 | | | | | | | |
| | Total | 6628911 | | | | | | | |

**Table 4.3** Estimated annual surface irrigation water needs for existing and ongoing projects in basins

| Basin | Category | Area (ha) | | Water requirements (MCM) | | Total water requirements (MCM) |
|---|---|---|---|---|---|---|
| | | Madhya Pradesh | Rajasthan | Madhya Pradesh | Rajasthan | |
| Upper Chambal | **Existing** | | | | | |
| | Major | - | - | - | - | - |
| | Medium | 2951.92 | - | 16.45 | - | 16.45 |
| | Minor | 24225.67 | 330.00 | 132.61 | 2.63 | 135.32 |
| | | | | | | Total=151.77 |
| | **Ongoing** | | | | | |
| | Major | - | - | - | - | - |
| | Medium | 8262.00 | - | 42.20 | - | 42.20 |
| | Minor | 2921.00 | 207 | 16.84 | 1.44 | 18.28 |
| | | | | | | Total=60.48 |
| Lower Chambal | **Existing** | | | | | |
| | Major | 104143.0 | 205571.0 | 790.56 | 1168.00 | 1958.56 |
| | Medium | 3725.00 | 9430.00 | 26.05 | 90.67 | 116.72 |
| | Minor | 1009.00 | 18324.00 | 3.32 | 116.45 | 119.77 |
| | | | | | | Total=2195.05 |
| | **Ongoing** | | | | | |
| | Major | 9207.00 | 10785.00 | 50.64 | 93.60 | 144.24 |
| | Medium | - | - | - | - | - |
| | Minor | 1619.00 | 17795 | 9.10 | 107.26 | 116.36 |
| | | | | | | Total=260.60 |
| Kalisindh | **Existing** | | | | | |
| | Major | 47000.00 | - | 540 (Import) | - | 540 (Import) |
| | Medium | 6812.16 | - | 89.96 | - | 89.96 |
| | Minor | 7782.00 | 2397.00 | 45.14 | 24.42 | 69.56 |
| | | | | | | Total=699.52 |
| | **Ongoing** | | | | | |
| | Major | - | - | - | - | - |
| | Medium | 24353 | 57482 | 104.07 | 517.34 | 621.41 |
| | Minor | 3334 | 4271 | 18.52 | 21.59 | 40.11 |
| | | | | | | Total=661.52 |
| Parbati | **Existing** | | | | | |
| | Major | 10769 | 30941 | 85.39 (Import) | 272.00 (Import) | 357.39 (Import) |
| | Medium | 19007 | 31091 | 96.82 | 263.78 | 360.60 |
| | Minor | 17491 | 6545 | 178.60 | 61.55 | 240.15 |
| | | | | | | Total=958.14 |
| | **Ongoing** | | | | | |
| | Major | - | - | - | - | - |
| | Medium | 8354 | 3846 | 42.33 | 28.84 | 71.17 |
| | Minor | 2219 | 1085 | 15.80 | 7.70 | 23.50 |
| | | | | | | Total=94.67 |

The water requirements for the identified future projects have been calculated based on the climatological approach. For annual irrigation from the identified major, medium and minor projects, irrigation intensities of 150%, 125% and 100%, respectively are adopted. Normal monthly values of potential evapotranspiration at Neemuch, Indore and Ratlam observatory for Upper Chambal basin; Sheopur and Kota observatory for Lower Chambal basin; Jhalawar observatory for Kalisindh basin and Guna observatory for Parbati basin are used for estimating the water requirements of crops. The water requirements for different crops are presented in Annexure-V.

The areas under different crops for the identified future major, medium and minor projects are computed from the suggested cropping pattern given in Table 4.4 and are presented in Table 4.5. The gross irrigation requirements of the crops have been worked out considering an irrigation efficiency of 70% for the crops under proposed minor projects and 55% for the crops under major and medium projects. In the absence of reliable evaporation data, evaporation losses have been considered at the rate of 10% of annual utilization for major reservoirs and 20% for medium and minor reservoirs and included under irrigation water needs. The details of calculation are presented in Annexure-VI. The annual surface irrigation water needs for all the existing, ongoing and proposed projects are presented in Table 4.6.

Table 4.4 Suggested cropping pattern for future projects

| Crops | Upper Chambal | | | Lower Chambal | | | Kalisindh | | | Parbati | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Major projects | Medium projects | Minor projects | Major projects | Medium projects | Minor projects | Major projects | Medium projects | Minor projects | Major projects | Medium projects | Minor projects |
| **Kharif** | | | | | | | | | | | | |
| Paddy | 30.0 | 25.0 | 21.0 | 12.0 | 10.0 | 7.0 | 30.0 | 25.0 | 21.0 | 30.0 | 25.0 | 21.0 |
| Jowar | 6.0 | 5.0 | 5.0 | 4.8 | 4.0 | 3.0 | 6.0 | 5.0 | 5.0 | 6.0 | 5.0 | 5.0 |
| Maize | 6.0 | 5.0 | 4.0 | 6.0 | 5.0 | 3.0 | 6.0 | 5.0 | 4.0 | 6.0 | 5.0 | 4.0 |
| Oilseeds | 6.0 | 5.0 | 4.0 | 7.2 | 6.0 | 6.0 | 6.0 | 5.0 | 4.0 | 6.0 | 5.0 | 4.0 |
| Pulses | 6.0 | 5.0 | 4.0 | 7.2 | 6.0 | 6.0 | 6.0 | 5.0 | 4.0 | 6.0 | 5.0 | 4.0 |
| Fodder | 6.0 | 5.0 | 4.0 | 4.8 | 4.0 | 3.0 | 6.0 | 5.0 | 4.0 | 6.0 | 5.0 | 4.0 |
| Cotton | | | | 4.8 | 4.0 | 3.0 | | | | | | |
| Bajra | | | | 4.8 | 4.0 | 3.0 | | | | | | |
| **Rabi** | | | | | | | | | | | | |
| Wheat | 36.0 | 30.0 | 30.0 | 60.0 | 50.0 | 35.0 | 36.0 | 30.0 | 30.0 | 36.0 | 30.0 | 30.0 |
| Barley | 12.0 | 10.0 | 8.0 | 3.6 | 3.0 | 3.0 | 12.0 | 10.0 | 8.0 | 12.0 | 10.0 | 8.0 |
| Gram | 12.0 | 10.0 | 4.0 | 6.0 | 5.0 | 5.0 | 12.0 | 10.0 | 4.0 | 12.0 | 10.0 | 4.0 |
| Pulses | 12.0 | 10.0 | 4.0 | | | | 12.0 | 10.0 | 4.0 | 12.0 | 10.0 | 4.0 |
| Oilseed | 6.0 | 5.0 | 5.0 | 12.0 | 10.0 | 10.0 | 6.0 | 5.0 | 5.0 | 6.0 | 5.0 | 5.0 |
| Vegetable | 6.0 | 5.0 | 4.0 | 6.0 | 5.0 | 5.0 | 6.0 | 5.0 | 4.0 | 6.0 | 5.0 | 4.0 |
| Fodder | | | | 3.6 | 3.0 | 3.0 | | | | | | |
| **Pernnnial** Sugarcane | 6.0 | 5.0 | 3.0 | 7.2 | 6.0 | 5.0 | 6.0 | 5.0 | 3.0 | 6.0 | 5.0 | 3.0 |
| **Total** (Cropping intensity) | 150.0 | 125.0 | 100.0 | 150.0 | 125.0 | 100.0 | 150.0 | 125.0 | 100.0 | 150.0 | 125.0 | 100.0 |

Unit: % of total cropped area

**Table 4.5** Area under different crops for the identified future projects

| Crops | Upper Chambal | | | Lower Chambal | | | Kalisindh | | | Parbati | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Major projects | Medium projects | Minor projects | Major projects | Medium projects | Minor projects | Major projects | Medium projects | Minor projects | Major projects | Medium projects | Minor projects |
| **Kharif** | - | | | | | | | | | | | |
| Paddy | | 8826.0 | 3763.2 | 6232.2 | 4981.4 | 1795.2 | 42601.6 | 21630.0 | 19480.4 | 44216.0 | 9729.0 | 12672.2 |
| Jowar | | 1765.2 | 896.0 | 2492.9 | 1992.6 | 769.4 | 8520.3 | 4326.0 | 4638.2 | 8843.2 | 1945.8 | 3017.2 |
| Maize | | 1765.2 | 716.8 | 3116.1 | 2490.7 | 769.4 | 8520.3 | 4326.0 | 3710.6 | 8843.2 | 1945.8 | 2413.8 |
| Oilseeds | | 1765.2 | 716.8 | 3739.3 | 2988.9 | 1538.8 | 8520.3 | 4326.0 | 3710.6 | 8843.2 | 1945.8 | 2413.8 |
| Pulses | | 1765.2 | 716.8 | 3739.3 | 2988.9 | 1538.8 | 8520.3 | 4326.0 | 3710.6 | 8843.2 | 1945.8 | 2413.8 |
| Fodder | | 1765.2 | 716.8 | 2492.9 | 1992.6 | 769.4 | 8520.3 | 4326.0 | 3710.6 | 8843.2 | 1945.8 | 2413.8 |
| Cotton | | | | 2492.9 | 1992.6 | 769.4 | | | | | | |
| Bajra | | | | 2492.9 | 1992.6 | 769.4 | | | | | | |
| **Rabi** | - | | | | | | | | | | | |
| Wheat | | 10591.2 | 5376.0 | 31161.2 | 24907.2 | 8976.1 | 51121.9 | 25956.0 | 27829.2 | 53059.2 | 11674.8 | 18103.2 |
| Barley | | 3530.4 | 1433.6 | 1869.7 | 1494.4 | 769.4 | 17040.6 | 8652.0 | 7421.1 | 17686.4 | 3891.6 | 4827.5 |
| Gram | | 3530.4 | 716.8 | 3116.1 | 2490.7 | 1282.3 | 17040.6 | 8652.0 | 3710.6 | 17686.4 | 3891.6 | 2413.8 |
| Pulses | | 3530.4 | 716.8 | | | | 17040.6 | 8652.0 | 3710.6 | 17686.4 | 3891.6 | 2413.8 |
| Oilseed | | 1765.2 | 896.0 | 6232.2 | 4981.4 | 2564.6 | 8520.3 | 4326.0 | 4638.2 | 8843.2 | 1945.8 | 3017.2 |
| Vegetable | | 1765.2 | 716.8 | 3116.1 | 2490.7 | 1282.3 | 8520.3 | 4326.0 | 3710.6 | 8843.2 | 1945.8 | 2413.8 |
| Fodder | | | | 1869.7 | 1494.4 | 769.4 | | | | | | |
| **Perennial** | | | | | | | | | | | | |
| Sugarcane | - | 1765.2 | 537.6 | 3739.3 | 2988.9 | 1282.3 | 8520.3 | 4326.0 | 2782.9 | 8843.2 | 1945.8 | 1810.3 |
| **Total** | - | 44130.0 | 17920.0 | 77903.0 | 62268.0 | 25646.0 | 213008.0 | 108150.0 | 92764.0 | 221080.0 | 48645.0 | 60344.0 |

Unit: Ha

**Table 4.6** Estimated annual surface irrigation water needs

| Basin | Project | Irrigation area (ha) | | | | Utilization (MCM) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Existing | Ongoing | Proposed | Total | Existing | Ongoing | Proposed | Total |
| Upper Chambal | Major | - | - | - | 100948 | - | - | - | 643 |
| | Medium | 2951.92 | 8262 | 44130 | | 16.45 | 42.20 | 327.44 | |
| | Minor | 24555.67 | 3128 | 17920 | | 135.32 | 18.28 | 103.26 | |
| Lower Chambal | Major | 309714 | 19912 | 77903 | 547346 | 1958.56 | 144.24 | 412.82 | 3330 |
| | Medium | 13155 | - | 62268 | | 116.72 | - | 350.18 | |
| | Minor | 19333 | 19415 | 25646 | | 119.77 | 116.36 | 111.19 | |
| Kalisindh | Major | 47000 | - | 213008 | 569452 | 540.00 | - | 1297.51 | 3858 |
| | Medium | 8911 | 81835 | 108150 | | 89.96 | 621.41 | 718.67 | |
| | Minor | 10179 | 7605 | 92764 | | 69.56 | 40.11 | 481.01 | |
| Parbati | Major | 41710 | - | 221080 | 461417 | 357.39 | - | 1421.16 | 3148 |
| | Medium | 50098 | 12200 | 48645 | | 360.60 | 71.17 | 341.13 | |
| | Minor | 24036 | 3304 | 60344 | | 240.15 | 23.50 | 333.21 | |

The total irrigation areas of each basin considering the existing, ongoing and identified proposed projects are compared with the culturable areas of the corresponding basin. The culturable area of each basin is considered to be the total of the land falling under miscellaneous crops and tree, culturable waste lands, other fallows, currents fallows and net area sown. The maximum culturable areas available from the data are considered for each basin. The ratio of the total annual irrigation to the culturable area for each basin is presented in Table 4.7.

**Table 4.7** Comparison of the total annual irrigation and culturable area

| Basin | Total irrigation (ha) | Culturable area (ha) | Ratio of annual irrigation to culturable area (%) |
|---|---|---|---|
| Upper Chambal | 100947.59 | 1690260 | 5.97 |
| Lower Chambal | 547346 | 1033834 | 52.94 |
| Kalisindh | 569452 | 1657737 | 34.35 |
| Parbati | 461417 | 974168 | 47.37 |

The annual irrigation through existing, ongoing and identified future projects based on surface water in the Upper Chambal basin is 100948 ha (5.97% of the culturable area of the basin), which is less than 30% of the culturable area of the basin. The NWDA suggests that the minimum ratio of annual irrigation to culturable area should be 30%. For the enhancement of level of irrigation to the extent of 30%, a provision of 2677 MCM surface water has been made. Details are given below.

Balance of 30% of the culturable area for which irrigation provision has been kept

= 0.30 x 1690260 - 100948

= 406130 ha

It is assumed that 50% of this area will be irrigated through medium projects and 50% will be irrigated through minor projects.

Additional water requirement = water requirement for medium projects + water requirement for minor projects

= (327.44/44130) x 0.5x406130 + (103.26/17920) x 0.5 x 406130

= 1506.72 + 1170.12

= 2676.84 MCM

Say 2677 MCM

### 4.5.3 Industrial Water Needs

Information regarding the existing, ongoing and proposed industries in the basins is not readily available. In the absence of relevant information, the water requirement for industrial use has been assumed to be of the same order as that for domestic use for each basin. This is proposed to be met from surface water.

### 4.5.4 Water Requirement for Hydropower Generation

There are three hydel projects located in the Chambal basin, namely Gandhi Sagar, Ranapratap Sagar and Jawahar Sagar. The average annual evaporation losses from Gandhi Sagar, Ranapratap Sagar and Jawahar Sagar reservoirs are 584 MCM, 286 MCM and 16 MCM, respectively. These evaporation losses are considered as requirement for hydropower generation. For Upper Chambal, evaporation losses from Gandhi Sagar reservoir and for Lower Chambal, evaporation losses from Ranapratap Sagar and Jawahar Sagar reservoirs are considered. No hydroelectric projects are proposed in the Kalisindh and Parbati basins.

### 4.5.5 Water Requirement for Environmental and Ecological Purposes

As recommended by NWDA, 10% of average annual lean season flow is assumed as the water requirement for environmental and ecological purposes for each basin.

## 4.6 REGENERATION

The regeneration from industrial water use and from surface water utilized for domestic purposes is assumed as 80%. For regeneration from irrigation water, 10% of the water to be utilized from the existing, ongoing and identified future major and medium irrigation projects, excluding evaporation losses from the storages, is considered to be available to the stream. The regeneration from irrigation water is presented in Table 4.8.

**Table 4.8** Regeneration from irrigation water

| Basin | Project | Estimated utilization (MCM) | Estimated utilization excluding evaporation (MCM) | Regeneration (MCM) |
|---|---|---|---|---|
| Upper Chambal | **Existing** | | | |
| | Medium | 16.45 | 13.71 | 1.37 |
| | **Ongoing** | | | |
| | Medium | 42.20 | 35.17 | 3.52 |
| | **Future** | | | |
| | Medium | 327.44 | 272.87 | 27.29 |
| | | | | **Total**=32.17 |
| | **Additional Water** | 1506.72 | 1255.60 | 125.56 |
| | | | | **Total**=157.73 |
| Lower Chambal | **Existing** | | | |
| | Major | 1958.56 | 1780.51 | 178.05 |
| | Medium | 116.72 | 97.27 | 9.73 |
| | **Ongoing** | | | |
| | Major | 144.24 | 131.13 | 13.11 |
| | **Future** | | | |
| | Major | 412.82 | 375.29 | 37.53 |
| | Medium | 350.18 | 291.82 | 29.18 |
| | | | | **Total**= 267.60 |
| Kalisindh | **Existing** | | | |
| | Major | 540.00 | 490.91 | 49.09 |
| | Medium | 89.96 | 74.97 | 7.50 |
| | **Ongoing** | | | |
| | Medium | 621.41 | 517.84 | 51.78 |
| | **Future** | | | |
| | Major | 1297.51 | 1179.55 | 117.96 |
| | Medium | 718.67 | 598.89 | 59.89 |
| | | | | **Total**= 286.22 |
| Parbati | **Existing** | | | |
| | Major | 357.39 | 324.90 | 32.49 |
| | Medium | 360.60 | 300.50 | 30.05 |
| | **Ongoing** | | | |
| | Medium | 71.17 | 59.31 | 5.93 |
| | **Future** | | | |
| | Major | 1421.16 | 1291.96 | 129.20 |
| | Medium | 341.13 | 284.28 | 28.43 |
| | | | | **Total**= 226.09 |

## 4.7 WATER BALANCE

The water balance study is carried out taking into account the surface and ground water availability, imports into the basins, exports from the basins, water needs for domestic, irrigation, industrial, hydropower and environment and ecology; and regeneration from domestic, industrial and irrigation water. The water balance study reports for Patanpur, Mohanpura and Kundaliya dam sites are collected from NWDA and directly incorporated into this report. The water balance study results are presented in Table 4.9 (a) to Table 4.9 (c).

It is observed that the Lower Chambal, Kalisindh and Parbati basins are surplus in water resources at 75% water year dependability. The Upper Chambal basin is deficit in surface as well as overall water (surface and ground) at 75% water year dependability; and is also deficit in surface water at 50% water year dependability. If the additional surface irrigation water requirement to enhance the level of surface water irrigation from 5.97% to 30% of the culturable area of the basin is not considered, this basin is deficit in surface water, but marginally surplus in overall water at 75% water year dependability.

The results of the water balance studies show that the Upper Chambal basin needs serious consideration for water import from Parbati and/or Kalisindh basin/basins through inter basin water transfers. The proposal of water transfer to Lower Chambal basin from Parbati and/or Kalisindh basin/basins may also be considered to reduce the load on Upper Chambal basin which is presently exporting 3363 MCM of water to Lower Chambal basin.

**Table 4.9 (a)** Water balance of Upper Chambal and Lower Chambal basins (Unit: MCM)

| Item | Upper Chambal | Lower Chambal |
|---|---|---|
| **1. SURFACE WATER** | | |
| **Availability** | | |
| (a) At 75% water year dependability | **3024.35** | **5114.42** |
| (b) At 50% water year dependability | **5489.22** | **7464.70** |
| (c) Surface water import (+) | 71.00 | 3378.00 |
| (d) Surface water export (-) | 3363.00 | 3006.00 |
| **Over all availability** | | |
| (e) At 75% water year dependability (a+c-d) | **-267.65** | **5486.42** |
| (f) At 50% water year dependability (b+c-d) | **2197.22** | **7836.70** |
| **2. WATER DEMANDS FROM SURFACE WATER** | | |
| (a) Irrigation | 642.95 | 3329.84 |
| (b) Domestic<br>(100% of urban and 50% of rural population requirements) | 821.80 | 610.06 |
| (c) Industrial | 985.61 | 812.03 |
| (d) Hydropower | 584.00 | 302.00 |
| (e) Environment and ecology<br>(10% of non-monsoon 75% dependable water year flow) | 18.60 | 36.67 |
| (f) Additional water requirement to enhance level of irrigation | 2677.00 | 0 |
| (g) Total of (a) to (e) | **3052.96** | **5090.60** |
| (h) Total of (a) to (f) | **5729.96** | **5090.60** |
| **3. REGENERATION** | | |
| (a) Irrigation (10% of major and medium projects excluding evaporation) | 32.17 | 267.60 |
| (b) Domestic (80% of 2b) | 657.44 | 488.04 |
| (c) Industrial (80% of 2c) | 788.49 | 649.62 |
| (d) Additional irrigation (10% of major and medium projects excluding evaporation) | 125.56 | 0 |
| (e) Total of (a) to (c) | **1478.10** | **1405.26** |
| (f) Total of (a) to (d) | **1603.66** | **1405.26** |
| **4. SURFACE WATER BALANCE** | | |
| Without considering additional water to enhance level of irrigation | | |
| (a) At 75% water year dependability (1e-2g+3e) | **-1842.24** | **1796.21** |
| (b) At 50% water year dependability (1f-2g+3e) | **622.63** | **4146.49** |
| Considering additional water to enhance level of irrigation | | |
| (c) At 75% water year dependability (1e-2h+3f) | **-4393.68** | **1796.21** |
| (d) At 50% water year dependability (1f-2h+3f) | **-1928.81** | **4146.49** |
| **5. GROUND WATER (GW)** | | |
| (a) Ground water potential | 2517.32 | 3255.29 |
| (b) Provision for domestic and industrial needs, @ 15% of (a) as per CGWB | 377.60 | 488.29 |
| (c) Projected rural domestic and livestock need<br>(50% of rural population and 100% of livestock requirements) | 163.81 | 201.98 |
| (d) Available GW for irrigation (a-b) | 2139.72 | 2767.00 |
| (e) Utilizable GW for irrigation (90% of d) | 1925.75 | 2490.30 |
| (f) Existing net draft | 874.51 | 564.99 |
| (g) Balance GW for future use (d-f) | 1265.21 | 2202.01 |
| (h) Utilizable GW potential after meeting projected needs (90% of (a-c)) | **2118.16** | **2747.98** |
| **6. OVER ALL WATER BALANCE** | | |
| Without considering additional water to enhance level of irrigation | | |
| (a) At 75% water year dependability (4a+5h) | **275.92** | **4544.19** |
| (b) At 50% water year dependability (4b+5h) | **2740.79** | **6894.47** |
| Considering additional water to enhance level of irrigation | | |
| (c) At 75% water year dependability (4c+5h) | **-2275.52** | **4544.19** |
| (d) At 50% water year dependability (4c+5h) | **189.35** | **6894.47** |

**Table 4.9 (b)** Water balance of Kalisindh basin (Unit: MCM)

| Item | Up to MOH dam site | Up to KUN dam site | Rest of the basin | Basin total |
|---|---|---|---|---|
| **1. SURFACE WATER** | | | | |
| **Availability** | | | | |
| (a) At 75% water year dependability | **862.00** | **1267.00** | **2967.16** | **5096.16** |
| (b) At 50% water year dependability | **1266.00** | **1820.00** | **5581.91** | **8667.91** |
| (c) Surface water import (+) | - | - | 540.00 | 540.00 |
| (d) Surface water export (-) | - | - | - | - |
| **Over all availability** | | | | |
| (e) At 75% water year dependability (a+c-d) | 862.00 | 1267.00 | 3507.16 | 5636.16 |
| (f) At 50% water year dependability (b+c-d) | 1266.00 | 1820.00 | 6121.91 | 9207.91 |
| **2. WATER DEMANDS FROM SURFACE WATER** | | | | |
| (a) Irrigation | 179.23 | 752.00 | 2927.00 | 3858.23 |
| (b) Domestic (100% of urban and 50% of rural population requirements) | 61.69 | 96.04 | 289.20 | 446.92 |
| (c) Industrial | 79.51 | 125.94 | 461.06 | 666.51 |
| (d) Hydropower | - | - | - | - |
| (e) Environment and ecology (10% of non-monsoon 75% dependable water year flow) | 2.00 | 1.00 | 15.62 | 18.62 |
| (f) Total | **322.42** | **974.98** | **3692.88** | **4990.28** |
| **3. REGENERATION** | | | | |
| (a) Irrigation (10% of major and medium projects excluding evaporation) | 6.07 | 53.72 | 226.43 | 286.22 |
| (b) Domestic (80% of 2b) | 49.35 | 76.83 | 231.36 | 357.54 |
| (c) Industrial (80% of 2c) | 63.61 | 100.75 | 368.85 | 533.21 |
| (d) Total | **119.03** | **231.30** | **826.63** | **1176.97** |
| **4. SURFACE WATER BALANCE** | | | | |
| (a) At 75% water year dependability (1e-2f+3d) | **658.60** | **523.32** | **640.92** | **1822.85** |
| (b) At 50% water year dependability (1f-2f+3d) | **1062.60** | **1076.32** | **3255.67** | **5394.60** |
| **5. GROUND WATER (GW)** | | | | |
| (a) Ground water potential | 327.00 | 539.00 | 1862.52 | 2728.52 |
| (b) Provision for domestic and industrial needs, @ 15% of (a) as per CGWB | 49.05 | 80.85 | 279.38 | 409.28 |
| (c) Projected rural domestic and livestock need (50% of rural population and 100% of livestock requirements) | 17.83 | 29.90 | 171.87 | 219.60 |
| (d) Available GW for irrigation (a-b) | 277.95 | 458.15 | 1583.14 | 2319.24 |
| (e) Utilizable GW for irrigation (90% of d) | 250.16 | 412.34 | 1424.83 | 2087.32 |
| (f) Existing net draft | 116.00 | 196.00 | 408.39 | 720.39 |
| (g) Balance GW for future use (d-f) | 161.95 | 262.15 | 1174.75 | 1598.85 |
| (h) Utilizable GW potential after meeting projected needs (90% of (a-c)) | 278.26 | 458.19 | **1521.59** | **2258.03** |
| **6. OVER ALL WATER BALANCE** | | | | |
| (a) At 75% water year dependability (4a+5h) | **936.86** | **981.51** | **2162.50** | **4080.88** |
| (b) At 50% water year dependability (4b+5h) | **1340.86** | **1534.51** | **4777.25** | **7652.63** |

**Table 4.9 (c)** Water balance of Parbati basin (Unit: MCM)

| Item | Up to PAT dam site | Rest of the basin | Basin total |
|---|---|---|---|
| **1. SURFACE WATER** | | | |
| **Availability** | | | |
| (a) At 75% water year dependability | **1733.00** | **3015.02** | **4748.02** |
| (b) At 50% water year dependability | **2163.00** | **4243.89** | **6406.89** |
| (c) Surface water import (+) | - | 576.00 | 357.00 |
| (d) Surface water export (-) | 219.00 | - | - |
| **Over all availability** | | | |
| (e) At 75% water year dependability (a+c-d) | **1514.00** | **3591.02** | **5105.02** |
| (f) At 50% water year dependability (b+c-d) | **1944.00** | **4819.89** | **6763.89** |
| **2. WATER DEMANDS FROM SURFACE WATER** | | | |
| (a) Irrigation | 744.11 | 2404.20 | 3148.31 |
| (b) Domestic<br>(100% of urban and 50% of rural population requirements) | 59.64 | 144.87 | 204.51 |
| (c) Industrial | 88.27 | 227.09 | 315.36 |
| (d) Hydropower | - | - | - |
| (e) Environment and ecology<br>(10% of non-monsoon 75% dependable water year flow) | 3.90 | 16.99 | 20.89 |
| (f) Total | **895.92** | **2793.15** | **3689.07** |
| **3. REGENERATION** | | | |
| (a) Irrigation (10% of major and medium projects excluding evaporation) | 38.62 | 187.47 | 226.09 |
| (b) Domestic (80% of 2b) | 47.71 | 115.90 | 163.60 |
| (c) Industrial (80% of 2c) | 70.62 | 181.67 | 252.29 |
| (d) Total | **156.94** | **485.04** | **641.98** |
| **4. SURFACE WATER BALANCE** | | | |
| (a) At 75% water year dependability (1e-2f+3d) | **775.03** | **1282.91** | **2057.94** |
| (b) At 50% water year dependability (1f-2f+3d) | **1205.03** | **2511.78** | **3716.81** |
| **5. GROUND WATER (GW)** | | | |
| (a) Ground water potential | 494.00 | 1349.29 | 1843.29 |
| (b) Provision for domestic and industrial needs, @ 15% of (a) as per CGWB | 74.10 | 202.39 | 276.49 |
| (c) Projected rural domestic and livestock need<br>(50% of rural population and 100% of livestock requirements) | 28.64 | 82.22 | 110.86 |
| (d) Available GW for irrigation (a-b) | 419.90 | 1146.90 | 1566.80 |
| (e) Utilizable GW for irrigation (90% of d) | 377.91 | 1032.21 | 1410.12 |
| (f) Existing net draft | 139.00 | 128.95 | 267.95 |
| (g) Balance GW for future use (d-f) | 280.90 | 1017.95 | 1298.85 |
| (h) Utilizable GW potential after meeting projected needs (90% of (a-c)) | **418.83** | **1140.36** | **1559.19** |
| **6. OVER ALL WATER BALANCE** | | | |
| (a) At 75% water year dependability (4a+5h) | **1193.86** | **2423.27** | **3617.13** |
| (b) At 50% water year dependability (4b+5h) | **1623.86** | **3652.14** | **5276.00** |

*Chapter 5*

# YIELD MODEL FOR REASONABLE RESERVOIR DESIGN

## 5.1 INTRODUCTION

Yield model serves as an efficient preliminary screening model for reasonable reservoir design with release reliability targets. The concept of the yield model was introduced by Loucks et al. (1981). It is an implicit stochastic linear programming model that incorporates several approximations to reduce the size of the constraint set needed to describe reservoir system operation and to capture the desired reliability of target releases considering the entire length of historical flow record. The yield model estimates separately over year and within year reservoir capacity requirements to meet the specific release reliability targets. Over year capacity is governed by the distribution of annual stream flows and the annual reservoir yields to be provided. The maximum of all over year storage volumes is the over year storage capacity. Any distribution of within year yields that differs from the distribution of within the year inflows may require additional active reservoir capacity. The maximum of all within year storage volumes is within the year storage capacity. The total active reservoir storage capacity is simply the sum of the over year storage and within year storage capacities. Dahe and Srivastava (2002) have extended the basic yield model for multiple yields and multiple reservoir system.

This study extends the yield model as available in the present form and presents an *improved general-purpose yield model* applicable to a multiple reservoir system consisting of single purpose and multipurpose reservoirs. The model considers priority yield and second yield, instead of the well-defined conventional firm and secondary yields to include more than two numbers of reservoir yields (water uses) and is capable of considering different reliabilities for each yield, and allows deficit in annual yields during failure years. The present model is an improvement of the yield model as available in the present form in the sense that it can consider more number of water uses, deals with both compatible and incompatible uses and allows redistribution of regenerated flows in within the year periods. The model offers better flexibility in selecting reliabilities of water uses and deciding optimal yield failure fractions during failure years for different water uses.

The following discussion presents the concept of the basic yield model, its further extension by Dahe and Srivastava (2002) and now an improved general-purpose yield model to be employed in the present study.

## 5.2 RELIABILITY OF ANNUAL YIELDS

The maximum release that can be made available at a specific site by the regulation of the historic stream flows, from a reservoir of a given size is referred to as the 'firm yield' or 'safe yield'. These terms imply that the firm or safe yield is that yield which the reservoir will always be able to provide and that larger yields are not firm in the sense that they cannot always be met. The firm or safe yield is 100% reliable only if during the future reservoir operation periods no low flow more severe than the historic flows will occur. Cleary, this is not likely to be the case, as the future is uncertain. Hence associated with every historic yield there is a probability that that yield can be provided in any future year by a given-size reservoir with a particular operating policy.

The mean probability of any particular stream flow being equaled or exceeded is based on the assumption that any future flow has an equal probability of falling within any interval defined by a sequence of historic stream flows. If there exists a record of n unregulated annual stream flows, then the probability that a future unregulated annual stream flow will equal or exceed a certain flow in the record is given by m/(n+1) by Weibull's formula, where m is rank of the flow in the record when they are arranged in descending order of magnitude. As the lowest stream flow has highest rank (m=n), it has the highest probability of being equaled or exceeded. Mathematically it is not possible to attain 100% probability, as the highest probability that can be achieved is n/(n+1), which is less than unity.

The reliability of a reservoir yield can be defined in the similar way as that of the probability of a given unregulated stream flow from the historic record of stream flows. From annual record of reservoir releases, the historic firm yield is the lowest reservoir release on record. The reliability of this annual yield is the probability that the reservoir yield in any year is greater than or equal to this value. In other words, it is the probability that this yield will always be exceeded. The expected value of exceedence probability of the lowest flow in a n year record is approximately n/(n+1). Thus with 99 years of record, the firm yield with a maximum annual reliability is only 99 percent firm. In other words, the meaning of firm yield is defined by the mean probability of that yield being exceeded, which in turn is a function of n, the total number of years of recorded yields. Once the firm yield is defined, the yield other than the firm yield, having reliability less than the firm yield, is termed as the secondary yield.

## 5.3 THE COMPLETE YIELD MODEL

The active over year reservoir capacity $Y^o$ (superscript 'o' is used to denote 'over year') required to deliver a safe or firm annual reservoir yield, $Oy^{f,p}$ (superscript 'f' is used for 'firm yield' and 'p' for 'exceedence probability'), when annual safe or firm reservoir yield differs from annual flows, $I_j$, can be determined by minimizing the active over year reservoir capacity $Y^0$ required to satisfy continuity and reservoir capacity constraint equations, i.e.,

$$\text{Minimize } Y^0 \tag{5.1}$$

Subject to

$$S^0_{j-1} + I_j - Oy^{f,p} - Sp_j = S^0_j \qquad \forall j \tag{5.2}$$

$$S^0_{j-1} \le Y^0 \qquad \forall j \tag{5.3}$$

where

$S^0_{j-1}$ = initial storage at the beginning of year j,

$S^0_j$ = final storage at the end of year j, and

$Sp_j$ = excess release (spill) in year j.

If j is the last year of record, then j+1=1.

The model presented above considers annual flows, annual reservoir yield and over year active storage volumes. A distribution of within year yields that differs from the distribution of within year inflows may require additional active reservoir storage capacity. Within year reservoir yields, $Oy^{j,t}_{f,p}$, that sum to the annual reservoir yield, $Oy^{f,p}$, may also be considered in the estimation of the required active storage capacity. Both the storage capacity requirements can be obtained by minimizing the total capacity, Ya, subject to continuity and capacity constraints for every within year period in every year. This model is defined by equations 5.4 through 5.6 for each period t in each year j, and is called the 'complete yield model'.

$$\text{Minimize } Ya \tag{5.4}$$

Subject to

$$S_{j,t-1} + I_{j,t} - Oy^{j,t}_{f,p} - Sp_{j,t} = S_{j,t} \qquad \forall j,t \tag{5.5}$$

$$S^0_{j,t-1} \le Ya \qquad \forall j,t \qquad (5.6)$$

where

$Oy^{j,t}_{f,p}$ = reservoir yield during period t in year j;

$S_{j,t-1}$ = initial storage at the beginning of period t in year j;

$S_{j,t}$ = final storage at the end of period t in year j; and

$Sp_{j,t}$ = excess release (spill) during period t in year j.

In equation 5.5 if t is the last period in year j, then the next period is t=1 in year j+1, or year 1 if j is the last year of record.

## 5.4 THE APPROXIMATE YIELD MODEL

The number of continuity and reservoir capacity constraints in the complete yield model can become very large when a long period of analysis and a large number of within year periods are considered. This is more true if a number of reservoir sites are being considered. However, examination of solutions from above reservoir storage models shows that it is only a relatively short sequence of flows within the total record of flows that generally determines the required active storage capacity in a reservoir. This critical drought period is often used in engineering studies to estimate the firm yield of any particular reservoir or a system of reservoirs. Even though the severity of future droughts is unknown, many people accept the traditional practice of using the critical drought period for reservoir design and operation studies on the assumption that having observed such an event in the past, it is certainly possible to experience similar conditions in the future (Hall and Dracup, 1970).

One limitation of the optimization model is its size when long time periods are considered. In general, the longer the period addressed, the more representative the results are of the system operation. The use of a short time period to estimate yield may produce inaccurate results because it may not include the critical period of flows. Thus a method that can approximate the optimization model but has the ability of using a long period of data without becoming computationally intractable may be used to estimate the yield.

Since the reservoir storage requirements are determined from critical periods of record, this suggests that it may not be necessary to include every period of every year in a reservoir storage yield model such as that defined by equations 5.4 through 5.6. The within year storage constraint is applied to the model to ensure that within the year time (say, monthly) yield of a system can be supplied. An example of a situation where the monthly period is critical may occur during the end of a non-monsoon period where the inflows into the reservoirs are low and the water demands are high. With the additional possibility of low storage levels, a situation may occur where the demands cannot be satisfied. The within year constraint is designed to ensure that within the year time demand can always be satisfied for a specific reliability in the yield. An illustration of the problem of ignoring the within year constraint is shown in Fig. 5.1. The figure shows the monthly fluctuations in storage volume

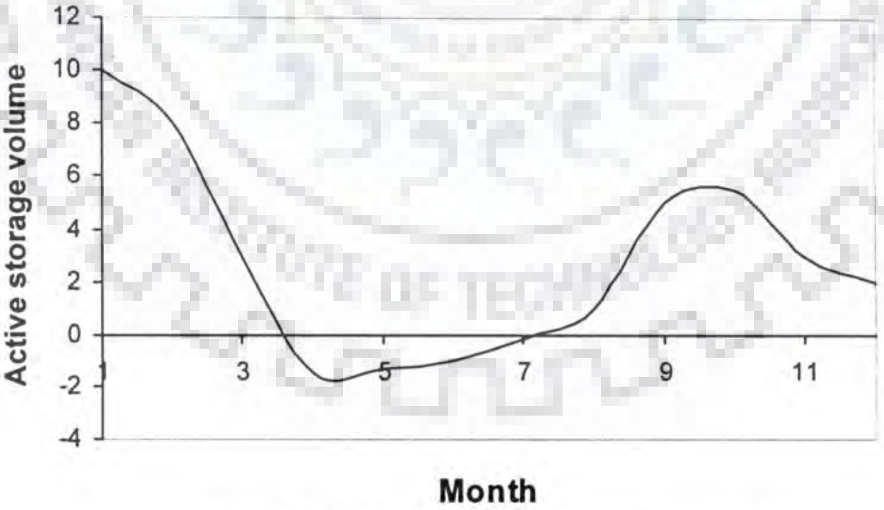

**Figure 5.1** Within year storage volume versus time

of a reservoir during a dry year. The ends of year storage values are 10 and 2 units and therefore give the appearance that the system can satisfy the particular demand in question.

However, the area under the dead storage shows that the storage will fall below zero during the months 4 to 7. The safe yield of a system is defined as that annual demand that can be met without the reservoir falling to its dead storage level. Cleary in this case, the safe yield needs to be reduced because of the within year constraints.

The reservoir storage capacity obtained from equations 5.4 to 5.6 can also be obtained from a model having year to year over year continuity equations to define each years initial storage volume plus a set of within year continuity constraints for the critical year. Writing the within year continuity constraints for the critical year requires the identification of the critical year and its inflows. In studies where reservoir yields in each period of each year are to be determined, it is not possible to identify the critical year at the time of model development. This is because the critical year depends in part on the values of the annual and within year reservoir yields. However, good results are generally obtained by letting some appropriate fraction $\beta_t$ of the total annual reservoir yield to be the inflow in each period t within the critical year. Hence $\sum_t \beta_t = 1$. A good choice for $\beta_t$ is the ratio of the inflow in period t of the driest year of record to the total inflow in that year. Each $\beta_t$ thus reflects the relative proportion of the critical year's inflow that is likely to occur in period t (Loucks et al., 1981).

The within year continuity constraints for a single yield can be written as

$$S^w_{t-1} + \beta_t Oy^{f,p} - Oy^t_{f,p} = S^w_t \qquad \forall t \qquad (5.7)$$

where

superscript 'w' denotes within year period;

$S^w_{t-1}$ =initial storage at the beginning of within year period t;

$S^w_t$ =final storage at the end of within year period t; and

$Oy^t_{f,p}$ =firm within year reservoir yield in period t.

As $\sum_t \beta_t = 1$, these constraints ensure that $\sum_t Oy^{t}_{f,p}$ equals the annual reservoir yield $Oy^{f,p}$.

In the equation 5.7, the inflows and required releases are just in balance, so that the reservoir neither fills nor empties during the modeled critical year. This is similar to what would be expected in a critical year that generally occurs at the end of a draw down period.

The within year capacity, $Y^w$, is the maximum of all within year storage volumes, i.e.,

$$S^w_{t-1} \leq Y^w \qquad \forall t \qquad (5.8)$$

The total active storage capacity, $Ya$, is simply the sum of the over year storage and within year storage capacities, i.e.,

$$Ya = Y^0 + Y^w \qquad (5.9)$$

Combining equations 5.8 and 5.9,

$$Y^0 + S^w_{t-1} \leq Ya \qquad \forall t \qquad (5.10)$$

The approximate yield model is then defined by equations 5.4, 5.2, 5.3, and 5.7 through 5.10. This approximate yield model shall be referred to as the yield model. The yield model reduces the number of storage continuity constraints and storage capacity constraints from twice the product of the number of years times the number of within year periods (equations 5.5 and 5.6) to twice the sum of the number of years plus the number of within year periods (equations 5.2 and 5.3 for over year constraints plus another set of within year continuity and capacity constraints). Thus for a hydrologic record of n years, each year having t periods, the number of constraint equations is reduced from 2nt to 2(n+t) and the number of variables is reduced from 2nt+t+2 to 2n+2t+3.

## 5.5 DEVELOPMENT OF THE YIELD MODEL

### 5.5.1 Single Reservoir Single Yield Model

#### 5.5.1.1 Firm reservoir yield

The single reservoir yield model to determine the maximum safe reservoir yield for a known reservoir capacity can be written as

$$\text{Maximize } Oy^{f,p} \tag{5.11}$$

Subject to the constraints

1. Over year storage continuity (equation 5.2), i.e.,

$$S^0_{j-1} + I_j - Oy^{f,p} - Sp_j = S^0_j \qquad \forall j \tag{5.12}$$

2. Over year active storage volume capacity (equation 5.3), i.e.,

$$S^0_{j-1} \le Y^0 \qquad \forall j \tag{5.13}$$

3. Within year storage continuity (equation 5.7), i.e.,

$$S^w_{t-1} + \beta_t Oy^{f,p} - Oy^t_{f,p} = S^w_t \qquad \forall t \tag{5.14}$$

4. Total reservoir capacity (equation 5.10), i.e.,

$$Y^0 + S^w_{t-1} \le Ya \qquad \forall t \tag{5.15}$$

5. Proportioning of yield in within year period t

$$Oy^t_{f,p} = D_t\left(Oy^{f,p}\right) \qquad \forall t \tag{5.16}$$

where $D_t$ defines a predetermined fraction of annual reservoir yield for the within year yield in period t.

In the above model, $Oy^{f,p}$ is the firm yield, which the reservoir is capable of supplying for all the years in record.

### 5.5.1.2 Annual reservoir yields having less than maximum reliability

The yield model can be used to incorporate reservoir yields having less than the maximum possible probability of exceedence p. In this case a reservoir yield failure is permitted. The number of years of reservoir yield failure determines the estimated annual reliability of reservoir yield. An annual reservoir yield that fails in f years has an estimated probability [(n-f)/(n+1)] of being equaled or exceeded in any future year. Once the desired reliability of an annual reservoir yield is known, the problem is to select the appropriate number f of failure years and the specific failure years themselves.

The over year storage continuity constraints can be written in a form appropriate for identifying a single annual reservoir yield having an exceedence probability p, i.e.,

$$S^0_{j-1} + I_j - \theta_{p,j} Oy^{f,p} - Sp_j = S^o_j \qquad \forall j \qquad (5.17)$$

where

$\theta_{p,j}$ =1, if the annual reservoir yield is to be provided in year j (a successful year);

=0, if the annual reservoir yield is not to be provided in year j (a failure year). (5.18)

The failure year or years should be selected from among those in which permitting a failure decreases the required reservoir capacity for a given reservoir yield, or increases the reservoir yield for a given reservoir capacity. If a failure year is selected in which excess release (spill) would be made anyway, no reduction in the required active storage capacity will result, and annual reliability of the reservoir yield may be higher than intended.

The failure years, if any, may be selected from within the critical drought periods for the desired reservoir yield. The critical year or years that determine the required active storage volume capacity may be dependent on the reservoir yield itself. When the magnitudes of reservoir yields are unknown, some trial and error procedures may be necessary to ensure that any failure years are within the critical period of years for the associated reservoir yields. To ensure a wider range of applicable reservoir yield magnitudes, the year having the lowest flow within the critical period should be selected as the failure year if only one failure year is to be selected.

### 5.5.1.3 Incorporation of allowable deficit in annual reservoir yield

The value of $\theta_{p,j}$ in equation 5.17 when set to zero indicates that the annual reservoir yield is not being provided in that year. It means a year can be either treated as successful year or there shall be complete failure, even though it may be possible to provide some reservoir yield depending upon the flows during the failure years in actual reservoir operation. The complete yield failure is never desirable. If a partial failure or an allowable deficit in annual reservoir yield during failure years is to be incorporated in the yield model, the factor $\theta_{p,j}$ can be redefined as

$\theta_{p,j}=1$, if the annual reservoir yield is to be provided in year j (a successful year), and

$0< \theta_{p,j} <1$, if the annual reservoir yield is to be provided partially in year j (a failure year).

The value of $\theta_{p,j}$ when greater than zero and less than one, indicates the extent of permissible failure or an allowable deficit in annual reservoir yield during a failure year. For example a value of $\theta_{p,j}=0.8$, indicates a 20% failure or deficit in annual reservoir yield. The value of $\theta_{p,j}$ is in part dependent on the consequences of failure and on the ability to forecast when a failure may occur and to adjust the reservoir operating policy accordingly. This factor $\theta_{p,j}$ shall be called as 'failure fraction'. It can be effectively used to exercise a control over the extent of failure or deficit in annual reservoir yield during failure years. This factor may affect the annual reservoir yield depending upon the flows during the critical period. A high value of $\theta_{p,j}$ is likely to reduce the annual reservoir yield. However, it shall always be preferable to know the extent of failure than to face unexpected failures as in case when the value of $\theta_{p,j}$ is set to zero.

### 5.5.2 Single Reservoir Multiple Yield Model

The yield model discussed so far defines only single annual reservoir yield (firm yield with a given annual reliability). Incremental secondary reservoir yields having reliabilities less than the firm yield can also be included in the model. Let us assume that a data set of 99 years of stream flow record is available, and two reservoir yields are desired, one firm yield with 99% annual reliability [p=99/(99+1), i.e., no failure years] and the other secondary yield with 75% annual reliability [p=75/(99+1), i.e., 24 failure years are allowed]. Let $Oy^{f,p}$ (p=0.99) and $Oy^{s,p}$ (p=0.75) represent the firm annual reservoir yield with maximum possible annual reliability (99%) and secondary annual reservoir yield with 75% annual reliability, respectively.

The over year storage continuity equation now can be written as

$$S^0_{j-1} + I_j - Oy^{f,p} - \theta_{0.75,j}Oy^{s,p} - Sp_j = S^0_j \qquad \forall j \qquad (5.19)$$

where $\theta_{0.75,j}$ =1, in successful years for secondary annual yield, and

=0, in failure years for secondary annual yield.

It is to be noted that if j is the last year of record, then j+1=1. Also, for multiple yield problems, failure fractions $\theta_{p,j}$ for secondary yields are zero for failure years; otherwise, the firm yield is essentially increased by $\theta_{p,j}Oy^{s,p}$.

#### 5.5.2.1 Incorporation of evaporation losses

Since the approximate yield model discussed earlier does not identify the exact storage volumes at the beginning of each period in each year, evaporation losses must be based on an expected storage volume in each period and year. The approximate expected storage volume in any period t in year j can be defined as the initial over year volume $S^0_{j-1}$, plus the estimated average within year volume $[(S^w_{t-1} + S^w_t)/2]$. The annual evaporation volume loss $El_j$ in each year j can be based on these estimated average storage volumes. The storage area relationship and approximation of surface area per unit active storage volume is shown in Fig. 5.2.

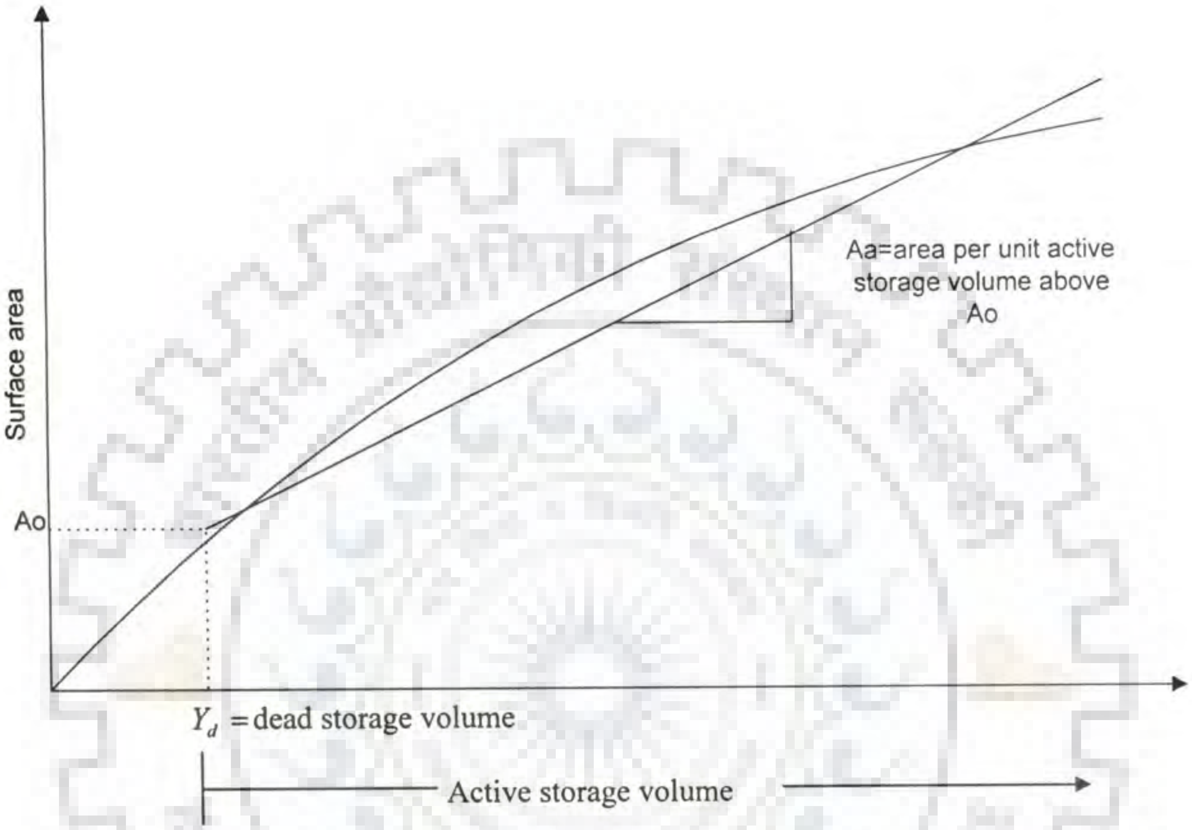

**Figure 5.2** Storage area relationship and approximation of surface area per unit active storage volume

Using the average annual depth of evaporation,

$El^{r} = A_a$ x average annual depth of evaporation, and

$E0 = A_0$ x average annual depth of evaporation;

where

$El^{r}$ = average annual volume loss rate per unit of active storage volume, and

$E0$ = average annual fixed evaporation volume loss due to dead storage.

The evaporation loss will be approximately equal to the average annual fixed loss E0 from the dead storage, plus the sum of each period's volume loss per unit of active storage volume times the expected storage volume in the period. Let $\gamma_t$ be the fraction of the annual evaporation loss that occurs in period t, then the annual evaporation loss in year j equals

$$El_j = \sum_t [\gamma_t E0 + (S^0_{j-1} + \frac{S^w_{t-1} + S^w_t}{2})\gamma_t El^r] \qquad \forall j \qquad (5.20)$$

Since the sum of all fractions $\gamma_t$ equals 1, equation 5.20 can be simplified to

$$El_j = E0 + [S^0_{j-1} + \sum_t (\frac{S^w_{t-1} + S^w_t}{2})\gamma_t]El^r \qquad \forall j \qquad (5.21)$$

The within year evaporation loss in each period t of the critical year is approximately

$$El^t = \gamma_t E0 + (S^0_{cr} + \frac{S^w_{t-1} + S^w_t}{2})\gamma_t El^r \qquad \forall t \qquad (5.22)$$

where

$S^0_{cr}$ = initial over year storage volume in the critical year.

### 5.5.2.2 Mathematical statement of the single reservoir multiple yield Model

The single reservoir multiple yield model now can be written to include two desired reservoir yields and the evaporation losses. The objective function may be to maximize the yields or to minimize the active reservoir capacity.

Objective function

$$\text{Maximize } \sum_t (Oy^t_{f,p} + Oy^t_{s,p}) \qquad (5.23)$$

or

Minimize Ya (5.24)

Subject to the constraints

1. Over year storage continuity

$$S^0_{j-1} + I_j - Oy^{f,p} - \theta_{p,j} Oy^{s,p} - Sp_j = S^0_j \qquad \forall j \qquad (5.25)$$

where $\theta_{p,j}$ =1, in successful years for secondary annual yield, and

=0, in failure years for secondary annual yield.

If j is the last year of record, then j+1=1. Also, for multiple yield problems, failure fractions $\theta_{p,j}$ for secondary yields are zero for failure years; otherwise, the firm yield is essentially increased by $\theta_{p,j} Oy^{s,p}$.

2. Over year active storage volume capacity

$$S^0_{j-1} \le Y^0 \qquad \forall j \qquad (5.26)$$

3. Within year storage continuity

$$S^w_{t-1} + \beta_t \{(Oy^{f,p} + Oy^{s,p}) + \sum_t El^t\} - (Oy^t_{f,p} + Oy^t_{s,p}) - El^t = S^w_t \qquad \forall t \qquad (5.27)$$

4. Definition of estimated annual evaporation losses

$$El_j = E0 + [S^0_{j-1} + \sum_t (\frac{S^w_{t-1} + S^w_t}{2}) \gamma_t ] El^r \qquad \forall j \qquad (5.28)$$

5. The within year evaporation loss in each period t of the critical year

$$El^t = \gamma_t E0 + (S^0_{cr} + \frac{S^w_{t-1} + S^w_t}{2}) \gamma_t El^r \qquad \forall t \qquad (5.29)$$

where $S^0_{cr}$ is initial over year storage volume in the critical year and is assumed to be zero.

6. Total reservoir capacity

$$Y^0 + S^w_{t-1} \le Ya \qquad \forall t \qquad (5.30)$$

The equations 5.23 to 5.30 present the single reservoir multiple yield model, which can incorporate annual firm and secondary reservoir yields and the evaporation losses. A within year distribution of annual reservoir yields can be specified in this model by writing additional constraints.

### 5.5.3 Extension of Multiple Yield Model to Multireservoir System

#### 5.5.3.1 Essential requirements for multireservoir problems

The yield model can be extended to multisite planning problems. An essential requirement is that the yield failure year or years must be the same at all allocation sites throughout the basin. For basins having multiple gauge sites, the identification of the failure years may be difficult, especially if the annual flows at different sites are not highly, and positively, cross-correlated. Another requirement is that the incremental flow yields must be of the same annual reliability as the reservoir release yields if they are to be added to define the yield available at any point downstream from one or more reservoirs (Loucks et al., 1981). To maintain continuity, the number of yields considered for each reservoir in the system of reservoirs, should be the same, i.e., if X number of yields are considered for one reservoir, than all the reservoirs in the system, should have X number of yields. So in a multireservoir system, yield model as discussed in Section 5.5.1.3 and Section 5.5.2 cannot be joined.

The requirement for the same annual reliability of reservoir yields throughout the basin can be satisfied if the multireservoir system is single purpose as demonstrated by Stedinger et al. (1983) and Dandy et al. (1997). A single purpose multireservoir system can also incorporate an allowable deficit in annual firm reservoir yield during failure years employing the failure fraction (Stedinger et al., 1983) as discussed in Section 5.5.1.3. It is also possible to satisfy the reliability requirement in a multipurpose multireservoir system with same number of purposes at each reservoir and same reliability for each purpose at all the reservoirs. However, an allowable deficit criterion for the water use represented by the annual secondary reservoir yield cannot be incorporated, i.e., $\theta_{p,j}$ is equal to zero for failure years (Dahe, 2001).

### 5.5.3.2 Yield model extended by Dahe and Srivastava (2002)

The single reservoir model presented in Section 5.5.2.2 illustrates the incorporation of an allowable deficit criterion by converting a single yield problem to a multiple yield problem, while maintaining the desired annual reliability. Such a conversion can overcome the difficulty in maintaining the continuity of reservoir yields at different reservoir sites in a multiple reservoir problem consisting of a combination of single and multipurpose reservoirs.

Dahe and Srivastava (2002) have considered a system of reservoirs consisting of a combination of single purpose irrigation reservoirs, single purpose hydropower reservoirs and multipurpose reservoirs having the purposes of irrigation and hydropower. A multiple yield model was formulated which is equivalent to the available single yield formulation and capable of incorporating an allowable annual deficit criterion while maintaining the reliability for annual irrigation water use. The annual reliabilities to be achieved for the different water uses were: irrigation, 74%; firm energy generation, 96%; and secondary energy generation, 74%. Two yields, one firm, with maximum possible annual reliability of 96% (no failure years in a data set of 22 years), and the other, secondary, with an annual reliability of 74% (5 failure years out of 22 years) were considered for each reservoir. The annual irrigation target was considered to be the sum of annual firm and secondary reservoir yields. An allowable deficit criterion was incorporated, permitting a maximum of 20% deficit for the annual irrigation target during failure years. An additional constraint was included in case of reservoirs having irrigation component to represent the allowable annual irrigation deficit criterion by monitoring the proportions of the annual firm and secondary reservoir yields. In simple, the constraint says that the firm yield at any within year time is greater than or equal to the failure fraction times the total yield (i.e. sum of the firm and secondary yield) at that time. The individual annual firm and secondary reservoir yields were used separately for annual firm and secondary energy generations, respectively; in a multipurpose reservoir before being put to irrigation use. The single purpose hydropower reservoirs in the system were modeled using the multiple yield model without the additional constraint for allowable deficit criterion, with annual firm and secondary reservoir yields used separately for annual firm and secondary energy generations, respectively. As every reservoir in the system now has two yields, each having the same reliability throughout the basin, there was no difficulty in writing the continuity equations at different sites in the system.

The objective of the model was to maximize the returns from energy generation for known reservoir and hydro plant capacities. Let p denotes the exceedence probabilities to be considered. The index i refers to a reservoir site, index j refers to a year, index t refers to a within year period, and index k refers to a reservoir amongst the set of m contributing reservoirs upstream of reservoir i. The basic equations in the model are presented below.

Objective function:

Maximize returns from energy generations, i.e.,

$$\text{Maximize } \sum_{i}[(B_i^f E_i) + (B_i^s \overline{E}_i)] \qquad \forall i \qquad (5.31)$$

$B_i^f$ and $B_i^s$ are the returns from annual firm $(E_i)$ and secondary $(\overline{E}_i)$ energies for reservoir i, respectively.

Subject to:

1. Over year storage continuity for year j at reservoir i

$$S_{i,j-1}^0 + \sum_{k \in m} Sp_{k,j} + I_{i,j} - Oy_i^{f,p} - \theta_{p,j} Oy_i^{s,p} - El_{i,j} - Sp_{i,j} = S_{i,j}^0 \qquad \forall i, j \qquad (5.32)$$

where

$\theta_{p,j}$ =1, in successful years for secondary annual yield, and

=0, in failure years for secondary annual yield.

$El_{i,j}$ = annual evaporation volume loss from reservoir i in year j.

2. Over year active storage volume capacity for year j at reservoir i

$$S_{i,j-1}^{0} \leq Y_{i}^{0} \qquad \forall i,j \qquad (5.33)$$

3. Within year storage continuity for reservoir i in time t (regenerated flows are to be added for each of the ith reservoir having m upstream contributing reservoirs)

$$S_{i,t-1}^{w} + \beta_{i,t}\left[\left(Oy_{i}^{f,p} + Oy_{i}^{s,p}\right) + \sum_{t} El^{i,t}\right] + \sum_{k \epsilon m}\left[\delta_{k}^{f}\left(Oy_{f,p}^{k,t}\right) + \delta_{k}^{s}\left(Oy_{s,p}^{k,t}\right)\right] - \left(Oy_{f,p}^{i,t} + Oy_{s,p}^{i,t}\right) - El^{i,t} = S_{i,t}^{w}$$

$$\forall i,t \qquad (5.34)$$

where $\delta_{k}^{f}$ and $\delta_{k}^{s}$ are fractions of firm and secondary yields respectively coming as regenerated flows from upstream reservoir k, and $El^{i,t}$ = evaporation volume loss from reservoir i in period t.

If a reservoir i is affected by the regulation of upstream reservoirs, the within year yields, $Oy_{f,p}^{i,t}$ and $Oy_{s,p}^{i,t}$, are the total yields at that reservoir site in each period t. They include the contribution from upstream yields that flow into the reservoir i (equation 5.34). Whereas the annual yields $Oy_{i}^{f,p}$ and $Oy_{i}^{s,p}$ do not include the contribution from upstream yields that flow into the reservoir i. Hence the upstream yields are not included in the over year storage continuity equation (equation 5.32) at site i, so that it is possible to define the within year inflow distribution of the incremental annual yields $Oy_{i}^{f,p}$ and $Oy_{i}^{s,p}$. This within year inflow distribution of the natural incremental annual yield $(Oy_{i}^{f,p} + Oy_{i}^{s,p})$ defined by $\beta_{i,t}$'s in equation 5.34 is not likely to be the same as the controlled within year outflow distributions of the yields $Oy_{f,p}^{k,t}$ and $Oy_{s,p}^{k,t}$ from the upstream reservoirs (Loucks et al., 1981, Dahe and Srivastava, 2002).

4. Total active reservoir storage capacity for reservoir i

$$Y_{i}^{0} + S_{i,t-1}^{w} \leq Ya_{i} \qquad \forall i,t \qquad (5.35)$$

5. Definition of estimated evaporation losses in year j for reservoir i

$$El_{i,j} = E0_i + [S^0_{i,j-1} + \sum_t (\frac{S^w_{i,t-1} + S^w_{i,t}}{2})\gamma_{i,t}]El^r_i \qquad \forall i, j \qquad (5.36)$$

where $El^r_i$ = average annual evaporation volume loss rate per unit of active storage volume for reservoir i;

$E0_i$ = average annual fixed evaporation volume loss due to dead storage for reservoir i; and

$\gamma_{i,t}$ = fraction of annual evaporation volume loss from reservoir i in period t.

6. Definition of estimated evaporation losses in time t (assuming that the initial over year storage volume $S^0_{i,cr}$ in the critical year is zero) for reservoir i

$$El^{i,t} = \gamma_{i,t} E0_i + \left( S^0_{i,cr} + \frac{S^w_{i,t-1} + S^w_{i,t}}{2} \right)\gamma_{i,t} El^r_i \qquad \forall i,t \qquad (5.37)$$

where $S^0_{i,cr}$ =initial over year storage volume in the critical year.

7. Continuity of annual yields at each reservoir site (regenerated flows are to be added for each of the ith reservoir having m upstream reservoirs)

For firm reservoir yield

$$\sum_t Oy^{i,t}_{f,p} = Oy^{f,p}_i + \sum_{k \in m} \left\{ \delta^f_k \sum_t \left( Oy^{k,t}_{f,p} \right) \right\} \qquad \forall i \qquad (5.38)$$

For secondary reservoir yield

$$\sum_t Oy^{i,t}_{s,p} = Oy^{s,p}_i + \sum_{k \in m} \left\{ \delta^s_k \sum_t \left( Oy^{k,t}_{s,p} \right) \right\} \qquad \forall i \qquad (5.39)$$

8. Irrigation target constraint for reservoir i in time t

$$Oy^{i,t}_{f,p} + Oy^{i,t}_{s,p} = K_{i,t} \left[ \left( Oy^{f,p}_i + Oy^{s,p}_i \right) + \sum_{k \in m} \left\{ \delta^f_k \sum_t \left( Oy^{k,t}_{f,p} \right) + \delta^s_k \sum_t \left( Oy^{k,t}_{s,p} \right) \right\} \right] \qquad \forall i,t \qquad (5.40)$$

where $K_{i,t}$ is a predetermined fraction of annual irrigation yield from reservoir i for the within year yield in period t.

9. Constraint for allowable annual deficit criterion (for reservoirs having irrigation component)

$$\sum_{t} Oy_{f,p}^{i,t} \geq \left\{ \frac{\theta_{p,j}}{(1-\theta_{p,j})} \right\} \left(\sum_{t} Oy_{s,p}^{i,t}\right) \quad \text{for reservoirs having irrigation component} \quad \forall i \qquad (5.41)$$

The sign greater than or equal to is used in the above equation to allow the model to have flexibility in deriving the benefits of energy generation from single purpose hydropower and multipurpose reservoirs.

10. Firm energy generation

$$E_{i,t} = \left(C_f e_i Ha_{i,t}\right) Oy_{f,p}^{i,t} \qquad \forall i,t \qquad (5.42)$$

where $C_f$ = conversion factor for computation of hydroelectric energy;

$e_i$ = hydropower plant efficiency for reservoir i; and

$Ha_{i,t}$ = productive storage head for reservoir i in period t.

11. Secondary energy generation

$$\overline{E}_{i,t} = \left(C_f e_i Ha_{i,t}\right) Oy_{s,p}^{i,t} \qquad \forall i,t \qquad (5.43)$$

12. Plant capacity limitation

$$E_{i,t} + \overline{E}_{i,t} \leq \left(\alpha_{i,t} h_{i,t} H_i\right) \qquad \forall i,t \qquad (5.44)$$

where $\alpha_{i,t}$ = hydropower plant factor for reservoir i in period t;

$H_i$ = hydropower plant capacity for reservoir i; and

$h_{i,t}$ = number of hours for generation of energy for reservoir i in time t.

13. Firm energy target constraint

$$E_{i,t} = \eta_{i,t} E_i \qquad \forall i,t \qquad (5.45)$$

where $\eta_{i,t}$ = percentage fraction of annual firm energy target for reservoir i in period t.

14. Annual secondary energy generation

$$\sum_{t} \overline{E}_{i,t} = \overline{E}_{i} \qquad \forall i,t \qquad (5.46)$$

The model illustrated above is applied successfully to a system of eight major reservoirs in the Narmada river basin system in Central India. Out of these reservoirs four are single purpose irrigation, three single purpose hydropower, and one multipurpose.

## 5.6 THE IMPROVED GENERAL PURPOSE YIELD MODEL

### 5.6.1 Difficulties Faced in Applying the Yield Model of Dahe and Srivastava (2002)

The model presented in Section 5.5.3.2 is the last available form of yield model using linear programming. The model served well in its intended purpose for application in the upper basin of the Narmada river. The following paragraphs discuss the difficulties faced during the application of the yield model of Section 5.5.3.2.

It is not always necessary that the annual reliability of one reservoir yield for a specific water purpose should always be the maximum possible, i.e., n/(n+1) in a sample size of n. In actual practice, some deficit in annual yields for some water purposes may be permitted. For example, in India, the target reliability for irrigation and water export is 75%. In the model presented in Section 5.5.3.2, as the reliability considered is higher than target reliability for one purpose, the estimated reservoir capacity will also be higher to meet known target demands for the purposes, or estimated water release from reservoir will be less for known reservoir capacity.

The value of failure fraction, which defines the proportion of the annual secondary reservoir yield to be made available during failure years, is one for successful years and zero for failure years. Failure fractions cannot be greater than zero during failure years, as the firm yield is essentially increased by an amount equal to failure fraction times the secondary yield. The water purposes considered in Dahe and Srivastava (2002) are irrigation and hydropower generation, which are compatible, i.e., water put to irrigation use can also generate power. In cases, where the purposes are incompatible, e.g., irrigation and water export to other reservoirs; a lower priority purpose will not be served at all during failure years, as the failure fraction is zero for failure years. The complete failure of a purpose (zero yield) during a whole year may not be accepted at all.

When regulation of upstream reservoirs affects a downstream reservoir, the model does not allow in the downstream reservoir redistribution of the flows regenerated from the regulated releases made from upstream reservoirs. It is assumed that the regenerated flows from a particular yield (firm or secondary) from an upstream reservoir at any within year time will simply pass through the downstream reservoir and add to the corresponding yield (firm or secondary) from the downstream reservoir at that time. When regenerated flows are very high from a yield, its contribution to the corresponding yield from the downstream reservoir may be even greater than the demand.

The firm reservoir yield is used for firm irrigation and firm energy generation. The fractions of annual irrigation target and firm energy target in a within year time period are different. During secondary yield failure years, the within year firm yields may not satisfy both the within year yields, and the model may be infeasible, as experienced by Dahe (2001).

### 5.6.2 Priority Yield and Second Yield

To have more flexibility in model application, two new terms, i.e., priority yield and second yield are introduced in this work, which may not be the same as firm yield and secondary yield, respectively, specified in the previous yield models. The firm yield is that yield, which the reservoir will always be able to provide and that higher yields are not firm in the sense that they cannot be always met. In probabilistic terms, the firm yield has the maximum possible reliability, i.e., no failure years, and is given by, $n/(n+1)$, in an n year record by using the Weibull plotting position formula. All yields in addition to the firm yield having reliability less than the firm yields are secondary yields.

For multipurpose reservoirs, serving water needs say, X1 and X2, it is useful to know at what reliability, each purpose can be served; for reservoir planning, design and operation. Let us assume that the required annual reliabilities are 90% for the water need X1, and 75% for the water need X2; and W1 and W2 are their corresponding annual yields, respectively. Then, we can say that firm yield for water need X1 is W1 at 90% annual reliability and firm yield for water need X2 is W2 at 75% annual reliability. But the term 'firm yield' is generally associated with the highest possible reliability, i.e., no failure years in record. So when we say that firm yield with certain reliability, less than the highest possible reliability, it may be confusing. The terms priority yield and second yield are used for the yields that have no restrictions on reliability in the possible range of reliabilities given by 1/(n+1) to n/(n+1). Here, the planner can prefix or obtain from model results, the reliabilities of both these yields. Either of the two yields or both may be used partially or fully for a single purpose or multi purpose water use. It is to be remembered that the names 'priority yield' and 'second yield' are given only to distinguish the two yields.

### 5.6.3 The Improved General Purpose Yield Model Development

The yield model as available in the present form is improved and extended to have more freedom of application and to include more number of water needs, both compatible and incompatible. Let indices i, j and t refer to a reservoir site, a year, and a within year period, respectively; and k refers to a reservoir amongst the set of m contributing reservoirs upstream of the reservoir i. Let $Oy_i^{P,p1}$ is annual priority yield of reservoir i with reliability p1; $Oy_i^{S,p2}$ is annual second yield of reservoir i with reliability p2; $I_{i,j}$ is inflow to reservoir i in year j; $S_{i,j}^{0}$ is over year storage of reservoir i at the end of year j; $S_{i,t}^{w}$ is within year storage of reservoir i at the end of period t; $Y_i^0$ and $Ya_i$ are over year storage capacity and total active storage capacity for reservoir i, respectively; $El_{i,j}$ is evaporation from reservoir i in year j; $Sp_{i,j}$ is annual spill from reservoir i in year j; $Sp_{k,j}$ is spill from upstream reservoir k in year j; $\theta_{p1,j}$ is failure fraction of priority yield with reliability p1 to be made available during failure years; and $\theta_{p2,j}$ is failure fraction of second yield with reliability p2 to be made available during failure years.

#### 5.6.3.1 Over year storage continuity

The over year storage continuity equation can be written as

$$S^0_{i,j-1} + \sum_{k\in m} Sp_{k,j} + I_{i,j} - \theta_{p1,j} Oy_i^{P,p1} - \theta_{p2,j} Oy_i^{S,p2} - El_{i,j} - Sp_{i,j} = S^0_{i,j} \qquad \forall i,j \quad (5.47)$$

where $\theta_{p1,j}, \theta_{p2,j} \le 1$ for failure years, and

$= 1$ for successful years.

Here, both priority and second yields can fail during failure years, and both the failure fractions $\theta_{p1,j}$ and $\theta_{p2,j}$ may be greater than zero during failure years. The firm yield of the reservoir is $\left(\theta_{p1,j} Oy_i^{P,p1} + \theta_{p2,j} Oy_i^{S,p2}\right)$ and the secondary yield is $\left\{Oy_i^{P,p1}(1-\theta_{p1,j}) + Oy_i^{S,p2}(1-\theta_{p2,j})\right\}$. The annual reliabilities of priority yield and second yield can be same or different for each reservoir. Similarly the failure fractions $\theta_{p1,j}$ and $\theta_{p2,j}$ need not be same for all the reservoirs. If a reservoir has four incompatible water purposes to serve, say, X1, X2, X3 and X4, where X1 and X2 require maximum possible annual reliability (no failure years), then X1 and X3 may be clubbed together and considered as priority yield, and X2 and X4 may be clubbed together and considered as second yield. The values $\theta_{p1,j}$ and $\theta_{p2,j}$ should be so selected that the values of $\theta_{p1,j} Oy_i^{P,p1}$ and $\theta_{p2,j} Oy_i^{S,p2}$ are more than or equal to the firm water requirements for X1 and X2, respectively. Here, if

$\theta_{p1,j} Oy_t^{P,p1}$ is equal to the firm water requirement for X1, X3 will completely fail [zero yield, i.e., $Oy_t^{P,p1}(1-\theta_{p1,j}) = 0$] during failure years. Similarly if $\theta_{p2,j} Oy_t^{S,p2}$ is equal to the firm water requirement for X2, X4 will completely fail [i.e., $Oy_t^{S,P2}(1-\theta_{p2,j}) = 0$] during failure years. But this problem already existed earlier, when yield model was to be applied to two incompatible purposes. If a reservoir has two distinct purposes, one firm and another secondary, then $\theta_{p1,j}$ can be made one for all the years and $\theta_{p2,j}$ can be made zero during failure years. Here priority and second yields will serve like the firm and secondary yields, respectively.

The following modifications are made in the downstream reservoir to allow redistribution of the regenerated flows from upstream reservoirs. The annual regenerated flows from upstream reservoirs are added to the downstream reservoir's inflow in the over year storage continuity equation, then

$$\begin{aligned} & S_{i,j-1}^{0} + \sum_{k \in m} \left( Sp_{k,j} \right) + I_{i,j} + \sum_{k \in m} \left\{ \delta_k^P \sum_t \left( Oy_{P,p1}^{k,t} \right) + \delta_k^S \sum_t \left( Oy_{S,p2}^{k,t} \right) \right\} \\ & - \theta_{p1,j} Oy_t^{P,p1} - \theta_{p2,j} Oy_t^{S,p2} - El_{i,j} - Sp_{i,j} = S_{i,j}^{0} \end{aligned} \qquad \forall i,t \qquad (5.48)$$

where $\delta_k^P$ and $\delta_k^S$ are fractions of priority yield, $\sum_t (Oy_{P,p1}^{k,t})$, and second yield, $\sum_t (Oy_{S,p2}^{k,t})$, respectively coming as regenerated flows from water uses of upstream reservoir k.

### 5.6.3.2 Within year storage continuity

The basic assumption in the yield model is that the total inflow in the critical year is equal to the total yearly yield, so that the reservoir neither fills nor empties during the modeled critical year (Loucks et al. 1981). In the within year storage continuity equation, $\beta_{i,t}$ times the total yearly regenerated flow from upstream reservoirs is subtracted from reservoir's inflow at time t and at the same time the regenerated flow is added as reservoir's inflow.

$$S^{w}_{i,t-1}+\beta_{i,t}\left[Oy_i^{P,p1}+Oy_i^{S,p2}+\sum_{t}El^{i,t}-\sum_{k\in m}\left\{\delta_k^P\sum_{t}\left(Oy^{k,t}_{P,p1}\right)+\delta_k^S\sum_{t}\left(Oy^{k,t}_{S,p2}\right)\right\}\right]$$

$$+\sum_{k\in m}\left\{\delta_k^P\left(Oy^{k,t}_{P,p1}\right)+\delta_k^S\left(Oy^{k,t}_{S,p2}\right)\right\}-\left(Oy^{i,t}_{P,p1}+Oy^{i,t}_{S,p2}+El^{i,t}\right)=S^{w}_{i,t} \qquad \forall i,t \qquad (5.49)$$

where $Oy^{i,t}_{P,p1}$ and $Oy^{i,t}_{S,p2}$ are priority and second yields for reservoir i at within year time t, respectively, and $El^{i,t}$ is evaporation from reservoir i at time t. If all the within year storage continuity equations for a reservoir are added, the total assumed yearly inflow is equal to the total yearly yields including evaporation. So, the basic assumption regarding critical years inflow in Loucks et al. (1981) is not violated and at the same time the model allows redistribution of regenerated flows in within year time periods also.

### 5.6.3.3 Incorporation of water transfer

Water export from a reservoir is to be dealt as a yield (priority or second or a part of them). For reservoirs having import of water from other reservoirs, the over year storage continuity equation may be written as:

$$\begin{aligned}&S^{0}_{i,j-1}+\sum_{k\in m}\left(Sp_{k,j}\right)+I_{i,j}+\mathrm{Im}^{k}_{i,j}+\sum_{k\in m}\left\{\delta_k^P\sum_{t}\left(Oy^{k,t}_{P,p1}\right)+\delta_k^S\sum_{t}\left(Oy^{k,t}_{S,p2}\right)\right\}\\&-\theta_{p1,j}Oy_i^{P,p1}-\theta_{p2,j}Oy_i^{S,p2}-El_{i,j}-Sp_{i,j}=S^{0}_{i,j}\end{aligned} \qquad \forall i,j \qquad (5.50)$$

where $\mathrm{Im}^{k}_{i,j}$ is import to reservoir i in year j from reservoir k. Accordingly, the within year storage continuity equation will change. The total import multiplied by $\beta_{i,t}$ is deducted from inflow and import water that is entering into reservoir i at time t, $\mathrm{Im}^{i,t}_{k}$, is added to inflow. So like regenerated flows, the redistribution of import water is possible.

$$S^{w}_{i,t-1}+\beta_{i,t}\left[Oy_i^{P,p1}+Oy_i^{S,p2}+\sum_{t}El^{i,t}-\sum_{k\in m}\left\{\delta_k^P\sum_{t}\left(Oy^{k,t}_{P,p1}\right)+\delta_k^S\sum_{t}\left(Oy^{k,t}_{S,p2}\right)+\mathrm{Im}^{k}_{i,j}\right\}\right]$$

$$+\sum_{k\in m}\left\{\delta_k^P\left(Oy^{k,t}_{P,p1}\right)+\delta_k^S\left(Oy^{k,t}_{S,p2}\right)+\mathrm{Im}^{i,t}_{k}\right\}-\left(Oy^{i,t}_{P,p1}+Oy^{i,t}_{S,p2}+El^{i,t}\right)=S^{w}_{i,t} \qquad \forall i,t \qquad (5.51)$$

### 5.6.3.4 Storage bounds and evaporation losses

The over year active storage volume capacity constraint, total active storage capacity constraint and definition of estimated evaporation losses presented in Loucks et al. (1981) and Dahe and Srivastava (2002) remain unchanged.

Over year active storage volume capacity for year j at reservoir i,

$$S^0_{i,j-1} \le Y^0_i \qquad \forall i,j \qquad (5.52)$$

Total active storage capacity for reservoir i,

$$Y^0_i + S^w_{i,j-1} \le Ya_i \qquad \forall i,t \qquad (5.53)$$

Definition of estimated evaporation losses in year j for reservoir i,

$$El_{i,j} = EO_i + \left[ S^0_{i,j-1} + \sum_t \left( \frac{S^w_{i,t-1} + S^w_{i,t}}{2} \right) \gamma_{i,t} \right] El^a_i \qquad \forall i,j,t \qquad (5.54)$$

where $EO_i$ is average annual fixed evaporation volume loss from dead storage for reservoir i; $El^a_i$ is average annual evaporation volume loss rate per unit of active storage volume for reservoir i; and $\gamma_{i,t}$ is fraction of annual evaporation volume loss from reservoir i in period t.

Definition of estimated evaporation losses in time t (assuming that the initial over year storage volume $S^0_{i,cr}$ in the critical year is zero) for reservoir i is:

$$El^{i,t} = \gamma_{i,t} EO_i + \left( S^0_{i,cr} + \frac{S^w_{i,t-1} + S^w_{i,t}}{2} \right) \gamma_{i,t} El^a_i \qquad \forall i,t \qquad (5.55)$$

### 5.6.3.5 Distribution of within year yields

As regenerated flows are redistributed, the continuity of annual yields at each reservoir site, may be written without referring to the regenerated flows as:

For annual priority yield

$$\sum_{t} Oy^{i,t}_{P,p1} = Oy_i^{P,p1} \qquad \forall i,t \qquad (5.56)$$

For annual second yield

$$\sum_{t} Oy^{i,t}_{S,p2} = Oy_i^{S,p2} \qquad \forall i,t \qquad (5.57)$$

The release target constraints for priority and second yields as per within year requirements in time t are,

$$Oy^{i,t}_{P,p1} = D^{P}_{i,t}\left(Oy_i^{P,p1}\right) \qquad \forall i,t \qquad (5.58)$$

$$Oy^{i,t}_{S,p2} = D^{S}_{i,t}\left(Oy_i^{S,p2}\right) \qquad \forall i,t \qquad (5.59)$$

However, for a single purpose reservoir, a common release target is adopted, i.e.,

$$Oy^{i,t}_{P,p1} + Oy^{i,t}_{S,p2} = D_{i,t}\left(Oy_i^{P,p1} + Oy_i^{S,p2}\right) \qquad \forall i,t \qquad (5.60)$$

where $D^{P}_{i,t}$, $D^{S}_{i,t}$ and $D_{i,t}$ are proportions of annual priority, second and total yields in time t for reservoir i, respectively.

#### 5.6.3.6 Relationship between priority yield and second yield

If the objective of the model is to maximize total annual yield, i.e., $\left(Oy_i^{P,p1} + Oy_i^{S,p2}\right)$, it may tend to maximize a yield, which may have less reliability and less failure fraction, and this may be at the cost of another yield, which is not be desirable. In order to have a relationship between priority yield and second yield, a constraint relation is added, i.e.,

$Oy_i^{P,p1} = \alpha_i Oy_i^{S,p2}$ $\forall i \in$ reservoirs where both priority and second yields are unknown

(5.61)

where $\alpha_i$ is the desired ratio of priority yield to second yield for reservoir i. Equation (5.61) is not required if either of the yields is already known.

#### 5.6.3.7 Consideration of hydropower

If a reservoir has two compatible purposes, say, irrigation and hydropower generation, and irrigation water is also available for power generation, firm yield and secondary yields are required for firm and secondary energy calculations. The following constraints are added:

Firm water yield of reservoir i in time t

$$OFy_i^t = \theta_{p1,j} Oy_{P,p1}^{i,t} + \theta_{p2,j} Oy_{S,p2}^{i,t} \qquad \forall i,t \qquad (5.62)$$

Secondary water yield of the reservoir i in time t

$$OSy_i^t = (1-\theta_{p1,j}) Oy_{P,p1}^{i,t} + (1-\theta_{p2,j}) Oy_{S,p2}^{i,t} \qquad \forall i,t \qquad (5.63)$$

Continuity for annual firm yield

$$OFy_i = \sum_t OFy_i^t \qquad \forall i,t \qquad (5.64)$$

Continuity for annual secondary yield

$$OSy_i = \sum_t OSy_i^t \qquad \forall i,t \qquad (5.65)$$

To allow distribution of firm energy as per time-wise requirement, $\eta_{i,t}$, the volume of water required to generate firm energy at time t may not be same as firm water yield available at that time. The part of the firm water yield at time t, $OFEy_i^t$, which is actually used for firm power generation is made less than or equal to the firm water yield at time t, i.e.,

$$OFEy_i^t \le OFy_i^t \qquad \forall i,t \qquad (5.66)$$

The part of the firm water yield in time t, which is not used for firm energy generation is added to the secondary water yield for secondary power generation in time t. As reliability of firm yield is higher than reliability of secondary yield, it can be added to secondary yield without any change in reliability of secondary yield, i.e.,

$$OSEy_i^t \le OSy_i^t + \left(OFy_i^t - OFEy_i^t\right) \qquad \forall i,t \qquad (5.67)$$

where $OSEy_i^t$ is the part of the secondary water yield which is used for secondary energy generation at time t; and this yield is made less than or equal to the secondary yield available for power generation, to allow the plant capacity limitation constraint to play its part.

Firm energy generation

$$E_{i,t} = \left(CF.e_i.Ha_{i,t}\right)OFEy_i^t \qquad \forall i,t \qquad (5.68)$$

Secondary energy generation

$$\overline{E}_{i,t} = \left(CF.e_i.Ha_{i,t}\right)OSEy_i^t \qquad \forall i,t \qquad (5.69)$$

Plant capacity limitation

$$E_{i,t} + \overline{E}_{i,t} \le \left(\alpha_{i,t} h_{i,t} H_i\right) \qquad \forall i,t \qquad (5.70)$$

Firm energy target constraint

$$E_{i,t} = \eta_{i,t} E_i \qquad \forall i,t \qquad (5.71)$$

Annual secondary energy generation

$$\sum_t \overline{E}_{i,t} = \overline{E}_i \qquad \forall i,t \qquad (5.72)$$

where CF is conversion factor for computation of hydro-electric energy; $e_i$ is hydropower plant efficiency for reservoir i; $E_{i,t}$ is firm energy generation for reservoir i in time t; $\overline{E}_{i,t}$ is secondary energy generation for reservoir i in time t; $E_i$ is annual firm energy generation from reservoir i; $\overline{E}_i$ is annual secondary energy generation from reservoir i; $H_i$ is hydropower plant capacity for reservoir i; $Ha_{i,t}$ is productive storage head for reservoir i in period t; $h_{i,t}$ is number of hours for generation of energy for reservoir i in period t; $\alpha_{i,t}$ is hydropower plant factor for reservoir i in period t; and $\eta_{i,t}$ is percentage fraction of annual firm energy target for reservoir i in period t

The equations (5.50) through (5.72) define the improved general-purpose yield model (IGPYM), which can be applied to a system of reservoirs having compatible, incompatible, single and multi uses. The objective function may be to maximize yields, or return from yields, or to minimize reservoir capacity. The reliability of priority yield for all the reservoirs, or the reliability of second yield for all the reservoirs need not be same. In case of models, presented in Loucks et al. (1981) and Dahe and Srivastava (2002), the failure fraction, $\theta_{p,j}$, is zero for failure years, so the secondary yield does not appear in the over year storage continuity equations for failure years, which may violate the continuity conditions. But in the IGPYM, the failure fraction values are not zero which is more practical for real life reservoir operation. Both the yields, priority and second, will always appear in the over year storage continuity equations, regardless the reliabilities of their yields. So the continuity may be maintained in a better way.

## 5.7 THE EFFECT OF ALLOWABLE FAILURE FRACTIONS

The improved general-purpose yield model (IGPYM) presented here uses two failure fractions, instead of one as used in Loucks et al. (1981), Stendinger et al. (1983), Dandy et al. (1997), and Dahe and Srivastava (2002). The two failure fractions defined in the current study allow both the yields to have desired annual reliabilities, unlike the previous yield models where one of the yield must acquire maximum possible reliability. As the desired reliabilities can be achieved for both the yields, it will have some impact on the required reservoir capacity or annual yield from a reservoir with known capacity. The following section compares the IGPYM with two existing yield models for a single reservoir case, and shows how the incorporation of failure fractions for both the yields can affect the reservoir capacity and reservoir yield.

### 5.7.1 Comparison of the Models

To compare the earlier available models mentioned above and the IGPYM, a nine-year two-season stream flow data given in Loucks et al. (1981) shall be used, neglecting evaporation losses. The flow data is presented in Table 5.1.

**Table 5.1** Recorded unregulated historical stream flows at a reservoir site

| Year | Within year period flow | | Annual flow |
|---|---|---|---|
| j | $I_{j,1}$ | $I_{j,2}$ | $I_j$ |
| 1 | 1.0 | 3.0 | 4.0 |
| 2 | 0.5 | 2.5 | 3.0 |
| 3 | 1.0 | 2.0 | 3.0 |
| 4 | 0.5 | 1.5 | 2.0 |
| 5 | 0.5 | 0.5 | 1.0 |
| 6 | 0.5 | 2.5 | 3.0 |
| 7 | 1.0 | 5.0 | 6.0 |
| 8 | 2.5 | 5.5 | 8.0 |
| 9 | 1.5 | 4.5 | 6.0 |
| Total | 9.0 | 27.0 | 36.0 |
| Av. flow | 1.0 | 3.0 | 4.0 |

The $\beta_t$ values are taken as 0.5 for both the periods. The fractions of annual reservoir yield ($D_t$ in equation 5.16; $K_{i,t}$ in equation 5.40; and $D_{i,t}$ in equation 5.60) are assumed to be 0.6 for the first period and 0.4 for the second period. The three models formulated for these data are as follows:

#### Case-1: Model of Loucks et al. (1981)

To determine the maximum annual reservoir yield with 70% reliability and 20% allowable deficit, for a known reservoir capacity of 2.5, a single yield model is formulated. The fourth and fifth years are taken as failure years. A failure fraction of $\theta_{p,j} = 0.8$ is applied to the annual reservoir yield during failure years to satisfy the allowable deficit criterion. The complete formulation according to the data is as follows:

*Objective function:*

Maximize $Oy^{f,p}$

*Constraints:*

Over-year storage continuity (equation 5.17)

$S_1^o - S_0^o + Oy^{f,p} + Sp_1 = 4.0$

$S_2^o - S_1^o + Oy^{f,p} + Sp_2 = 3.0$

$S_3^o - S_2^o + Oy^{f,p} + Sp_3 = 3.0$

$S_4^o - S_3^o + 0.8.Oy^{f,p} + Sp_4 = 2.0$ (failure year)

$S_5^o - S_4^o + 0.8.Oy^{f,p} + Sp_5 = 1.0$ (failure year)

$S_6^o - S_5^o + Oy^{f,p} + Sp_6 = 3.0$

$S_7^o - S_6^o + Oy^{f,p} + Sp_7 = 6.0$

$S_8^o - S_7^o + Oy^{f,p} + Sp_8 = 8.0$

$S_0^o - S_8^o + Oy^{f,p} + Sp_9 = 6.0$

where $S_9^o$ is assumed equal to $S_0^o$.

Over-year active storage volume capacity (equation 5.13)

$S_0^o - Y^o \leq 0$

$S_1^o - Y^o \leq 0$

$S_2^o - Y^o \leq 0$

$S_3^o - Y^o \le 0$

$S_4^o - Y^o \le 0$

$S_5^o - Y^o \le 0$

$S_6^o - Y^o \le 0$

$S_7^o - Y^o \le 0$

$S_8^o - Y^o \le 0$

Within-year storage continuity (equation 5.14)

$S_0^w - S_1^w + 0.5Oy^{f,p} - Oy_{f,p}^1 = 0$

$S_1^w - S_0^w + 0.5Oy^{f,p} - Oy_{f,p}^2 = 0$

Total reservoir capacity (equation 5.15)

$Y^o + S_0^w - Ya \le 0$

$Y^o + S_1^w - Ya \le 0$

Proportioning of yields in within-year periods (equation 5.16)

$Oy_{f,p}^1 - 0.6(Oy^{f,p}) = 0$

$Oy_{f,p}^2 - 0.4(Oy^{f,p}) = 0$

Total reservoir capacity

$Ya = 2.5$

The model is solved and the value of annual reservoir yield $Oy^{f,p}$ is found to be 3.0851.

**Case-2:** Model of Dahe and Srivastava (2002)

A multiple yield model is formulated by incorporating two annual reservoir yields, one firm, i.e., with maximum possible annual reliability with the given set of data (here 90%) and another secondary with 70% annual reliability. The fourth and fifth years are taken as failure years for secondary yield. The value of failure fraction in the constraint for the allowable annual deficit criterion is taken as 0.8, to maintain the proportion of annual reservoir yields during successful and failure years as that of the single yield problem of Case-1. The objective in this case is to determine the minimum capacity of a reservoir, to obtain an annual reservoir yield of 3.0851 (sum of firm and secondary yields).

*Objective function:*

Minimize Ya

*Constraints:*

Over-year storage continuity (equation 5.32)

$$S_1^o - S_0^o + Oy^{f,p} + Oy^{s,p} + Sp_1 = 4.0$$

$$S_2^o - S_1^o + Oy^{f,p} + Oy^{s,p} + Sp_2 = 3.0$$

$$S_3^o - S_2^o + Oy^{f,p} + Oy^{s,p} + Sp_3 = 3.0$$

$S_4^o - S_3^o + Oy^{f,p} + Sp_4 = 2.0$ (failure year for secondary yield)

$S_5^o - S_4^o + Oy^{f,p} + Sp_5 = 1.0$ (failure year for secondary yield)

$$S_6^o - S_5^o + Oy^{f,p} + Oy^{s,p} + Sp_6 = 3.0$$

$$S_7^o - S_6^o + Oy^{f,p} + Oy^{s,p} + Sp_7 = 6.0$$

$$S_8^o - S_7^o + Oy^{f,p} + Oy^{s,p} + Sp_8 = 8.0$$

$$S_0^o - S_8^o + Oy^{f,p} + Oy^{s,p} + Sp_9 = 6.0$$

where $S_9^o$ is assumed equal to $S_0^o$.

Over-year active storage volume capacity (equation 5.33)

$$S_0^o - Y^o \leq 0$$

$$S_1^o - Y^o \leq 0$$

$$S_2^o - Y^o \leq 0$$

$$S_3^o - Y^o \leq 0$$

$$S_4^o - Y^o \leq 0$$

$$S_5^o - Y^o \leq 0$$

$$S_6^o - Y^o \leq 0$$

$$S_7^o - Y^o \leq 0$$

$$S_8^o - Y^o \leq 0$$

Within-year storage continuity (equation 5.34)

$$S_0^w - S_1^w + 0.5(Oy^{f,p} + Oy^{s,p}) - Oy_{f,p}^1 - Oy_{s,p}^1 = 0$$

$$S_1^w - S_0^w + 0.5(Oy^{f,p} + Oy^{s,p}) - Oy_{f,p}^2 - Oy_{s,p}^2 = 0$$

Total reservoir capacity (equation 5.35)

$$Y^o + S_0^w - Ya \leq 0$$

$$Y^o + S_1^w - Ya \leq 0$$

Continuity of annual yields (equation 5.38)

$$Oy_{f,p}^1 + Oy_{f,p}^2 - Oy^{f,p} = 0$$

$$Oy_{s,p}^1 + Oy_{s,p}^2 - Oy^{s,p} = 0$$

Proportioning of yields in within-year periods (equation 5.40)

$$Oy^{1}_{f,p} + Oy^{1}_{s,p} - 0.6(Oy^{f,p} + Oy^{s,p}) = 0$$

$$Oy^{2}_{f,p} + Oy^{2}_{s,p} - 0.4(Oy^{f,p} + Oy^{s,p}) = 0$$

Constraint for the allowable deficit criterion (equation 5.41)

$$Oy^{1}_{f,p} + Oy^{2}_{f,p} = \frac{\theta_{p,j}}{1-\theta_{p,j}}(Oy^{1}_{s,p} + Oy^{2}_{s,p})$$

here $\theta_{p,j} = 0.8$.

Total annual yield

$$Oy^{f,p} + Oy^{s,p} = 3.0851$$

The solution of this model gives results identical to Case-1 with a reservoir capacity of 2.5. The values of annual yields obtained are $Oy^{f,p} = 2.4681$ and $Oy^{s,p} = 0.6170$.

### **Case-3:** The improved general-purpose yield model (IGPYM)

It is assumed that the reliabilities of priority and second yields are 80% (one failure year) and 70% (two failure years), respectively. The fifth year is taken as failure year for the priority yield and the fourth and fifth years are taken as failure years for second yield. It is also decided that 50% of the priority yield would be supplied during priority yield failure year and 20% of second yield would be supplied during second yield failure years. That means, both priority and second yields will not fail totally. The value of $\alpha_i$ in the relation constraint is made equal to 4 to make the ratio of priority yield and second yield equal to as that of firm yield and secondary yield in Case-2. The constraints for proportioning of yields (release target constraint) are kept same as Case-2 to have better comparison.

The complete formulation according to the data for an objective function to determine the minimum capacity of the reservoir, to obtain an annual reservoir yield of 3.0851 (sum of priority and second yields) is as follows:

*Objective function:*

Minimize Ya

*Constraints:*

Over-year storage continuity (equation 5.50)

$S_1^o - S_0^o + Oy^{P,p1} + Oy^{S,P2} + Sp_1 = 4.0$

$S_2^o - S_1^o + Oy^{P,p1} + Oy^{S,P2} + Sp_2 = 3.0$

$S_3^o - S_2^o + Oy^{P,p1} + Oy^{S,p2} + Sp_3 = 3.0$

$S_4^o - S_3^o + Oy^{P,p1} + 0.2Oy^{S,p2} + Sp_4 = 2.0$ (failure year for second yield)

$S_5^o - S_4^o + 0.5Oy^{P,p1} + 0.2Oy^{S,p2} + Sp_5 = 1.0$ (failure year for priority and second yields)

$S_6^o - S_5^o + Oy^{P,p1} + Oy^{S,p2} + Sp_6 = 3.0$

$S_7^o - S_6^o + Oy^{P,p1} + Oy^{S,p2} + Sp_7 = 6.0$

$S_8^o - S_7^o + Oy^{P,p1} + Oy^{S,p2} + Sp_8 = 8.0$

$S_0^o - S_8^o + Oy^{P,p1} + Oy^{S,p2} + Sp_9 = 6.0$

where $S_9^o$ is assumed equal to $S_0^o$.

Within-year storage continuity (equation 5.51)

$S_0^w - S_1^w + 0.5(Oy^{P,p1} + Oy^{S,p2}) - Oy_{P,p1}^1 - Oy_{S,p2}^1 = 0$

$S_1^w - S_0^w + 0.5(Oy^{P,p1} + Oy^{S,p2}) - Oy_{P,p1}^2 - Oy_{S,p2}^2 = 0$

Over-year active storage volume capacity (equation 5.52)

$$S_0^o - Y^o \leq 0$$

$$S_1^o - Y^o \leq 0$$

$$S_2^o - Y^o \leq 0$$

$$S_3^o - Y^o \leq 0$$

$$S_4^o - Y^o \leq 0$$

$$S_5^o - Y^o \leq 0$$

$$S_6^o - Y^o \leq 0$$

$$S_7^o - Y^o \leq 0$$

$$S_8^o - Y^o \leq 0$$

Total reservoir capacity (equation 5.53)

$$Y^o + S_0^w - Ya \leq 0$$

$$Y^o + S_1^w - Ya \leq 0$$

Continuity of annual yields (equations 5.56 and 5.57)

$$Oy_{P,p1}^1 + Oy_{P,p2}^2 - Oy^{P,p1} = 0$$

$$Oy_{S,p2}^1 + Oy_{S,p2}^2 - Oy^{S,p2} = 0$$

Proportioning of yields in within-year periods (equation 5.60)

$$Oy_{P,p1}^1 + Oy_{S,p2}^1 - 0.6(Oy^{P,p1} + Oy^{S,p2}) = 0$$

$$Oy_{P,p1}^2 + Oy_{S,p2}^2 - 0.4(Oy^{P,p1} + Oy^{S,p2}) = 0$$

Relationship between priority yield and second yield (equation 5.61)

$$Oy^{P,p1} = \alpha . Oy^{S,p2}$$

here $\alpha = 4$.

Total annual yield

$$Oy^{P,p1} + Oy^{S,p2} = 3.0851$$

The solution of the model gives identical values for priority and second yields as that of firm and secondary yields in Case-2. But the required reservoir capacity is reduced from 2.5 to 1.5. Simulation also confirms this result of the IGPYM. The firm yield in Case-1 and Case-2 is 2.468085. But in the present case the firm yield is reduced from 2.468085 to 1.3574467 (0.5 X 2.468085 + 0.2 X 0.617021).

The model is run changing the objective function and eliminating the total annual yield constraint. The new objective function taken is to maximize total yield for a known active reservoir capacity, Ya = 2.5. The solution of the model gives priority yield and second yield equals to 2.648402 and 0.662100, respectively, i.e., a total yield of 3.310502 against 3.0851 in Case-1 and Case-2. Simulation confirms this result also. The firm yield in this case is 1.46 (0.5 X 2.65 + 0.2 X 0.66), and secondary yield is 1.85 (3.31-1.46).

That is, at a given reservoir, if the desired reliabilities of both the priority and second yields are less than the maximum possible reliability given by n/(n+1), with or without complete yield failures for any yield (priority or second) during failure years, the system represented by the IGPYM is capable of:

(a) supplying the same annual yields with desired reliabilities from reduced reservoir capacity, and/or

(b) supplying higher annual yields with desired reliabilities with the given reservoir capacity, compared to the system represented by the earlier yield models.

It shows that the model presented here can be considered as an improvement over the previous yield models.

## 5.8 DISCUSSION

The objective of the work is to present a realistic and efficient yield model for screening purpose, related to multi site multipurpose reservoir systems. The IGPYM developed in this study is an extension of the previous yield models available in literature, which successfully addresses the aspects of incorporating the desired prespecified reliabilities for different water uses, as well as an allowable annual deficit criterion for yields, in a multi reservoir system consisting of a combination of single and multipurpose reservoirs. The LP based yield model offers a flexible modeling structure with a straight forward translation of the concept of annual yield reliability and allowable deficit while maintaining the identities of the individual reservoir yields.

The focus is on dealing different reservoir yields for various reservoir purposes individually as much as possible, both for compatible and incompatible uses. An attempt is made to allow regenerated flows to redistribute in the within year period in the present model. Though the model considered priority yield and second yield, it is also possible to calculate firm and secondary yields whenever required. Previous yield models did not permit yield failure for both the yields, and yield was zero for secondary yield during failure years. The model presented here permits complete or partial yield failures for both the yields. The use of priority yield and second yield allows selecting different number of failure years for each yield. Thus, yield corresponding to different reliabilities, for each water need can be estimated by changing the number of failure years for that yield. The incorporation of yield relation constraint (equation 5.61) helps in finding the trade-off between priority yield and second yield for each reservoir in the system. The flexibility in specifying separate values of failure fractions for both the priority yield and second yield at each reservoir site in the system allows the planner to monitor the extent of failure for each water uses at each reservoir site to get the desired annual yields. When water allocation priorities for different water needs are known, the failure fraction values can represent the vulnerability of the reservoir systems. The presented model is an improvement over the previous yield models and can be applied to any multi site multipurpose reservoirs system. It can act as a better screening tool in planning by providing outputs that can be very useful in improving the efficiency and accuracy of analysis using methods such as dynamic programming and detailed simulation.

## NOTATION

### Single Reservoir Yield Model

$A_a$=area per unit active storage volume above $A_o$;

$A_o$=area at dead storage;

$D_t$ =a predetermined fraction of annual reservoir yield for the within year yield in period t;

$E0 =$ average annual fixed evaporation volume loss due to dead storage;

$El^r =$ average annual volume loss rate per unit of active storage volume;

$El^t$ =evaporation loss in within year time t;

$El_j$ =evaporation loss in year j;

$I_j$ =annual inflows;

$Oy^{j,t}_{f,p} =$ reservoir yield during period t in year j;

$Oy^t_{f,p}$ =firm within year reservoir yield;

$Oy^t_{s,p}$ =secondary within year reservoir yield;

$Oy^{f,p}$ =firm annual reservoir yield;

$Oy^{s,p}$ =annual secondary reservoir yield;

$S_{j,t-1}$ = initial storage at the beginning of period t; in year j;

$S_{j,t}$ = final storage at the end of period t; in year j;

$S_{t-1}^{w}$ =initial storage at the beginning of within year period t;

$S_{t}^{w}$ =final storage at the end of within year period t;

$S_{j-1}^{0}$ = initial storage at the beginning of year j;

$S_{j}^{0}$ = final storage at the end of year j;

$S_{cr}^{0}$ = initial over year storage volume in the critical year;

$Sp_{j}$ = excess release (spill) in year j.

$Sp_{j,t}$ = excess release (spill) during period t in year j;

$Ya$ = total active storage capacity;

$Y^{0}$ =active over year reservoir capacity;

$Y^{w}$ =within year reservoir capacity;

$\beta_{t}$ = ratio of the inflow in period t of the critical year of record to the total inflow in that year;

$\gamma_{t}$ =the fraction of the annual evaporation loss that occurs in period t; and

$\theta_{p,j}$ =failure fraction for the yield with reliability p in year j.

### Multisite Multireservoir Yield Model

i = a reservoir site;

j =a year;

t= a within year period;

k= a reservoir amongst the set of m contributing reservoirs upstream of reservoir i;

p =the exceedence probabilities to be considered;

$B_i^f$ =returns from annual firm $(E_i)$ energy for reservoir i;

$B_i^s$ = returns from annual secondary $(\overline{E}_i)$ energy for reservoir i;

$C_f$ =conversion factor for computation of hydroelectric energy;

$e_i$ = hydropower plant efficiency for reservoir i;

$E_i$ =annual firm energy generation from reservoir i;

$\overline{E}_i$ = annual secondary energy generation from reservoir i;

$El_i^r$ =average annual evaporation volume loss rate per unit of active storage volume for reservoir i;

$El^{i,t}$ = evaporation volume loss from reservoir i in period t;

$El_{i,j}$ = annual evaporation volume loss from reservoir i in year j;

$E0_i$ =average annual fixed evaporation volume loss due to dead storage for reservoir i;

$h_{i,t}$ =number of hours for generation of energy for reservoir i in time t;

$H_i$ =hydropower plant capacity for reservoir i;

$Ha_{i,t}$ =productive storage head for reservoir i in period t;

$I_{i,j}$ = inflow to reservoir i in year j;

$K_{i,t}$ =a predetermined fraction of annual irrigation yield from reservoir i for the within year yield in period t;

$Oy_{f,p}^{i,t}$ = within year firm yield at time t from reservoir i;

$Oy_{s,p}^{i,t}$ =within year secondary yield at time t from reservoir i;

$Oy_i^{f,p}$ =annual firm yield from reservoir i;

$Oy_i^{s,p}$ =annual secondary yield from reservoir i;

$Oy^{k,t}_{f,p}$ = within year firm yield at time t from upstream reservoir k;

$Oy^{k,t}_{s,p}$ = within year secondary yield at time t from upstream reservoir k;

$S^0_{i,j-1}$ =initial over year storage at the beginning of year j in reservoir i;

$S^0_{i,j}$ =final over year storage at the end of year j in reservoir i;

$S^0_{i,cr}$ =initial over year storage volume in the critical year for reservoir i;

$Sp_{k,j}$ =annual spill from upstream reservoir k in year j;

$Sp_{i,j}$ = annual spill from reservoir i in year j;

$Ya_i$ =total active storage capacity for reservoir i;

$Y_i^0$ =over year storage capacity for reservoir i;

$\alpha_{i,t}$ =hydropower plant factor for reservoir i in period t;

$\beta_{i,t}$ = ratio of the inflow in period t of the critical year of record in reservoir i to the total inflow in that year;

$\gamma_{i,t}$ =fraction of annual evaporation volume loss from reservoir i in period t;

$\delta_k^f$ =fraction of firm yield coming as regenerated flow from upstream reservoir k;

$\delta_k^s$ =fractions of secondary yield coming as regenerated flow from upstream reservoir k; and

$\eta_{i,t}$ =percentage fraction of annual firm energy target for reservoir i in period t.

### Additional and Changed Variables in IGPYM

$D^P_{i,t}$ = proportion of annual priority yield for reservoir i;

$D^S_{i,t}$ =proportion of annual second yield for reservoir i;

$D_{i,t}$ =proportion of annual total yield for reservoir i;

$El_i^a$=average annual evaporation volume loss rate per unit of active storage volume for reservoir i;

$\mathrm{Im}_{i,j}^k$ =annual water import to reservoir i in year j from reservoir k;

$\mathrm{Im}_k^{i,t}$ =water import to reservoir i in within year time t from reservoir k;

$OFy_i^t$ =firm water yield from reservoir i in time t;

$OSy_i^t$ =secondary water yield from reservoir i in time t;

$OFy_i$ =firm annual water yield from reservoir i;

$OSy_i$ =secondary annual water yield from reservoir i;

$OFEy_i^t$ =part of the firm water yield at time t; from reservoir i; which is actually used for firm power generation;

$OSEy_i^t$=part of the secondary water yield at time t from reservoir i; which is used for secondary energy generation;

$Oy_i^{P,p1}$= annual priority yield of reservoir i with reliability p1;

$Oy_i^{S,p2}$ = annual second yield of reservoir i with reliability p2;

$Oy_{P,p1}^{k,t}$ =within year priority yield with annual reliability p1 at time t from upstream reservoir k;

$Oy_{S,p2}^{k,t}$ =within year second yield with annual reliability p2 at time t from upstream reservoir k;

$Oy_{P,p1}^{i,t}$ =within year priority yield with annual reliability p1 at time t from reservoir i;

$Oy_{S,p2}^{i,t}$ =within year second yield with annual reliability p2 at time t from reservoir i;

$SSWB_i^{75D}$ =annual surplus surface water balance at 75% annual dependability;

$\alpha_i$ =desired ratio of priority yield to second yield for reservoir i;

$\theta_{p1,j}$ = failure fraction of priority yield with reliability p1; to be made available during failure years; and

$\theta_{p2,j}$ = failure fraction of second yield with reliability p2; to be made available during failure years.

# DYNAMIC PROGRAMMING MODELS FOR RESERVOIR PLANNING

## 6.1 INTRODUCTION

The results of the yield model are approximate and require refinement. Dynamic programming (DP) is especially suited for solving the resources allocation problem or the multistage decision-making problem. The popularity and success of DP can be attributed to the fact that the nonlinear and stochastic features that characterize a large number of water resources systems can be translated into a DP formulation. It is not unusual to find that a problem can be formulated in more than one way, and part of the art of DP lies in deciding the most efficient formulation for the problem at hand. For examples, stages may represent different points in time or in space, and states may be continuous rather than discrete. The key feature of DP application is that it usually identified as a serial or progressive directed network for an operation or planning problems, respectively (Hastings, 1973). From every state a terminal state is reached in some predetermined number of stages for serial problems, but it is reached in not more than a predetermined number of states for progressive problems (Yeh, 1985).

In most of the practical problems, decisions have to be made sequentially at different points in time, space and at different levels, say, for a component, for a subsystem and/or for a system. The problems in which the decisions are to be made sequentially are called sequential decision problems. Since these decisions are to be made at a number of stages, they are also referred to as multistage decision problems. The dynamic programming technique, when applicable, represents or decomposes a multistage decision problem as a sequence of single stage decision problems. Thus an N-variable problem is represented as a sequence of N single variable problems, which are solved successively. In most of the cases, these N sub-problems are easier to solve than the original problem, the decomposition of N sub-problems is done in such a manner that the optimal solution of the original N-variable problem can be obtained from the optimal solutions of the N one-dimensional problems. It is important to note that the particular optimization technique used for the optimization of the N-single variable problems is irrelevant. It may range from a simple enumeration process to a differential calculus or a nonlinear programming technique.

In this work it is decided to adopt DP models to find import water requirements, fixation of design demands and for reservoir operation for all the reservoirs in a system allowing inter basin water transfers.

The well known 'curse of dimensionality' is a major limitation in the use of dynamic programming (Bellman and Dreyfus, 1962; Yeh, 1985). The computational requirement for DP increases exponentially with each additional state variable and multiplicatively with each additional discrete class. Constraints, which restrict the state or decision space, are advantageous in (discrete) DP because they reduce the amount of computation. In contrast, state and decision space constraints may cause considerable procedural difficulties for other optimization techniques. However, when DP is applied to a multiple-reservoir system, the usefulness of the technique is limited by the so-called 'curse of dimensionality', which is a strong function of the number of state variables. To alleviate this problem, some decomposition methods are usually used. One such decomposition, a variation of the Dantzig-Wolfe approach to large-scale systems optimization, leads to the adroit use of linear programming in conjunction with dynamic programming. For computational efficiency, problems should not have more than a few state variables at a time. All methods of dimensionality reduction involve decomposition into subsystems and the use of iterative procedures (Yeh, 1985).

Labadie (2004) made a stat-of-the-art review on optimal operation of multireservoir systems. This review reported the successful application of stochastic DP to a single reservoir problem, but commented that extensions of SDP to multireservoir systems are more aggravated by state dimensionality than in the deterministic case, particularly when spatial correlation of unregulated inflows must be maintained. The sampling stochastic dynamic programming approach of Kelman et al. (1990) employs a scenario-based method similar to stochastic linear programming, but using DP as the solution algorithm. This method overcomes the complexities of representing multireservoir operations as a Markov decision process and accounting for all spatial and temporal dependencies in the stochastic process. Unfortunately, the method fails to alleviate the dimensionality problems associated with SDP, and is yet to be applied to multistate, multireservoir systems.

Few researchers have attempted to apply SDP to multireservoir systems, like Sherkat et al. (1985), Trezos and Yeh (1989), Ponnambalam and Adams (1996), Archibald et al. (1997), Braga et al. (1991), etc. Labadie (2004) has pointed out the limitations of these applications for multireservoir cases and commented that the methods of IDP, DPSA, and DDP have been useful techniques for solving multireservoir DP problems in the deterministic case. Attempts to extend these methods to stochastic problems have not in general been successful, mainly since these methods are highly dependent on knowledge of the system state vector $\mathbf{s}_t$ with certainty.

There are lots of examples in the literature where deterministic DP models are used for reservoir problems and are discussed in Chapter 2. Some examples of such works are Bhaskar and Whitlatch (1980), Karamouz and Houck (1982), Ozden (1984), Karamouz and Houck (1987), Srivastava and Patel (1992), Moncada et al. (1994), Raman and Chandramouli

(1996), Ferrero et al. (1998), Chandramouli and Raman (2001), Sarma and Srivastava (2003), Chaudhury (2003), Deepti Rani (2004), and Awchi (2004).

Karamouz and Houck (1987) tested and compared reservoir-operating rules by deterministic and stochastic optimization and concluded that SDP model performed better for small reservoirs (capacity of 20% of the mean annual flow), but for larger reservoirs (capacity exceeding 50% of mean annual flow) deterministic model performed better. In this work, as per the definition given by Karamouz and Houck (1987), PAT is a small reservoir, MOH is a medium reservoir, and KUN, GS and RPS are big reservoirs. So according to findings of Karamouz and Houck (1987), SDP will perform better only for PAT reservoir, whereas deterministic DP will perform better for KUN, GS and RPS reservoirs.

On the basis of the above discussions, the present work, which involves five reservoirs and water transfer among the reservoirs, it is decided to adopt deterministic DP as the solution method. A DP model with the objective function of minimizing the squared deviations from targets (total demands) may not be successful in the present work, since the total demands are not known. Also such a model would require penalty coefficients in the objective function for want of priority of water releases for different water needs (purposes), to allocate the total reservoir release at any stage to different water needs.

In this chapter due to the involvement of two decision variables, namely, fixation of water transfer (export) target demands and the design water demands at a site, in planning stage two dynamic programming models, namely, *procurement problem model* (PPM) and *controlled input model* (CIM) are formulated. The PPM is based on the procurement problem of Haimes (1977) with unlimited resources (i.e., available water at another source), and the CIM is also a procurement problem with limited resource (i.e., available reservoir inflow).

The PPM calculates amount of import water requirement at a reservoir to meet its water demands. The CIM estimates water demands that a reservoir can meet with specified reliabilities, and also amount of water it can export to other reservoirs. The objective of the work is to present a dynamic programming modeling approach to calculate the water transfer demands and to fix the design demands for different water needs; related to a multipurpose, multi site reservoirs system. The combined application of PPM and CIM can be very useful for inter basin water transfer projects.

## 6.2 PROBLEM STATEMENT

To study any proposal of inter basin water transfers involving multi reservoirs, it is important to know the amount of import water requirements by each reservoir in the system having water import options from some other reservoirs, to meet its all water demands. This knowledge will provide the target water export demands for reservoirs exporting water to the importing reservoirs in the system. This problem is treated by the *procurement problem model* (PPM).

The knowledge of target water demands for all water needs from a reservoir is not sufficient for reservoir operation planning. It is also important to judge the amount of each water need that can be satisfied with prescribed reliability. This problem of fixation of design water demands for each water need is treated by the *controlled input model* (CIM).

## 6.3 TERMINOLOGY

For both PPM and CIM using dynamic programming, the time period is considered as a stage variable, while reservoir storage is considered as a state variable in the model. The backward process of dynamic programming is used.

Let N = total number of stages to go;

r = number of stages to go, such that r = 1,2,-------,N;

$S_r^i$ = storage at reservoir i at the beginning of r stages to go;

$S_{r-1}^i$ = storage at reservoir i at the end of r stages to go;

$I_r^i$ = total flow input (including natural inflow, spill from up stream reservoirs and return flows) to reservoir i at r stages to go;

$P_r^i$ = precipitation directly upon reservoir i in r stages to go;

$\bar{I}_r^i$ = local inflow to reservoir i from surrounding area in r stages to go;

$EI_r^i$ = evaporation losses from reservoir i in r stages to go;

$NI_r^i$ = natural inflow to reservoir i at r stages to go,

$RI_r^i$ = return flow and spill from up stream reservoirs to reservoir i at r stages to go;

$Ya^i$ = live capacity of reservoir i;

$Y\max_r^i$ = storage capacity up to full reservoir level at i in r stages to go; and

$Y\min_r^i$ = storage capacity up to minimum draw down level (MDDL) of reservoir i in r stages to go.

## 6.4 PROCUREMENT PROBLEM MODEL (PPM)

For a reservoir, when demands are known and during water deficit periods option is open for water import from some other sources or reservoirs, it is important to know how much import of water is required to meet the demands fully. In PPM, the decision variable is import of water required to meet the demands completely. Fig.6.1 explains basic parameters of the model.

Let $O_r^i$ = import (or procurement) of water required (a decision variable) from other sources (export points) by reservoir i to meet its water demands without failure at r stages to go with an assumption that at the export point unlimited resource is available;

$D_{r,p}^i$ = target water demand for purpose p to be met from reservoir i at r stages to go; and

$g_r^i(S_r^i, O_r^i)$ = return function for r stages to go at reservoir i.

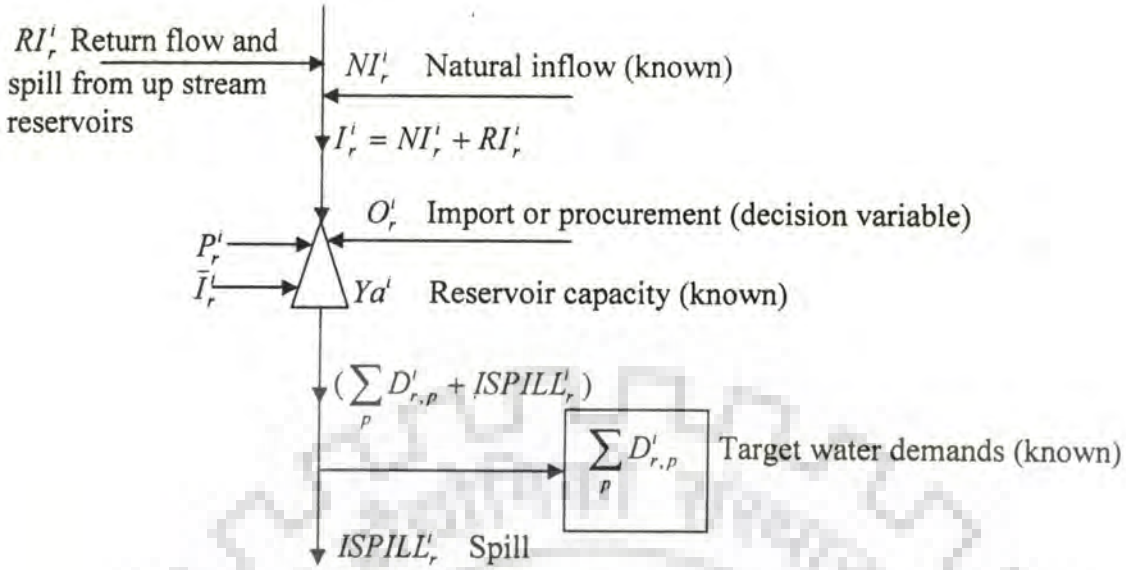

**Figure 6.1** Graphical illustration of PPM

### Objective function

The overall objective function is $$\text{Min.} \sum_i \sum_r g_r^i(S_r^i, O_r^i) \qquad (6.1)$$

where $$g_r^i(S_r^i, O_r^i) = CTR_r^i.O_r^i + CSR_r^i.S_{r-1}^i + CSP_r^i.ISPILL_r^i \qquad \text{for all r} \qquad (6.2)$$

$CTR_r^i$ = penalty for import or water transfer to reservoir i at r stages to go;

$CSR_r^i$ = penalty for storage at reservoir i at r stages to go;

$CSP_r^i$ = penalty for spill at reservoir i at r stages to go; and

$ISPILL_r^i$ = spill from reservoir i at r stages to go.

The penalty coefficients in the objective function are not for real situation costs but to indicate priority of execution amongst storage, spill and water transfer and also to indicate the within year priorities of each particular function. A higher storage is preferred over spill; hence penalty of spill may be made higher than penalty of end storage in a period. High penalty values may be taken for water import when less water is available in the donor reservoir. The purpose of using storage penalty is to encourage or discourage storage as per natural availability of water. In the model application, storage penalty at the beginning of monsoon period may be kept higher (as the importing reservoir itself may have enough water) and may be reduced with the advancement of the monsoon period to accommodate monsoon flows in a reservoir during the later monsoon period. Storage penalty at the end of the monsoon period may be kept least to encourage a higher storage, and the same may be maintained during the non-monsoon period also. This process may avoid unnecessary spills and storage.

The objective function is subject to the following constraints:

(a) $O_r^i \geq 0$ for all r (6.3)

(b) $I_r^i = NI_r^i + RI_r^i$ for all r (6.4)

(c) The continuity equation for the reservoir is

$$S_{r-1}^i = S_r^i + I_r^i + O_r^i + P_r^i + \bar{I}_r^i - El_r^i - \sum_p D_{r,p}^i - ISPILL_r^i \qquad \text{for all r} \qquad (6.5)$$

Put $X_r^i = P_r^i + \bar{I}_r^i - El_r^i$, then the equation (6.5) becomes

$$S_{r-1}^i = S_r^i + I_r^i + O_r^i + X_r^i - \sum_p D_{r,p}^i - ISPILL_r^i \qquad \text{for all r} \qquad (6.6)$$

(d) The equation for bounds on storage is

$$0 \leq Y\min_r^i \leq S_{r-1}^i \leq Y\max_r^i \leq Ya^i \qquad \text{for all r} \qquad (6.7)$$

A reservoir does not need import of water (i.e., $O_r^i$) while it spills. In such cases, the desired water requirements are met from reservoir storage and inflow. Then the unused inflow is the spilled water. Therefore, the spill water can be calculated directly from equation 6.6.

The general recursive equation using dynamic programming for PPM for reservoir i for all r stages to go can be written as:

$$f_r^i(S_r^i) = Min.[g_r^i(S_r^i, O_r^i) + f_{r-1}^i(S_{r-1}^i)] \qquad (6.8)$$

subject to constraint equations (6.3) to (6.7) where $f_r^i(S_r^i)$ represents the cumulative minimum value of the return functions for reservoir i up to r stages to go with a water storage level $S_r^i$ during r stages to go.

## 6.5 CONTROLLED INPUT MODEL (CIM)

After calculation of target water demands for various water use purposes, it is necessary to know if these demands can be satisfied by the reservoir releases. The decision variable in a reservoir is the amount of water that is being used out of the current reservoir inflow and imported water from other reservoirs (which is a limited resource unlike in PPM) apart from reservoir storage to meet these demands. If the target annual water demands cannot be met fully, these target demands are to be revised (design demands). The upper value of decision variable is limited to the sum of current inflow and water imported at any particular stage. Fig.6.2 gives basic parameters of the model.

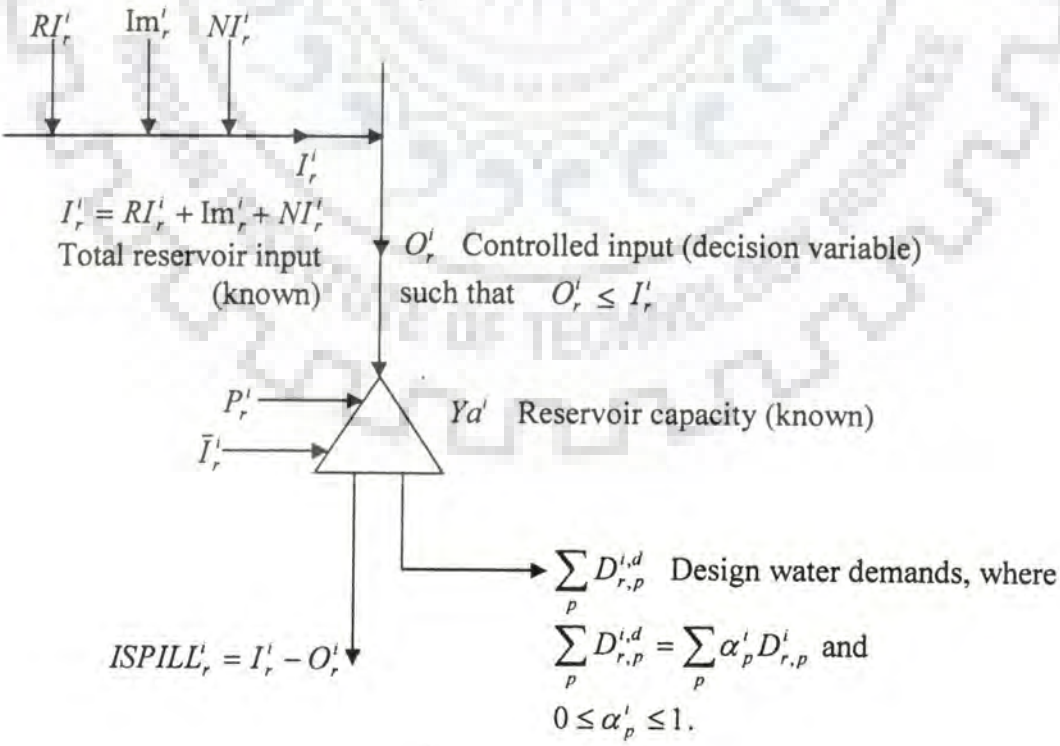

**Figure 6.2** Graphical illustration of CIM

**Objective function**

The overall objective function is $$\text{Min.} \sum_i \sum_r g_r^i(S_r^i, O_r^i) \qquad (6.9)$$

where $$g_r^i(S_r^i, O_r^i) = CSR_r^i.S_{r-1}^i + CSP_r^i.ISPILL_r^i + \sum_p \{CDD_{r,p}^i(D_{r,p}^i - D_{r,p}^{i,d})\} \text{ for all r} \qquad (6.10)$$

In the above equation

$O_r^i$ = amount of water that is being used (a decision variable) out of the current inflow (which is a limited resource) from reservoir i to meet the demands at r stages to go;

$g_r^i(S_r^i, O_r^i)$ = return function for r stages to go at reservoir i;

$CSR_r^i$ = penalty for storage at r stages to go at reservoir i;

$CSP_r^i$ = penalty for spill (unused water) at r stages to go at reservoir i;

$CDD_{r,p}^i$ = penalty for not being able to meet the demand for purpose p at r stages to go from reservoir i;

$ISPILL_r^i$ = total unused water (spill) from reservoir i;

$D_{r,p}^i$ = target water demand for purpose p to be met from reservoir i at r stages to go;

$D_{r,p}^{i,d}$ = design water demand (revised water target) for purpose p from reservoir i during planning, or the actual water release from reservoir i for purpose p during operation at r stages to go; where

$$D_{r,p}^{i,d} = \alpha_p^i D_{r,p}^i \qquad \text{for all r} \qquad (6.11)$$

$\alpha_p^i$ = coefficient for demand revision for purpose p from reservoir i, lying between 0 and 1.

The penalty coefficients in the objective function are not for real situation costs but to indicate priority of execution amongst storage, spill and meeting water demands for different purposes and also to indicate the within year priorities of each particular function. The penalties for storage and spill may be set as mentioned in the PPM (Section 6.4). To meet maximum demands, penalty for not meeting a demand (supply deficit cost, $CDD_{r,p}$) may be kept more as compared to penalty of storage and penalty of spill in a period, so that supply deficit is the least or in other words, maximum possible demand may be always met. Again, among different reservoir purposes, penalty for not meeting domestic water demand may be kept largest, then followed by penalty for not meeting irrigation demand, and lastly that for not meeting water export and energy demands, according to the accepted priority of purposes adopted in India.

The objective function is subject to the following constraints:

(a) $O^i_r \geq 0$ for all r (6.12)

(b) $I^i_r = RI^i_r + \mathrm{Im}^i_r + NI^i_r$ for all r (6.13)

where $\mathrm{Im}^i_r$ =imported water received by reservoir i from other reservoirs at r stages to go.

(c) $O^i_r \leq I^i_r$ for all r (6.14)

(d) As $O^i_r \leq I^i_r$, some inflow may remain unused and is called *spill from inflow* ($ISPILL^i_r$).

$\therefore ISPILL^i_r = I^i_r - O^i_r$ for all r (6.15)

(e) The continuity equation for reservoir i is

$$S^i_{r-1} = (S^i_r + I^i_r + P^i_r + \bar{I}^i_r - EI^i_r - ISPILL^i_r) - \sum_p D^{i,d}_{r,p} \quad \text{for all r} \qquad (6.16)$$

Put, $X^i_r = P^i_r + \bar{I}^i_r - EI^i_r$, then the equation (6.16) becomes

$$S^i_{r-1} = (S^i_r + I^i_r + X^i_r - ISPILL^i_r) - \sum_p D^{i,d}_{r,p} \quad \text{for all r} \qquad (6.17)$$

$$S^i_{r-1} = (S^i_r + O^i_r + X^i_r) - \sum_p D^{i,d}_{r,p} \quad \text{for all r} \qquad (6.17a)$$

The total water routed through the reservoir is not considered in the Eq. 6.17a. The reservoir spill is dealt outside the continuity equation, and $O^i_r$, the amount of water that is being used out of the current reservoir inflow is considered as an input to reservoir. The remaining water, i.e., the difference between the actual total inflow $I_r^i$ and decision variable $O_r^i$ is the reservoir spill $ISPILL_r^i$.

(f) The equation for bounds on storage is

$$0 \le Y\min_r^i \le S_{r-1}^i \le Y\max_r^i \le Ya_r^i \qquad \text{for all r} \qquad (6.18)$$

The general recursive equation using dynamic programming for CIM for reservoir i for all r stages to go can be written as:

$$f_r^i(S_r^i) = Min.[g_r^i(S_r^i, O_r^i) + f_{r-1}^i(S_{r-1}^i)] \qquad (6.19)$$

subject to constraint equations (6.12) to (6.19) where $f_r^i(S_r^i)$ represents the cumulative minimum value of return functions up to r stages to go with a water storage level $S_r^i$ from reservoir i during r stages to go.

For CIM, though the decision variable is the amount of water to be used from the current reservoir inflow apart from reservoir storage to meet reservoir demands, the main objective during planning stage is to get the design water demands by revising the target water demands.

In equation 6.17, the state variables $S_r^i$ and $S_{r-1}^i$ change their values only in a fixed discrete increment. While estimating the value of $O_r^i$ from equation 6.17, by putting $\sum_p D_{r,p}^{i,d} = \sum_p D_{r,p}^i$, for a given set of values of $S_r^i$ and $S_{r-1}^i$ at each iteration, following three cases are possible:

***Case-1:* $O_r^i$ *is greater than inflow* $I_r^i$**

When $O_r^i$ from equation 6.17 is greater than $I_r^i$, it means that the inflow and available reservoir storage are insufficient to meet the target demands, $\sum_p D_{r,p}^i$. Then the design demands for given values of $S_r^i$ and $S_{r-1}^i$ that can be met is determined by putting $O_r^i = I_r^i$ in equation 6.17 and is given by

$$\sum_p D_{r,p}^{i,d} = S_r^i + I_r^i + X_r^i - S_{r-1}^i \qquad \text{such that } 0 \le \alpha_p^i \le 1 \qquad \text{for all r} \qquad (6.20)$$

$$\text{such that } \sum_p D_{r,p}^{i,d} = \sum_p \alpha_p^i D_{r,p}^i \qquad \text{for all r} \qquad (6.21\text{ a})$$

In equation 6.20, if R.H.S. is positive, then design demands, $\sum_p D_{r,p}^{i,d}$, is equal to the value of R.H.S. If R.H.S. is negative, then the given final state, $S_{r-1}^i$, is infeasible.

Let p=1, 2 and 3 are three purposes to be served in order of their priorities by a reservoir. The following three cases are possible:

***Case-A***: If $\sum_p D_{r,p}^{i,d} < D_{r,1}^i$, then target demand for purpose 1 is partially met,

i.e., $\alpha_1^i < 1$, $\alpha_2^i = 0$, and $\alpha_3^i = 0$.

***Case-B***: If $D_{r,1}^i < \sum_p D_{r,p}^{i,d} < (D_{r,1}^i + D_{r,2}^i)$, then target demand for purpose 1 is fully met and for purpose 2 it is partially met,

i.e., $\alpha_1^i = 1$, $\alpha_2^i < 1$, and $\alpha_3^i = 0$.

***Case-C***: If $(D_{r,1}^i + D_{r,2}^i) < \sum_p D_{r,p}^{i,d} < \sum_p D_{r,p}^i$, then target demands for purposes 1 and 2 are fully met and for purpose 3 it is partially met,

i.e., $\alpha_1^i = 1$, $\alpha_2^i = 1$, and $\alpha_3^i < 1$.

***Case-2:*** *$O_r^i$ is less than or equal to $I_r^i$*

When $O_r^i$ from equation 6.17 is such that $O_r^i \le I_r^i$ indicates that target demands, $\sum_p D_{r,p}^i$, can be met from inflow and available reservoir storage.

Therefore, design demands, $\sum_p D^{i,d}_{r,p} = \sum_p D^i_{r,p}$, i.e., $\alpha^i_p = 1$ for all r (6.21)

***Case-3:*** *$O^i_r$ is negative*

If $O^i_r$ is negative from equation 6.17, it means that *no contribution* from inflow is required to meet the target demands, or, demands will be met from reservoir storage. Since storages (states) are changing only in a fixed discrete increment, in order to attain a desired final storage (state), $S^i_{r-1}$, from a given initial storage (state), $S^i_r$, the value of $O^i_r$ may be negative. This negative value of $O^i_r$ is considered as an additional spill and is called *spill from storage* ($SSPILL^i_r$). The *spill from storage* ($SSPILL^i_r$) is purely a computational aspect and arises due to the discrete nature of the problem.

Therefore, design demands, $\sum_p D^{i,d}_{r,p} = \sum_p D^i_{r,p}$, i.e., $\alpha^i_p = 1$ for all r (6.22)

$SSPILL^i_r = -O^i_r$, and $O^i_r = 0$ for all r (6.23)

The total unused water is given by

$ISPILL^i_r = (I^i_r - O^i_r) + SSPILL^i_r$ for all r (6.24)

For example at a given iteration in DP computations, say, storage increment = 10; initial storage (state), $S^i_r = 20$; resulting end storage (state), $S^i_{r-1} = 0$ (with a state increment of 10, storages can only be 0, 10, 20, 30 etc.); precipitation directly upon reservoir, local inflow and losses, $X^i_r = -8$; target demands, $\sum_p D^i_{r,p} = 10$; and inflow, $I^i_r = 15$; then the total target demands can be met and hence design demands for different water needs are equal to target demands. From equation 6.17 $O^i_r$ should be $-2^*$. This negative value of $O^i_r$ is the *spill from storage* ($SSPILL^i_r$). Therefore the total unused water (spill), $ISPILL^i_r = I^i_r - O^i_r + SSPILL^i_r$ (i.e., $15 + 2^* = 17$).

## 6.6 WORKING PRINCIPLE OF PPM AND CIM COMPUTER ALGORITHM

Available FORTRAN77 programs for the PPM and CIM are further improved and presented in Annexure-VII and Annexure-VIII, respectively. They comprise of nine subroutine subprograms and one function subprogram along with the main program. A general flow chart of the programme is presented in Fig. 6.3 (a) and Fig. 6.3 (b). The functions of the various subprograms are briefly highlighted below:

1. Subroutine CONNECT: This determines the transition feasibility between the reservoir's initial and resulting states for r stages to go.

2. Subroutine FUNCTION: This determines the return function $[g_r(S_r,O_r)]$ for the above feasible states at every r stages to go.

3. Subroutine EVAPO: This evaluates the reservoir evaporation losses at each feasible combination of initial and final states at every r stages to go.

4. Subroutine INTP2: This subroutine is required by the subroutine EVAPO, to locate the position of the storage and area at any r stages to go in the elevation-storage-area table.

5. Function YINTP: This function subprogram is required by the subroutine EVAPO. It returns the reservoir area at r stages to go through interpolation from reservoir storage –area table.

6. Subroutine POWER: It calculates the hydropower produced at r stages to go.

7. Subroutine HPHEAD: This subroutine is required by the subroutine POWER and PVOLDEM. It calculates the hydropower head at r stages to go.

8. Subroutine PVOLDEM: This calculates the volume of water required at r stages to go to meet the hydropower demand.

9. Subroutine OPTPA: This performs the forward tracing of the optimal path of reservoir operation starting with r = N. For CIM, it also calculates the reliability of the reservoir supply for different purposes.

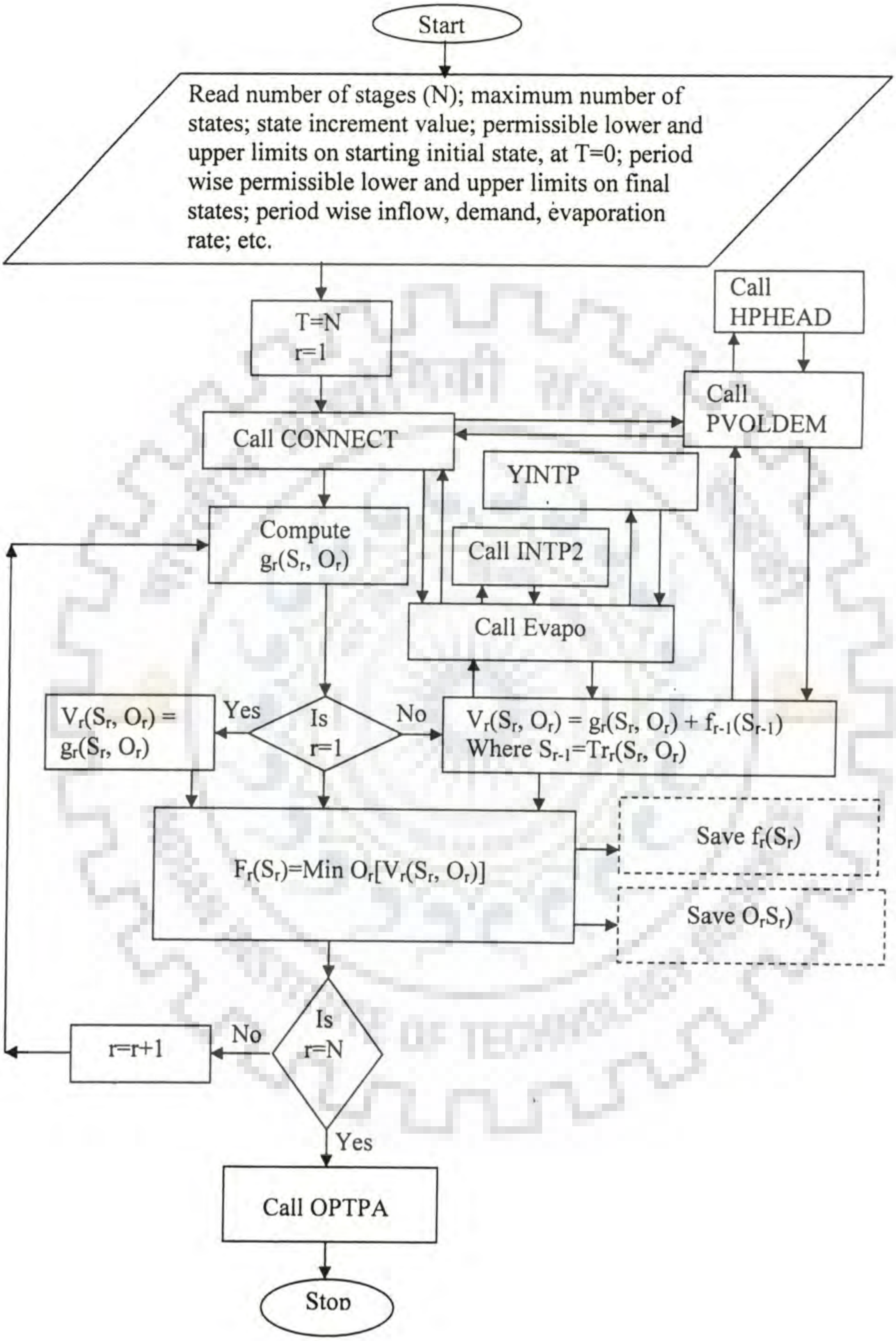

**Figure 6.3 (a)** General flowchart for PPM and CIM program

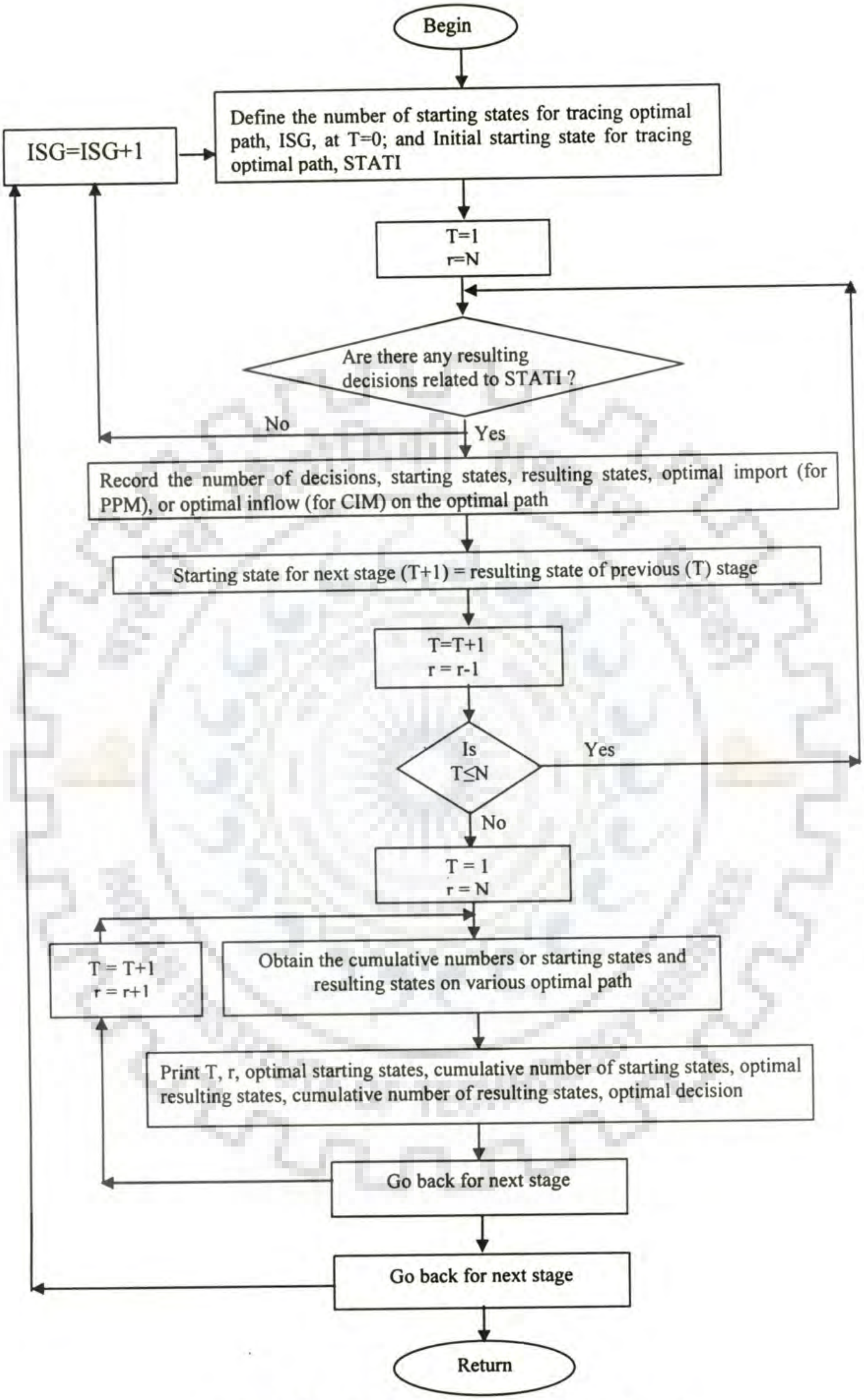

**Figure 6.3 (b)** Flowchart for subroutine OPTPA

## 6.7 DATA REQUIREMENT

To run the DP models discussed above the following input data are required.

### 6.7.1 Common Input Data Required for Both CIM and PPM

- Number of time periods or stages,
- Permissible lower limit on initial state,
- Permissible upper limit on initial state,
- Permissible lower limit on final state,
- Permissible upper limit on final state,
- The increment at which state (storage) changes,
- The monthly target demand,
- Monthly rate of evaporation,
- Reservoir elevation-area-capacity data,
- Possible number of desired starting states (storages) at $t = 0$,
- Values of possible desired starting states (storages) at $t = 0$,
- Penalty of storage at all r stages to go, and
- Penalty of spill at all r stages to go.

### 6.7.2 Additional Input Data Required for CIM

- For the permissible upper limit for the decision variable, the inflow to reservoir plus the regenerated flows from the upstream water uses at r stages to go may be used as permissible upper limit for the decision variable at r stages to go, for reservoir having no water import. For a reservoir, which has import of water in addition to inflows, the permissible upper limit of the decision variable at r stages to go may be taken as the inflow plus the regenerated flow from upstream water uses plus the import water entering the reservoir at r stages to go, for all r.

- Penalty of supply deficit, i.e., not being able to meet demands at all r stages to go.

### 6.7.3 Additional Input Data Required for PPM

- Inflow to the reservoir at all r stages to go, and
- Penalty of water transfer at all r stages to go.

## 6.8 DISCUSSION

Dynamic programming models are known to be efficient in resource allocation type of problems and in this work it is decided to adopt DP models to find import water requirements, fixation of design demands and for reservoir operation. To consider water transfer in a system of reservoirs (sites), it is important to look into two aspects (a) excess water availability at a source (export) point at a given time and (b) annual and within year time distribution of water demands at both source or donor (export) and destination or recipient (import) points. Due to the involvement of two decision variables, namely, fixation of water transfer (export) target demands and the design water demands at a site, in planning stage, use of the two DP models, namely PPM and CIM, are adopted. The size (number of reservoirs) did not restrict the use of a single comprehensive integrated model.

In a water transfer project involving multipurpose reservoirs, it is important to know the amount and timing of water to be transferred. When at a reservoir all the water demands, e.g., domestic, irrigation and water transfer (export) are known, then only a single DP model is sufficient. In the present case, domestic and irrigation demands are known from the field, but water export (transfer) demands are unknown. The water available at a reservoir may not be sufficient to meet all its water demands and a DP model, namely, *procurement problem model* (PPM) is formulated for such cases to calculate the import of water required by each reservoir in a system facing water shortage. In the application of CIM, the import water requirement by a recipient reservoir is considered as the target water export demand from the donor reservoir. During operation stage, a single model, namely CIM, does the reservoir operation.

In India, inter basin water transfer projects generate lot of controversy, debate and protest, especially when inter-states transboundaries are involved. Fears are expressed that water will be exported during lean period to meet the water demands in the recipient states at the cost of the donor state, and the donor state may suffer due to flood during monsoon period (Sharma and Sarma, 2003). The PPM assumes that unlimited water is available at the upper most exporting reservoir (starting point of the water transfer link) and hence all the annual target water demands can be met in the system. This assumption is not practical, but the model is successful in giving the annual target water export demands at all the water exporting reservoirs. But due to limited availability of water, it may not be possible to meet all the target water demands, and the CIM finds the design water supply for different water needs according to their priorities that can be met with prescribed annual reliabilities from a reservoir in planning stage.

The major differences between PPM and CIM are that in the PPM, the decision variable $O_r$, i.e., the water import requirement is not bounded by any upper limit. Because it is assumed that unlimited water is available at the source point from where import is to be made. Whereas in CIM, the decision variable $O_r$ is limited to the natural inflow ($I_r$) to the reservoir. Another difference is that, in PPM, the target water demands have to be met completely, and accordingly the model decides the requirements of water imports. In CIM, if sufficient water is not available, the target water demands ($D_{r,p}$) are revised to get design water demands ($D^{d}_{r,p}$) in planning stage. In reservoir operation, the design water demands for different purposes obtained in planning stage can be put as target water demands for that purpose (i.e., $D^{d}_{r,p}$ obtained in reservoir planning $= D_{r,p}$ in reservoir operation) and the reservoir releases for different purposes ($D^d_{r,p}$) can be obtained. If $D^d_{r,p} < D_{r,p}$, then it is a failure for purpose p at r stages to go. Hence reliability of release for different purposes can be calculated.

The PPM application starts from the lowermost reservoir to the uppermost reservoir, whereas the CIM application starts from the uppermost reservoir to the lowermost reservoir.

## NOTATION

$CDD_{r,p}$ = penalty for not being able to meet the demand for purpose p at r stages to go;

$CTR_r$ = penalty for import or water transfer at r stages to go;

$CSR_r$ = penalty for reservoir storage at r stages to go;

$CSP_r$ = penalty for reservoir spill at r stages to go;

$D_{r,p}$ = target water demand for purpose p to be met from reservoir at r stages to go;

$D^d_{r,p}$ = design water demand (revised water target) for purpose p during planning, or the actual water release from reservoir for purpose p during operation at r stages to go;

$El_r$ = reservoir evaporation losses in r stages to go;

$g_r(S_r, O_r)$ = return function for r stages to go;

$I_r$ = total inflow to reservoir at r stages to go ($I^i_r = NI^i_r + RI^i_r$ in PPM and $I^i_r = RI^i_r + \mathrm{Im}^i_r + NI^i_r$ in CIM);

$\bar{I}_r$ = local inflow to reservoir from surrounding area in r stages to go;

$\mathrm{ISPILL}_r$ = spill from reservoir at r stages to go;

N = total number of stages to go;

$NI^i_r$ = natural inflow to reservoir i at r stages to go,

$O_r$ = import (or procurement) of water required (a decision variable) from other sources (export points) by a reservoir to meet its water demands without failure at r stages to go in PPM;

$O_r$ = amount of water that is being used (a decision variable) out of the current reservoir inflow (which is a limited resource) to meet demands at r stages to go in CIM;

$P_r$ = precipitation directly upon reservoir in r stages to go;

r = number of stages to go; such that r = 1;2;-------;N;

$RI_r^i$ = return flow and spill from up stream reservoirs to reservoir i at r stages to go;

$S_r$ = reservoir storage at the beginning of r stages to go;

$S_{r-1}$ = reservoir storage at the end of r stages to go;

$SSPILL_r$ =spill from storage at r stages to go;

$Ya$ = live capacity of reservoir;

$Y\max_r$ = storage capacity up to full reservoir level in r stages to go;

$Y\min_r$ = storage capacity up to minimum draw down level (MDDL) of reservoir in r stages to go; and

$\alpha_p$ = coefficient for demand revision for purpose p; lying between 0 and 1.

*Chapter 7*

# SIMULATION MODEL FOR RESERVOIR OPERATION

## 7.1 INTRODUCTION

Simulation essentially duplicates the essence of a system or activity without actually attaining reality in itself. It is perhaps the most widely used method for evaluating alternative water resource systems. The reason for its popularity lies in its mathematical simplicity and versatility. The advent of high-speed computers has enabled planners to write very detailed simulation programs to describe the operation of water resources systems. It is not an optimizing procedure. Rather, for any set of design and operating policy parameter values, it merely provides a rapid means for evaluating the anticipated performances of the system. It is necessary for the analyst to specify the trial design (or, equivalently, to allow the computer to do so in accordance with some algorithm), whereupon the simulation model yields estimates of the responses associated with that trial. Simulation methods do not identify the optimal design and operating policy, but they are an excellent means of evaluating the expected performance resulting from any design and operating policy.

The simulation models are best suited to answer the questions of the type what if? A big advantage with simulation is that it allows for controlled experimentation on the problem without causing any disturbance to the real system. It also allows for significant time compression, i.e., the analysis of a system for 17 years may be completed within seconds on a computer. It is very easy to study the sensitivity of different parameters to the inputs. The following Sections discuss the multi yield multireservoir simulation model adopted to test the results of the reservoir operation by the Controlled Input Model (CIM).

## 7.2 THE SIMULATION MODEL

In absence of any operating policy, the model presented here is simple like a reservoir working table. Domestic water supply, irrigation, water export and hydropower demands are considered in the model. As per the standard practice in India, among various water uses, domestic water supply has the highest priority of water use, followed by irrigation and then water export and power generation. It is assumed that irrigation and water export yields are also available for power generation. Let, the index i refers to a reservoir site, index t refers to a time period, index u refers to an upper reservoir exporting water to reservoir i and index l refers to an lower reservoir importing water from reservoir i. Symbols iu and il refer upper and lower reservoirs, respectively, with respect to reservoir i.

*1. The continuity equation for a reservoir is*

$$S_{i,t} = S_{i,t-1} + I_{i,t} + \bar{I}_{i,t} + P_{i,t} + \sum_{u=1}^{NER_i}\left[(1 - TL_{i,t}^{iu,u})OEX_{i,t}^{iu,u}\right] + R_{i,t} + \sum_{u=1}^{NUR_i} Sp_{i,t}^{iu,u} - El_{i,t} - Oy_{i,t} - Sp_{i,t}^{AEX} - Sp_{i,t}$$

for all i, t (7.1)

where

$S_{i,t}$ = final storage at the end of time t for reservoir i;

$S_{i,t-1}$ = initial storage at the beginning of time t for reservoir i;

$I_{i,t}$ = inflow to reservoir i in time t;

$\bar{I}_{i,t}$ = local inflow to reservoir i from surrounding area in time t;

$El_{i,t}$ = evaporation at reservoir i in time t;

$Oy_{i,t}$ = total water yields in volume, excluding additional water export ($Sp_{i,t}^{AEX}$) from reservoir i in time t;

$OEX_{i,t}^{iu,u}$ = water exported from an upper reservoir u to reservoir i in time t;

$TL_{i,t}^{iu,u}$ = water transfer loss from reservoir u to i;

$P_{i,t}$ = precipitation directly upon reservoir i in time t;

$Sp_{i,t}$ = spill from reservoir i in time t;

$Sp_{i,t}^{iu,u}$ = spill from an upstream reservoir u entering to reservoir i in time t;

$Sp_{i,t}^{AEX}$ = additional water export from reservoir i at time t over and above water export demand, if excess water is available and canal capacity permits;

NER$_i$ = number of water exporting reservoirs to reservoir i;

NUR$_i$ = number of upstream reservoirs above reservoir i;

$R_{i,t}$ = regenerated flows coming from water uses of upstream reservoirs to reservoir i in time t; and is given by

$$R_{i,t} = \sum_{u=1}^{NUR_i} \left( \delta_{WS}^{iu,u} OWS_{i,t}^{iu,u} + \delta_{IR}^{iu,u} OIR_{i,t}^{iu,u} + \delta_{PW}^{iu,u} OPP_{i,t}^{iu,u} \right) \qquad \text{for all i, t} \qquad (7.2)$$

where

$\delta_{WS}^{iu,u}$ = fraction of domestic water supply yield coming as regenerated flow to reservoir i from an upstream reservoir u;

$\delta_{IR}^{iu,u}$ = fraction of irrigation yield coming as regenerated flow to reservoir i from an upstream reservoir u;

$\delta_{PW}^{iu,u}$ = fraction of the additional volume of water used for energy generation over and above what is required for irrigation and water export coming as regenerated flow to reservoir i from an upstream reservoir u;

$OWS_{i,t}^{iu,u}$ = volume of water released for domestic water supply from a reservoir u upstream of reservoir i in time t;

$OIR_{i,t}^{iu,u}$ = volume of water released for irrigation from a reservoir u upstream of reservoir i in time t; and

$OPP^{m,u}_{i,t}$ = volume of additional water released for energy generation over and above what is required for irrigation and water export from a reservoir u upstream of reservoir i in time t.

*2. Evaporation losses*

$El_{i,t} = A_{i,t} ev_{i,t}$ for all i, t (7.3)

where

$A_{i,t}$ = surface area of reservoir i in time t; and

$ev_{i,t}$ = average rate of evaporation from reservoir i in time t.

*3. Energy generation*

$DPW_{i,t} = DE_{i,t} / (C_f e_i Ha_{i,t})$ for all i, t (7.4)

$OE_{i,t} = (C_f e_i Ha_{i,t}) OPW_{i,t}$ for all i, t (7.5)

where

$DE_{i,t}$ = energy demand from reservoir i in time t;

$OE_{i,t}$ = energy generated from reservoir i in time t;

$DPW_{i,t}$ = volume of water required to generate target energy from reservoir i in time t;

$OPW_{i,t}$ = volume of water used to generate energy from reservoir i in time t;

$C_f$ = conversion factor for computation of hydroelectric energy;

$e_i$ = hydropower plant efficiency for reservoir i; and

$Ha_{i,t}$ = productive storage head for reservoir i in period t.

*4. Hydropower plant capacity limitation*

$OE_{i,t} \leq \alpha_{i,t} h_{i,t} H_i$ for all i, t (7.6) where

$\alpha_{i,t}$ = hydropower plant factor for reservoir i in period t;

$H_i$ = hydropower plant capacity for reservoir i; and

$h_{i,t}$ = number of hours for generation of energy for reservoir i in time t.

*5. Reservoir yields with given priority are*

(a) Yield for domestic water supply

$$OWS_{i,t} = DWS_{i,t} \quad \text{if} \quad S_{i,t} \geq DWS_{i,t} \qquad \text{for all i, t} \tag{7.7}$$

$$OWS_{i,t} = S_{i,t} \quad \text{if} \quad DWS_{i,t} \geq S_{i,t} \geq 0 \qquad \text{for all i, t} \tag{7.8}$$

$$OWS_{i,t} = 0 \quad \text{if} \quad S_{i,t} \leq 0 \qquad \text{for all i, t} \tag{7.9}$$

where

$OWS_{i,t}$ = domestic water supply from reservoir i in time t; and

$DWS_{i,t}$ = demand of domestic water supply from reservoir i in time t.

(b) Yield for irrigation

$$OIR_{i,t} = DIR_{i,t} \quad \text{if} \quad S_{i,t} - OWS_{i,t} \geq DIR_{i,t} \qquad \text{for all i, t} \tag{7.10}$$

$$OIR_{i,t} = S_{i,t} - OWS_{i,t} \quad \text{if} \quad DIR_{i,t} \geq S_{i,t} - OWS_{i,t} > 0 \qquad \text{for all i, t} \tag{7.11}$$

$$OIR_{i,t} = 0 \quad \text{if} \quad S_{i,t} - OWS_{i,t} \leq 0 \qquad \text{for all i, t} \tag{7.12}$$

where

$OIR_{i,t}$ = irrigation yield from reservoir i in time t; and

$DIR_{i,t}$ = irrigation demand from reservoir i in time t.

(c) Yield for water export

$$\sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} = \sum_{l=1}^{NIR_i} DEX_{i,t}^{il,l} \qquad \text{if } S_{i,t} - OWS_{i,t} - OIR_{i,t} \geq \sum_{l=1}^{NIR_i} DEX_{i,t}^{il,l} \qquad \text{for all i, t} \tag{7.13}$$

$$\sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} = S_{i,t} - OWS_{i,t} - OIR_{i,t} \qquad \text{if } \sum_{l=1}^{NIR_i} DEX_{i,t}^{il,l} \geq S_{i,t} - OWS_{i,t} - OIR_{i,t} > 0 \qquad \text{for all i, t} \tag{7.14}$$

$$\sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} = 0 \qquad \text{if } S_{i,t} - OWS_{i,t} - OIR_{i,t} \leq 0 \qquad \text{for all i, t} \tag{7.15}$$

where

$NIR_i$ = number of water importing reservoirs from reservoir i;

$OEX_{i,t}^{il,l}$ = water export yield from reservoir i to a lower reservoir l in time t; and

$DEX_{i,t}^{il,l}$ = demand for water export from reservoir i to a lower reservoir l in time t.

(d) Hydropower yield

$$OPW_{i,t} = DPW_{i,t} \qquad \text{if} \qquad S_{i,t} - OWS_{i,t} \geq DPW_{i,t} \qquad \text{for all i, t} \tag{7.16}$$

$$OPW_{i,t} = S_{i,t} - OWS_{i,t} \qquad \text{if} \qquad DPW_{i,t} \geq S_{i,t} - OWS_{i,t} \qquad \text{for all i, t} \tag{7.17}$$

$$OPW_{i,t} = 0 \qquad \text{if} \qquad S_{i,t} - OWS_{i,t} \leq 0 \qquad \text{for all i, t} \tag{7.18}$$

It is assumed that irrigation and water export yields are also available for power generation.

$$OPW_{i,t} = OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} + OPP_{i,t} \qquad \text{if} \quad OPW_{i,t} \geq OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} \quad \text{for all i, t} \tag{7.19}$$

$$OPW_{i,t} = OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} - OPM_{i,t} \qquad \text{if} \quad OPW_{i,t} \leq OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} \quad \text{for all i, t} \tag{7.20}$$

Combining equations 7.19 and 7.20, we have

$$OPW_{i,t} = OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,t} + OPP_{i,t} - OPM_{i,t} \qquad \text{for all i, t} \qquad (7.21)$$

where

$OPP_{i,t}$ = volume of water used for energy generation from reservoir i in time t, over and above what is required for irrigation and water export; and

$OPM_{i,t}$ = part of the water from irrigation and water export yields from reservoir i in time t that is not used for energy generation.

In the equation 7.21, at a particular time period, only one variable out of the variables $OPP_{i,t}$ and $OPM_{i,t}$ will appear.

*6. Target demand constraints*

$$DWS_{i,t} = D_{i,t}^{WS} DWS_i \qquad \text{for all i, t} \qquad (7.22)$$

$$DIR_{i,t} = D_{i,t}^{IR} DIR_i \qquad \text{for all i, t} \qquad (7.23)$$

$$DEX_{i,t}^{il} = D_{i,t}^{EX,il} DEX_i^{il} \qquad \text{for all i, t} \qquad (7.24)$$

$$E_{i,t} = \eta_{i,t} E_i \qquad \text{for all i, t} \qquad (7.25)$$

where

$D_{i,t}^{WS}$ = fraction of annual target domestic water supply yield from reservoir i in period t;

$D_{i,t}^{IR}$ = fraction of annual target irrigation yield from reservoir i in period t;

$D_{i,t}^{EX,il}$ = fraction of annual target water export yield from reservoir i to lower reservoirs in period t;

$\eta_{i,t}$ = fraction of annual firm energy target for reservoir i in period t;

$DWS_i$ = annual demand for domestic water supply from reservoir i;

$DIR_i$ = annual demand for irrigation from reservoir i; and

$DEX_i^{il}$ = annual demand for water export from reservoir i to lower reservoirs.

*7. Additional water export*

The priority of water export is the least among the considered water uses. So the chance of its failure is maximum compared to other water yields. To enhance yearly water transfer, it is decided that if there is a reservoir spill at any period, it is added to water export yield at that period up to the design water transfer link canal capacity. This additional water export over and above total water export demand is denoted by $Sp_{i,t}^{AEX}$. So whenever there is or would have been a reservoir spill (in absence of this additional water export), the water export yield at that period will be more than the target demand, provided the water transfer link canal capacity permits. The total water export is given by

$$\sum_{l=1}^{NIR_i} OEX_{i,t}^{T,il,l} = \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} + Sp_{i,t}^{AEX} \qquad \text{for all i, t} \quad (7.26)$$

where

$$Sp_{i,t}^{T} = Sp_{i,t} + Sp_{i,t}^{AEX} \qquad \text{for all i, t} \quad (7.27)$$

$$\sum_{l=1}^{NIR_i} OEX_{i,t}^{T,il,l} = CC_i \qquad \text{if} \quad \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} + Sp_{i,t}^{T} \geq CC_i \qquad \text{for all i, t} \quad (7.28)$$

$$\sum_{l=1}^{NIR_i} OEX_{i,t}^{T,il,l} = \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} + Sp_{i,t}^{T} \qquad \text{if} \quad \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} + Sp_{i,t}^{T} \leq CC_i \qquad \text{for all i, t} \quad (7.29)$$

where

$OEX_{i,t}^{T,il,l}$ = total water export including additional water export from reservoir i to a lower reservoir l in time t; and

$CC_i$ = water transfer link canal capacity from reservoir i.

*8. Total reservoir yield volume*

Total water yields in volume, excluding additional water export from reservoir i in time t is given by

$$Oy_{i,t} = OWS_{i,t} + OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} + OPP_{i,t} \quad \text{if} \quad OPW_{i,t} \geq OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} \quad \text{for all i, t} \tag{7.30}$$

$$Oy_{i,t} = OWS_{i,t} + OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} \quad \text{if} \quad OPW_{i,t} \leq OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} \quad \text{for all i, t} \tag{7.31}$$

Total water yields in volume, including additional water export from reservoir i in time t is given by

$$Oy_{i,t}^{T} = OWS_{i,t} + OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{T,il,l} + OPP_{i,t} \quad \text{if} \quad OPW_{i,t} \geq OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} \quad \text{for all i, t} \tag{7.32}$$

$$Oy_{i,t}^{T} = OWS_{i,t} + OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{T,il,l} \quad \text{if} \quad OPW_{i,t} \leq OIR_{i,t} + \sum_{l=1}^{NIR_i} OEX_{i,t}^{il,l} \quad \text{for all i, t} \tag{7.33}$$

where $Oy_{i,t}^{T}$ = total water yields in volume, including additional water export from reservoir i in time t.

*9. Reservoir spill*

The reservoir spill is given by

$$Sp_{i,t} = S_{i,t} - Oy_{i,t}^{T} - El_{i,t} - Y\max_i \quad \text{if} \quad S_{i,t} - Oy_{i,t}^{T} - El_{i,t} > Y\max_i \quad \text{for all i, t} \tag{7.34}$$

$$Sp_{i,t} = 0 \quad \text{if} \quad S_{i,t} - Oy_{i,t}^{T} \leq Y\max_i \quad \text{for all i, t} \tag{7.35}$$

where $Y\max_i$ is the gross storage capacity of reservoir i.

The equations 7.1 through 7.35 define the reservoir simulation model to get the responses of a multi reservoir system, for assumed parameters like reservoir capacities and target demands. The model is illustrated graphically in Fig. 7.1.

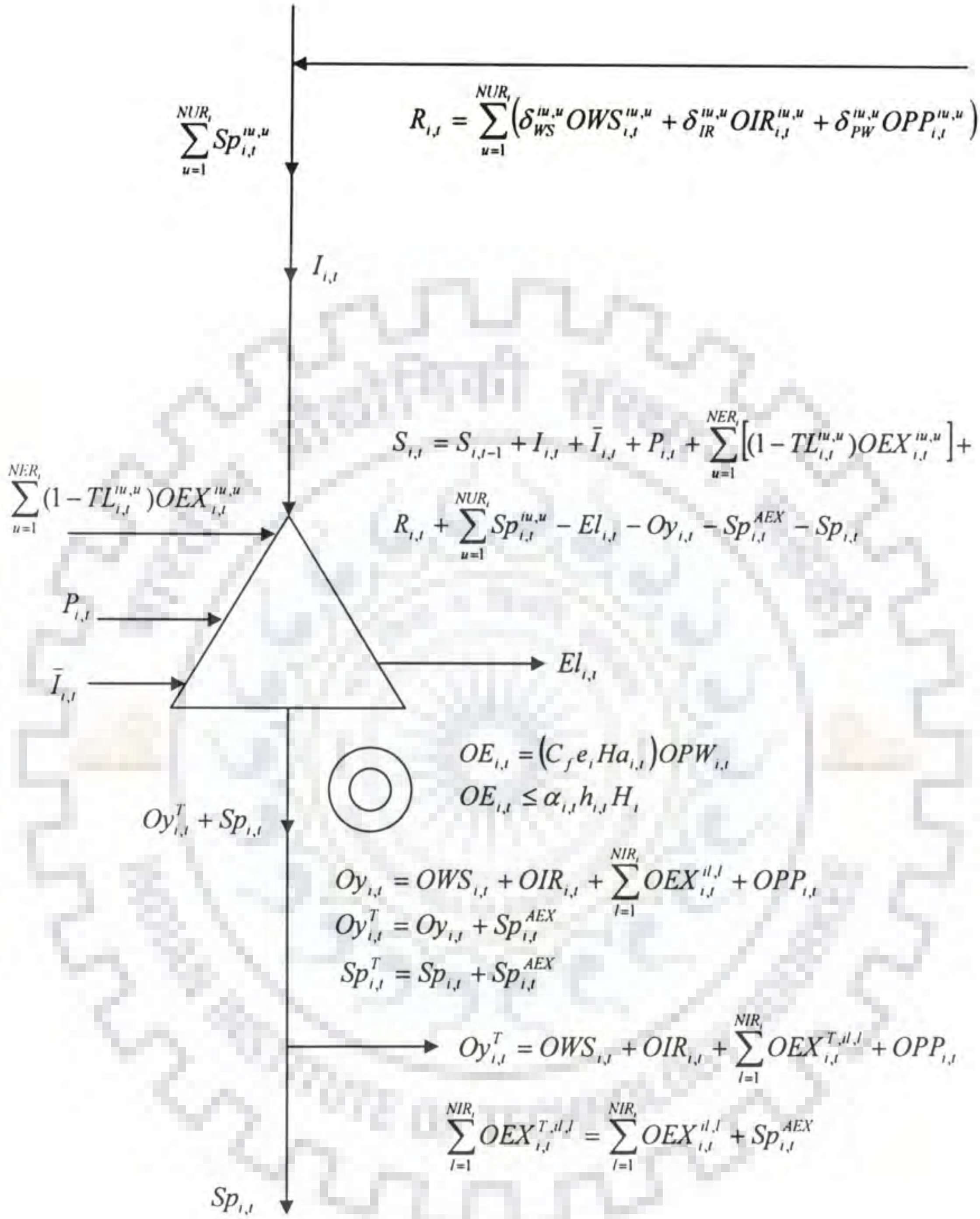

**Figure 7.1** Graphical illustration of the simulation model

## 7.3 DISCUSSION

Simulation is a modeling technique that approximates the behavior of a system on the computer, representing all the characteristics of the system by mathematical relationships. It is an effective tool for studying the management of a complex water resource system, for it can incorporate the experience and judgment of the planner or designer into the model. It does not yield an immediate optimal answer. Each answer basically pertains to a combination of selected variables. A number of iterations are to be performed to arrive at the optimum. In the above simulation model, provision is kept to add the spill of the reservoir at any given time to the target water export yield at that time up to the permissible link canal capacity. Thus annual reservoir spill will decrease and the annual water utilization from the reservoir will increase. This provision will also help in comparing the results of the reservoir operation by the CIM and simulation.

## NOTATION

$A_{i,t}$ = surface area of reservoir i in time t;

$C_f$ = conversion factor for computation of hydroelectric energy;

$CC_i$ = water transfer link canal capacity from reservoir i;

$DE_{i,t}$ = energy demand from reservoir i in time t;

$DPW_{i,t}$ = volume of water required to generate target energy from reservoir i in time t;

$DWS_{i,t}$ = demand of domestic water supply from reservoir i in time t;

$DIR_{i,t}$ = irrigation demand from reservoir i in time t;

$DEX_{i,t}^{il,l}$ = demand for water export from reservoir i to a lower reservoir l in time t;

$DWS_i$ = annual demand for domestic water supply from reservoir i;

$DIR_i$ = annual demand for irrigation from reservoir i;

$DEX_i^{il}$ = annual demand for water export from reservoir i to lower reservoirs;

$D_{i,t}^{WS}$ = fraction of annual target domestic water supply yield from reservoir i in period t;

$D_{i,t}^{IR}$ = fraction of annual target irrigation yield from reservoir i in period t;

$D_{i,t}^{EX,il}$ = fraction of annual target water export yield from reservoir i to lower reservoirs in period t;

$e_i$ = hydropower plant efficiency for reservoir i;

$ev_{i,t}$ = average rate of evaporation from reservoir i in time t;

$El_{i,t}$ = evaporation at reservoir i in time t;

$h_{i,t}$ = number of hours for generation of energy for reservoir i in time t;

$H_i$ = hydropower plant capacity for reservoir i;

$Ha_{i,t}$ = productive storage head for reservoir i in period t;

$I_{i,t}$ = inflow to reservoir i in time t;

$\bar{I}_{i,t}$ = local inflow to reservoir i from surrounding area in time t;

$NER_i$ = number of water exporting reservoirs to reservoir i;

$NUR_i$ = number of upstream reservoirs above reservoir i;

$NIR_i$ = number of water importing reservoirs from reservoir i;

$OE_{i,t}$ = energy generated from reservoir i in time t;

$OEX_{i,t}^{il,l}$ = water export yield from reservoir i to a lower reservoir l in time t;

$OEX_{i,t}^{iu,u}$ = water exported from an upper reservoir u to reservoir i in time t;

$OEX_{i,t}^{T,il,l}$ = total water export including additional water export from reservoir i to a lower reservoir l in time t;

$OIR_{i,t}^{iu,u}$ = volume of water released for irrigation from a reservoir u upstream of reservoir i in time t;

$OIR_{i,t}$ = irrigation yield from reservoir i in time t;

$OPM_{i,t}$ = part of the water from irrigation and water export yields from reservoir i in time t that is not used for energy generation;

$OPP_{i,t}^{iu,u}$ = volume of additional water released for energy generation over and above what is required for irrigation and water export from a reservoir u upstream of reservoir i in time t;

$OPP_{i,t}$ = volume of water used for energy generation from reservoir i in time t, over and above that from irrigation and water export yields;

$OPW_{i,t}$ = volume of water used to generate energy from reservoir i in time t;

$OWS_{i,t}^{iu,u}$ = volume of water released for domestic water supply from a reservoir u upstream of reservoir i in time t;

$OWS_{i,t}$ = domestic water supply yield from reservoir i in time t;

$Oy_{i,t}$ = total water yields in volume, excluding additional water export ($Sp_{i,t}^{AEX}$) from reservoir i in time t;

$Oy_{i,t}^{T}$ = total water yields in volume, including additional water export from reservoir i in time t

$P_{i,t}$ = precipitation directly upon reservoir i in time t;

$R_{i,t}$ = regenerated flows coming from water uses of upstream reservoirs to reservoir i in time t;

$S_{i,t}$ = final storage at the end of time t for reservoir i;

$S_{i,t-1}$ = initial storage at the beginning of time t for reservoir i;

$Sp_{i,t}$ = spill from reservoir i in time t;

$Sp_{i,t}^{iu,u}$ = spill from an upstream reservoir u entering to reservoir i in time t;

$Sp_{i,t}^{AEX}$ = additional water export over and above water export demand, if excess water is available and canal capacity permits, at time t from reservoir i;

$TL_{i,t}^{iu,u}$ = water transfer loss from reservoir u to i;

$Y\max_i$ = gross storage capacity of reservoir i;

$\alpha_{i,t}$ = hydropower plant factor for reservoir i in period t;

$\delta_{WS}^{iu,u}$ = fraction of domestic water supply yield coming as regenerated flow to reservoir i from an upstream reservoir u;

$\delta_{IR}^{iu,u}$ = fraction of irrigation yield coming as regenerated flow to reservoir i from an upstream reservoir u;

$\delta_{PW}^{iu,u}$ = fraction of the additional volume of water used for energy generation over and above what is required for irrigation and water export coming as regenerated flow to reservoir i from an upstream reservoir u; and

$\eta_{i,t}$ = fraction of annual firm energy target for reservoir i in period t.

# PLANNING OF RESERVOIR SYSTEM

## 8.1 INTRODUCTION

The feasibility and merits of the modeling approach discussed in Chapter 5 and Chapter 6 are demonstrated with an application to the system of five reservoirs in the Chambal river basin. The Improved General Purpose Yield Model (IGPYM) and the two dynamic programming models, namely, Procurement Problem Model (PPM) and Controlled Input Model (CIM) are used for planning of reservoirs. Out of these five reservoirs, three reservoirs, namely, PAT reservoir in Parbati river, MOH reservoir in Newaz river, and KUN reservoir in Kalisindh river are proposed reservoirs and the remaining two reservoirs, i.e., GS and RPS in Chambal river are existing. Out of these, the PAT, MOH and KUN are in parallel; and GS and RPS are in series. For water transfers, two alternative links are considered as mentioned in Section 3.7; Alternative I (Link-I) assumes that water will be exported from PAT to MOH, MOH to KUN and KUN to GS, and Alternative II (Link-II) assumes that the water transfer will be done from PAT to MOH, MOH to KUN, and KUN to RPS. The line diagram of the reservoirs is presented in Figure 3.2. The IGPYM is used for preliminary screening and for estimating the reasonable reservoir capacities of the proposed reservoirs. The dynamic programming models are applied to refine the results obtained through the IGPYM. The PPM calculates amount of import water requirements at a reservoir to meet its water demands. The CIM estimates water demands that a reservoir can meet with specified reliabilities, and also amount of water it can export to other sites. The applications of the above DP models require a definite sequence of steps to be followed. Different link alternatives, reservoir capacities and link canal capacities are considered under different cases. The objective of the work is to present a realistic and efficient system analysis modeling approach for reservoir planning, related to a multipurpose, multi site reservoir system.

## 8.2 THE IMPROVED GENERAL PURPOSE YIELD MODEL (IGPYM) APPLICATION

The IGPYM developed is to be solved using linear programming (LP) technique. Standard commercial linear programming package 'LINDO' (Linear Interactive aNd Discrete Optimizer, Copyright (C) 1986, 1987; LINDO Systems, Inc.) is used for this purpose. The main objective of the model application is to know at each reservoir the amount of water that can be exported after meeting all its water needs with given priorities, the annual reliabilities at which the water demands can be met at or above their respective prespecified target annual reliabilities, required reservoir capacity in case of proposed reservoir, and the trade-off between water uses in the system.

### 8.2.1 Additional Constraint for Reservoirs Exporting Water

One more constraint is added in the model for the reservoirs exporting water to satisfy the NWDA guidelines. The annual water export from a reservoir should not exceed the surplus surface water available at 75% water year dependability at the reservoir site. So, the annual export of water from reservoir i is made less than or equal to the annual surplus surface water available at 75% water year dependability at the site plus the import of water coming to the reservoir from a set of $NER_i$ (number of water exporting reservoirs to reservoir i) upper reservoirs.

$$Oy_i^{S,p2} \le \left( SSWB_i^{75D} + \sum_{u=1}^{NER_i} Oy_u^{S,p2} \right) \text{ for reservoirs having import from } NER_i \text{ upper reservoirs.} \tag{8.1}$$

where

$SSWB_i^{75D}$ is the surplus surface water available at 75% water year dependability at the reservoir i.

### 8.2.2 Data Preparation

The application of the IGPYM requires the following basic data:

- inflows at each reservoir site,
- elevation-area-capacity data at each reservoir site,
- average rates of evaporation,
- reservoir capacities for existing reservoirs and design reservoir capacities (if available) for proposed reservoirs,
- water demands at reservoirs for different water needs, and
- target reliabilities at which the above water demands should be met.

The inflow data at each reservoir site is available for seventeen years from 1977 to 1993 on monthly basis. The elevation-area-capacity data at each reservoir site, design gross and live storage capacities of reservoirs, average monthly rates of evaporation, and water demands at reservoirs for domestic water supply and irrigation are presented in Annexure-I, Table 3.9, Table 3.10 and Table 3.11, respectively. As per the standard practices followed in India, among various water uses, the domestic water supply has the highest priority of water use, followed by irrigation, water export and power generation. The specified target annual reliabilities for water supply, irrigation and hydropower generation are 100%, 75% and 90%, respectively. As per above, with 17 years of available inflows, the target annual reliabilities that can be practically achieved by Weibull's plotting position formula for water supply, irrigation and hydropower generation are 94.44%, 72.22% and 88.89%, respectively. An annual reliability of 94.44% is considered for annual firm power generation. For irrigation, water export and secondary energy, a minimum annual reliability of 72.22% is considered.

So, the number of permissible failure years for irrigation, water export and secondary energy is four in seventeen years. The number of failure years for domestic water supply and firm power generation is zero. From the inflow data, by visual inspection, the 3rd, 5th, 13th and 16th years are considered as failure years for all the reservoirs.

The application of the IGPYM needs the following parameters, which can be generated from the basic data mentioned above-

- the fraction of the annual evaporation loss in period (month) t, i.e., $\gamma_{i,t}$ values,
- the percentage fraction in period t of annual firm energy target, $\eta_{i,t}$, for reservoirs having power generations,
- the ratio of the inflow in period t of the critical year to the total inflow in that year for each reservoir, i.e., the $\beta_{i,t}$ values,
- the monthly fractional use of priority demand for each reservoir, i.e., $D^{P}_{i,t}$ values, and
- the monthly fractional use of second demand for each reservoir, i.e., $D^{S}_{i,t}$ values.

The fraction of the annual evaporation losses in month t, i.e., $\gamma_{i,t}$ are calculated for all reservoirs and are presented in Table 8.1. The percentage fractions of annual firm energy target ($\eta_{i,t}$) for GS and RPS reservoirs are assumed equal for all the months.

**Table 8.1** Fraction of the annual evaporation losses, $\gamma_{i,t}$

| Month | For PAT, MOH and KUN | For GS and RPS |
|---|---|---|
| Jun | 0.14 | 0.1415 |
| Jul | 0.09 | 0.0708 |
| Aug | 0.07 | 0.0425 |
| Sep | 0.08 | 0.0566 |
| Oct | 0.08 | 0.0660 |
| Nov | 0.05 | 0.0519 |
| Dec | 0.04 | 0.0472 |
| Jan | 0.04 | 0.0472 |
| Feb | 0.06 | 0.0566 |
| Mar | 0.09 | 0.1038 |
| Apr | 0.12 | 0.1368 |
| May | 0.15 | 0.1792 |
| Total | 1.00 | 1.0000 |

The model considers twelve within year time periods, starting from the month of June (start of water year). As the critical year is not known beforehand, the $\beta_{i,t}$ values are calculated for all the years and then some representative $\beta_{i,t}$ values, i.e., the $\beta_{i,t}$ values from average flows, the $\beta_{i,t}$ values based on the flow of the driest year in record, and the mean of the two $\beta_{i,t}$'s mentioned above are also calculated. The values of these $\beta_{i,t}$ for all the reservoirs are presented in Tables 8.2 (a) to 8.2 (e).

**Table 8.2 (a)** $\beta_{i,t}$ values for PAT reservoir

| Year | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Total | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1977 | 0.052 | 0.180 | 0.426 | 0.299 | 0.027 | 0.004 | 0.007 | 0.002 | 0.001 | 0.001 | 0.000 | 0.000 | 1.000 | 6 |
| 1978 | 0.008 | 0.176 | 0.607 | 0.135 | 0.012 | 0.005 | 0.006 | 0.008 | 0.008 | 0.005 | 0.032 | 0.000 | 1.000 | 12 |
| 1979 | 0.004 | 0.093 | 0.792 | 0.029 | 0.006 | 0.018 | 0.055 | 0.004 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 17 |
| 1980 | 0.034 | 0.102 | 0.730 | 0.106 | 0.012 | 0.005 | 0.002 | 0.007 | 0.002 | 0.000 | 0.000 | 0.000 | 1.000 | 11 |
| 1981 | 0.041 | 0.204 | 0.524 | 0.176 | 0.027 | 0.016 | 0.005 | 0.002 | 0.004 | 0.001 | 0.000 | 0.000 | 1.000 | 13 |
| 1982 | 0.000 | 0.053 | 0.794 | 0.111 | 0.013 | 0.017 | 0.005 | 0.004 | 0.002 | 0.000 | 0.000 | 0.000 | 1.000 | 8 |
| 1983 | 0.003 | 0.066 | 0.392 | 0.460 | 0.051 | 0.010 | 0.005 | 0.008 | 0.003 | 0.002 | 0.001 | 0.000 | 1.000 | 2 |
| 1984 | 0.000 | 0.032 | 0.708 | 0.221 | 0.026 | 0.007 | 0.004 | 0.002 | 0.001 | 0.000 | 0.000 | 0.000 | 1.000 | 7 |
| 1985 | 0.000 | 0.000 | 0.304 | 0.486 | 0.158 | 0.028 | 0.011 | 0.003 | 0.005 | 0.003 | 0.001 | 0.000 | 1.000 | 1 |
| 1986 | 0.025 | 0.662 | 0.290 | 0.016 | 0.004 | 0.001 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 4 |
| 1987 | 0.000 | 0.312 | 0.470 | 0.195 | 0.015 | 0.004 | 0.002 | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 | 1.000 | 14 |
| 1988 | 0.004 | 0.478 | 0.380 | 0.040 | 0.080 | 0.003 | 0.000 | 0.011 | 0.000 | 0.000 | 0.000 | 0.003 | 1.000 | 9 |
| 1989 | 0.009 | 0.043 | 0.617 | 0.282 | 0.007 | 0.004 | 0.009 | 0.028 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 16 |
| 1990 | 0.102 | 0.153 | 0.348 | 0.306 | 0.078 | 0.008 | 0.003 | 0.002 | 0.001 | 0.000 | 0.000 | 0.000 | 1.000 | 3 |
| 1991 | 0.000 | 0.126 | 0.774 | 0.088 | 0.009 | 0.002 | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 10 |
| 1992 | 0.000 | 0.047 | 0.778 | 0.155 | 0.015 | 0.004 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 15 |
| 1993 | 0.000 | 0.085 | 0.518 | 0.339 | 0.049 | 0.005 | 0.001 | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 | 1.000 | 5 |
| Total= | 0.282 | 2.812 | 9.453 | 3.444 | 0.589 | 0.142 | 0.116 | 0.084 | 0.029 | 0.013 | 0.033 | 0.004 |  |  |
| $\beta_{i,t}$ from average flows |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 0.017 | 0.165 | 0.556 | 0.203 | 0.035 | 0.008 | 0.007 | 0.005 | 0.002 | 0.001 | 0.002 | 0.000 | 1.000 |  |
| $\beta_{i,t}$ as the *mean* of $\beta_{i,t}$ values obtained from average and the driest year's flows |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 0.010 | 0.129 | 0.674 | 0.116 | 0.020 | 0.013 | 0.031 | 0.004 | 0.001 | 0.000 | 0.001 | 0.000 | 1.000 |  |

**Table 8.2 (b) $\beta_{u}$ values for MOH reservoir**

| Year | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Total | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1977 | 0.019 | 0.173 | 0.405 | 0.336 | 0.035 | 0.011 | 0.012 | 0.004 | 0.002 | 0.002 | 0.001 | 0.000 | 1.000 | 12 |
| 1978 | 0.034 | 0.189 | 0.566 | 0.169 | 0.015 | 0.004 | 0.008 | 0.004 | 0.005 | 0.004 | 0.001 | 0.000 | 1.000 | 8 |
| 1979 | 0.005 | 0.032 | 0.931 | 0.014 | 0.007 | 0.003 | 0.005 | 0.002 | 0.001 | 0.000 | 0.000 | 0.000 | 1.000 | 17 |
| 1980 | 0.144 | 0.133 | 0.508 | 0.201 | 0.009 | 0.003 | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 13 |
| 1981 | 0.020 | 0.118 | 0.663 | 0.148 | 0.019 | 0.007 | 0.001 | 0.005 | 0.017 | 0.001 | 0.000 | 0.000 | 1.000 | 14 |
| 1982 | 0.000 | 0.086 | 0.744 | 0.152 | 0.018 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 11 |
| 1983 | 0.003 | 0.072 | 0.125 | 0.335 | 0.448 | 0.007 | 0.003 | 0.002 | 0.002 | 0.001 | 0.000 | 0.000 | 1.000 | 4 |
| 1984 | 0.003 | 0.030 | 0.812 | 0.131 | 0.015 | 0.005 | 0.002 | 0.001 | 0.001 | 0.001 | 0.000 | 0.000 | 1.000 | 6 |
| 1985 | 0.000 | 0.320 | 0.446 | 0.214 | 0.012 | 0.004 | 0.002 | 0.003 | 0.000 | 0.001 | 0.000 | 0.000 | 1.000 | 2 |
| 1986 | 0.020 | 0.702 | 0.257 | 0.015 | 0.003 | 0.001 | 0.001 | 0.002 | 0.001 | 0.000 | 0.000 | 0.000 | 1.000 | 1 |
| 1987 | 0.000 | 0.123 | 0.672 | 0.159 | 0.033 | 0.006 | 0.004 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 7 |
| 1988 | 0.013 | 0.347 | 0.510 | 0.060 | 0.061 | 0.006 | 0.003 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 9 |
| 1989 | 0.039 | 0.061 | 0.722 | 0.169 | 0.009 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 16 |
| 1990 | 0.017 | 0.131 | 0.394 | 0.393 | 0.055 | 0.007 | 0.002 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 5 |
| 1991 | 0.000 | 0.163 | 0.755 | 0.074 | 0.005 | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 10 |
| 1992 | 0.000 | 0.051 | 0.663 | 0.263 | 0.016 | 0.005 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 15 |
| 1993 | 0.004 | 0.186 | 0.340 | 0.423 | 0.037 | 0.006 | 0.001 | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 | 1.000 | 3 |
| Total= | 0.322 | 2.917 | 9.512 | 3.255 | 0.797 | 0.078 | 0.047 | 0.028 | 0.030 | 0.010 | 0.002 | 0.000 | | |
| $\beta_{u}$ from average flows | | | | | | | | | | | | | | |
| | 0.019 | 0.172 | 0.560 | 0.191 | 0.047 | 0.005 | 0.003 | 0.002 | 0.002 | 0.001 | 0.000 | 0.000 | 1.000 | |
| $\beta_{u}$ as the *mean* of $\beta_{u}$ values obtained from average and the driest year's flows | | | | | | | | | | | | | | |
| | 0.012 | 0.102 | 0.745 | 0.103 | 0.027 | 0.004 | 0.004 | 0.002 | 0.001 | 0.000 | 0.000 | 0.000 | 1.000 | |

**Table 8.2 (c)** $\beta_{i,t}$ values for KUN reservoir

| Year | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Total | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1977 | 0.007 | 0.088 | 0.455 | 0.417 | 0.023 | 0.003 | 0.006 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 11 |
| 1978 | 0.029 | 0.081 | 0.675 | 0.200 | 0.015 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 9 |
| 1979 | 0.023 | 0.062 | 0.857 | 0.059 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 15 |
| 1980 | 0.144 | 0.130 | 0.508 | 0.212 | 0.005 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 14 |
| 1981 | 0.011 | 0.031 | 0.843 | 0.096 | 0.007 | 0.011 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 12 |
| 1982 | 0.000 | 0.102 | 0.801 | 0.094 | 0.000 | 0.003 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 13 |
| 1983 | 0.011 | 0.092 | 0.287 | 0.494 | 0.115 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 7 |
| 1984 | 0.000 | 0.023 | 0.890 | 0.079 | 0.008 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 4 |
| 1985 | 0.000 | 0.000 | 0.592 | 0.209 | 0.186 | 0.013 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 1 |
| 1986 | 0.020 | 0.533 | 0.437 | 0.010 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 3 |
| 1987 | 0.112 | 0.801 | 0.086 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 10 |
| 1988 | 0.000 | 0.312 | 0.421 | 0.103 | 0.162 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 6 |
| 1989 | 0.000 | 0.060 | 0.894 | 0.045 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 17 |
| 1990 | 0.011 | 0.071 | 0.541 | 0.323 | 0.050 | 0.003 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 2 |
| 1991 | 0.019 | 0.291 | 0.660 | 0.030 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 8 |
| 1992 | 0.000 | 0.000 | 0.943 | 0.057 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 16 |
| 1993 | 0.000 | 0.233 | 0.556 | 0.185 | 0.027 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 5 |
| Total= | 0.387 | 2.910 | 10.445 | 2.614 | 0.599 | 0.036 | 0.008 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | | |
| $\beta_{i,t}$ from average flows | | | | | | | | | | | | | | |
| | 0.023 | 0.171 | 0.614 | 0.154 | 0.035 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | |
| $\beta_{i,t}$ as the *mean* of $\beta_{i,t}$ values obtained from average and the driest year's flows | | | | | | | | | | | | | | |
| | 0.011 | 0.116 | 0.754 | 0.100 | 0.018 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | |

### Table 8.2 (d) $\beta_{i,t}$ values for GS reservoir

| Year | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Total | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1977 | 0.027 | 0.137 | 0.335 | 0.434 | 0.024 | 0.000 | 0.016 | 0.006 | 0.001 | 0.005 | 0.009 | 0.006 | 1.000 | 3 |
| 1978 | 0.019 | 0.146 | 0.559 | 0.238 | 0.015 | 0.000 | 0.003 | 0.000 | 0.001 | 0.003 | 0.008 | 0.008 | 1.000 | 5 |
| 1979 | 0.077 | 0.070 | 0.729 | 0.031 | 0.011 | 0.031 | 0.021 | 0.002 | 0.001 | 0.007 | 0.016 | 0.004 | 1.000 | 14 |
| 1980 | 0.147 | 0.160 | 0.382 | 0.257 | 0.002 | 0.002 | 0.021 | 0.004 | 0.015 | 0.000 | 0.002 | 0.008 | 1.000 | 10 |
| 1981 | 0.023 | 0.116 | 0.573 | 0.112 | 0.027 | 0.034 | 0.014 | 0.020 | 0.016 | 0.009 | 0.047 | 0.009 | 1.000 | 8 |
| 1982 | 0.014 | 0.139 | 0.604 | 0.083 | 0.004 | 0.075 | 0.027 | 0.006 | 0.013 | 0.015 | 0.011 | 0.008 | 1.000 | 15 |
| 1983 | 0.019 | 0.116 | 0.380 | 0.307 | 0.088 | 0.020 | 0.012 | 0.001 | 0.012 | 0.030 | 0.008 | 0.009 | 1.000 | 11 |
| 1984 | 0.006 | 0.029 | 0.901 | 0.043 | 0.001 | 0.001 | 0.001 | 0.000 | 0.003 | 0.009 | 0.001 | 0.005 | 1.000 | 2 |
| 1985 | 0.005 | 0.013 | 0.488 | 0.104 | 0.332 | 0.009 | 0.010 | 0.004 | 0.020 | 0.002 | 0.007 | 0.005 | 1.000 | 12 |
| 1986 | 0.010 | 0.442 | 0.520 | 0.001 | 0.005 | 0.003 | 0.000 | 0.000 | 0.002 | 0.008 | 0.000 | 0.009 | 1.000 | 1 |
| 1987 | 0.031 | 0.009 | 0.689 | 0.092 | 0.088 | 0.003 | 0.005 | 0.022 | 0.020 | 0.024 | 0.009 | 0.007 | 1.000 | 13 |
| 1988 | 0.041 | 0.085 | 0.468 | 0.053 | 0.266 | 0.011 | 0.014 | 0.011 | 0.009 | 0.012 | 0.027 | 0.005 | 1.000 | 7 |
| 1989 | 0.023 | 0.145 | 0.324 | 0.417 | 0.014 | 0.008 | 0.037 | 0.023 | 0.002 | 0.004 | 0.003 | 0.001 | 1.000 | 16 |
| 1990 | 0.000 | 0.073 | 0.404 | 0.440 | 0.052 | 0.005 | 0.002 | 0.003 | 0.003 | 0.005 | 0.005 | 0.008 | 1.000 | 4 |
| 1991 | 0.003 | 0.301 | 0.601 | 0.070 | 0.001 | 0.001 | 0.006 | 0.000 | 0.001 | 0.005 | 0.002 | 0.009 | 1.000 | 6 |
| 1992 | 0.036 | 0.301 | 0.232 | 0.311 | 0.070 | 0.002 | 0.010 | 0.008 | 0.009 | 0.010 | 0.008 | 0.004 | 1.000 | 17 |
| 1993 | 0.057 | 0.418 | 0.338 | 0.099 | 0.032 | 0.006 | 0.004 | 0.006 | 0.008 | 0.011 | 0.011 | 0.009 | 1.000 | 9 |
| Total= | 0.536 | 2.701 | 8.527 | 3.092 | 1.031 | 0.212 | 0.202 | 0.118 | 0.136 | 0.160 | 0.173 | 0.113 |  |  |
| $\beta_{i,t}$ from average flows |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 0.032 | 0.159 | 0.502 | 0.182 | 0.061 | 0.012 | 0.012 | 0.007 | 0.008 | 0.009 | 0.010 | 0.007 | 1.000 |  |
| $\beta_{i,t}$ as the *mean* of $\beta_{i,t}$ values obtained from average and the driest year's flows |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 0.034 | 0.230 | 0.367 | 0.246 | 0.065 | 0.007 | 0.011 | 0.007 | 0.008 | 0.010 | 0.009 | 0.005 | 1.000 |  |

**Table 8.2 (e)** $\beta_{i,t}$ values for RPS reservoir

| Year | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Total | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1977 | 0.000 | 0.483 | 0.353 | 0.164 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **13** |
| 1978 | 0.000 | 0.131 | 0.387 | 0.482 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **11** |
| 1979 | 0.035 | 0.394 | 0.572 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **14** |
| 1980 | 0.400 | 0.074 | 0.326 | 0.200 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **16** |
| 1981 | 0.000 | 0.383 | 0.506 | 0.111 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **17** |
| 1982 | 0.009 | 0.110 | 0.831 | 0.011 | 0.000 | 0.040 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **6** |
| 1983 | 0.037 | 0.162 | 0.397 | 0.274 | 0.130 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **8** |
| 1984 | 0.027 | 0.127 | 0.830 | 0.016 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **3** |
| 1985 | 0.004 | 0.187 | 0.594 | 0.041 | 0.173 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **5** |
| 1986 | 0.054 | 0.678 | 0.267 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **2** |
| 1987 | 0.000 | 0.012 | 0.705 | 0.105 | 0.033 | 0.000 | 0.016 | 0.000 | 0.000 | 0.000 | 0.000 | 0.129 | 1.000 | **12** |
| 1988 | 0.185 | 0.324 | 0.324 | 0.065 | 0.083 | 0.012 | 0.006 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 1.000 | **15** |
| 1989 | 0.030 | 0.078 | 0.257 | 0.061 | 0.016 | 0.261 | 0.029 | 0.005 | 0.004 | 0.259 | 0.000 | 0.000 | 1.000 | **1** |
| 1990 | 0.024 | 0.205 | 0.489 | 0.251 | 0.015 | 0.000 | 0.000 | 0.001 | 0.005 | 0.003 | 0.007 | 0.000 | 1.000 | **9** |
| 1991 | 0.000 | 0.248 | 0.576 | 0.176 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **4** |
| 1992 | 0.000 | 0.359 | 0.292 | 0.198 | 0.150 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **7** |
| 1993 | 0.165 | 0.418 | 0.246 | 0.164 | 0.006 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | **10** |
| Total= | 0.969 | 4.373 | 7.954 | 2.321 | 0.606 | 0.313 | 0.051 | 0.005 | 0.009 | 0.262 | 0.008 | 0.129 | | |
| $\beta_{i,t}$ from average flows | | | | | | | | | | | | | | |
| | 0.057 | 0.257 | 0.468 | 0.137 | 0.036 | 0.018 | 0.003 | 0.000 | 0.001 | 0.015 | 0.000 | 0.008 | 1.000 | |
| $\beta_{i,t}$ as the *mean* of $\beta_{i,t}$ values obtained from average and the driest year's flows | | | | | | | | | | | | | | |
| | 0.029 | 0.320 | 0.487 | 0.124 | 0.018 | 0.009 | 0.002 | 0.000 | 0.000 | 0.008 | 0.000 | 0.004 | 1.000 | |

To get the monthly fractional use of priority demand ( $D^{P}_{i,t}$ values), the water purposes that will be included (clubbed) in the priority demand have been pre-decided as follows:

(i) All the three proposed reservoirs, PAT, MOH and KUN have to serve three water purposes, i.e., domestic water supply, irrigation and water export. The domestic water supply and irrigation demands are clubbed together and termed as priority demand. Water transfer (export) to other reservoir is considered as second demand.

(ii) GS reservoir has two compatible water purposes, i.e., irrigation and power generation, where the water put to irrigation use is also available for power generation. The irrigation use is considered as priority demand. The annual firm yield is used for annual firm power generation and the annual secondary yield is used for annual secondary energy generation.

(iii) Like GS reservoir, for RPS reservoir also the annual firm yield is used for annual firm power generation and the annual secondary yield is used for annual secondary energy generation. Since RPS is a single purpose hydropower reservoir, it is assumed that entire annual priority yield will be used for annual firm power generation.

The priority demands and the monthly fractional use of priority demands for the reservoirs, excluding RPS reservoir where energy demands are unknown, are presented in Table 8.3.

**Table 8.3** Priority demands and monthly fractional use of priority demands

| Month | PAT | | MOH | | KUN | | GS | |
|---|---|---|---|---|---|---|---|---|
| | Priority demand | $D_{i,t}^{P}$ | Priority demand | $D_{i,t}^{P}$ | Priority demand | $D_{i,t}^{P}$ | Priority demand | $D_{i,t}^{P}$ |
| Jun | 9.84 | 0.07 | 10.12 | 0.07 | 22.51 | 0.07 | 109.63 | 0.0326 |
| Jul | 22.17 | 0.16 | 22.81 | 0.16 | 50.68 | 0.16 | 556.58 | 0.1655 |
| Aug | 15.32 | 0.11 | 15.76 | 0.11 | 35.03 | 0.11 | 1343.18 | 0.3994 |
| Sep | 9.84 | 0.07 | 10.12 | 0.07 | 22.51 | 0.07 | 996.12 | 0.2962 |
| Oct | 7.10 | 0.05 | 7.30 | 0.05 | 16.25 | 0.05 | 136.87 | 0.0407 |
| Nov | 9.84 | 0.07 | 10.12 | 0.07 | 22.51 | 0.07 | 51.12 | 0.0152 |
| Dec | 15.32 | 0.11 | 15.76 | 0.11 | 35.03 | 0.11 | 30.94 | 0.0092 |
| Jan | 20.80 | 0.15 | 21.40 | 0.15 | 47.55 | 0.15 | 27.91 | 0.0083 |
| Feb | 19.43 | 0.14 | 19.99 | 0.14 | 44.42 | 0.14 | 20.85 | 0.0062 |
| Mar | 4.36 | 0.03 | 4.48 | 0.03 | 9.99 | 0.03 | 29.59 | 0.0088 |
| Apr | 2.99 | 0.02 | 3.07 | 0.02 | 6.86 | 0.02 | 32.62 | 0.0097 |
| May | 2.99 | 0.02 | 3.07 | 0.02 | 6.86 | 0.02 | 27.58 | 0.0082 |
| Total | 140.00 | 1.00 | 144.00 | 1.00 | 320.20 | 1.00 | 3363.00 | 1.00 |

Note: For PAT, MOH and KUN reservoirs, priority demand = water supply demand + irrigation demand; for GS reservoir, priority demand = irrigation demand. Unit of priority demand is MCM.

To get the maximum possible annual water exports from each of the proposed reservoirs, the following options are tried for the water export release fraction ( $D_{i,t}^{S}$ ) values:

(a) transfer release fraction as per 75% water year dependable flows,

(b) transfer release fraction as per average inflow, and

(c) transfer release fraction as per the spills available from the reservoir operation (working) table of 75% water year dependable flows.

The volume of water export that can be achieved by using the above $D_{i,t}^{S}$ values are obtained through model run and compared. Slight adjustments in $D_{i,t}^{S}$ values are made to get better results by few trial model runs. The set of $D^S_{i,t}$ values, which gives the maximum export is adopted for each reservoir, and is presented in Table 8.4 and Fig. 8.1.

**Table 8.4** Monthly fractional use of second yield (water export) from proposed reservoirs

| Month | PAT | MOH | KUN |
|---|---|---|---|
| Jun | 0 | 0.01510 | 0.01805 |
| Jul | 0.15000 | 0.17210 | 0.18234 |
| Aug | 0.58000 | 0.50130 | 0.55796 |
| Sep | 0.25000 | 0.31150 | 0.20406 |
| Oct | 0.02000 | 0 | 0.03537 |
| Nov | 0 | 0 | 0.01920 |
| Dec | 0 | 0 | 0.00028 |
| Jan | 0 | 0 | 0.00002 |
| Feb | 0 | 0 | 0 |
| Mar | 0 | 0 | 0 |
| Apr | 0 | 0 | 0 |
| May | 0 | 0 | 0 |
| Total | 1.00000 | 1.00000 | 1.00000 |

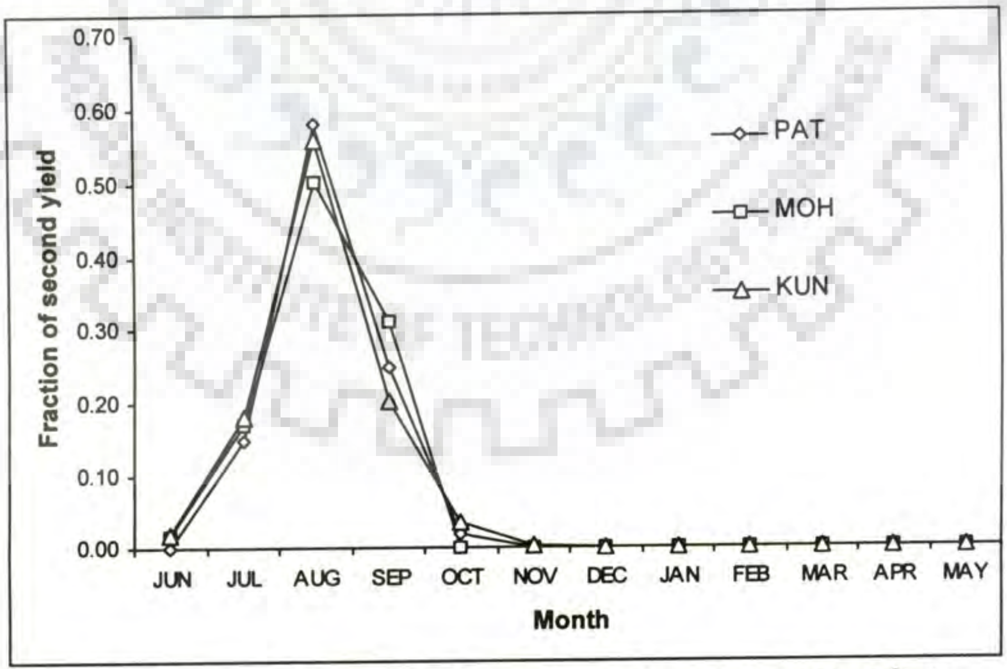

**Figure 8.1** Monthly proportion of annual second reservoir yield, $D^S_{i,t}$, for proposed reservoirs

### 8.2.2.1 Estimation of evaporation loss

The continuity equation in the IGPYM accounts for the loss due to evaporation from the surface of a reservoir. Estimation of the evaporation loss requires knowledge of depth of evaporation and surface area of the reservoir in period t. The surface area is determined from the storage-area relationship of the reservoir. The storage-area relationship (Annexure-II) is non-linear. The storage-area relationship above dead storage is assumed to be linear, and the best-fit straight lines for all reservoirs are obtained and are presented in Fig. 8.2. The area per unit active storage volume ( $A_a$ ) above dead storage, the fixed evaporation ($E0_i$) from the dead storage, and the average annual evaporation volume loss rate per unit of active storage volume ( $El_i^a$ ) are calculated for each reservoir, and are presented in Table 8.5.

**Table 8.5** Estimation of evaporation losses

| Model parameters | Reservoirs | | | | |
|---|---|---|---|---|---|
| | PAT | MOH | KUN | GS | RPS |
| 1. Area at dead storage (sq km), $A_o$ | 9.19 | 4.62 | 27.76 | 137.68 | 119.02 |
| 2. Average annual depth of evaporation (m) | 1.5114 | 1.5114 | 1.5114 | 2.12 | 2.12 |
| 3. Fixed evaporation from dead storage (MCM), $E0_i$<br>[$E0_i$= $A_0$ x Average annual depth of evaporation] | 13.8949 | 6.9866 | 41.9525 | 291.88 | 252.313 |
| 4. Area per unit active storage (obtained from the slope of the storage-area curve above dead storage), $A_a$ | 0.153 | 0.1524 | 0.0814 | 0.0744 | 0.0417 |
| 5. Average annual evaporation volume loss rate, $El_i^a$<br>[ $El_i^a$ =$A_a$ x Average annual depth of evaporation] | 0.23124 | 0.2303 | 0.1230 | 0.15773 | 0.088404 |

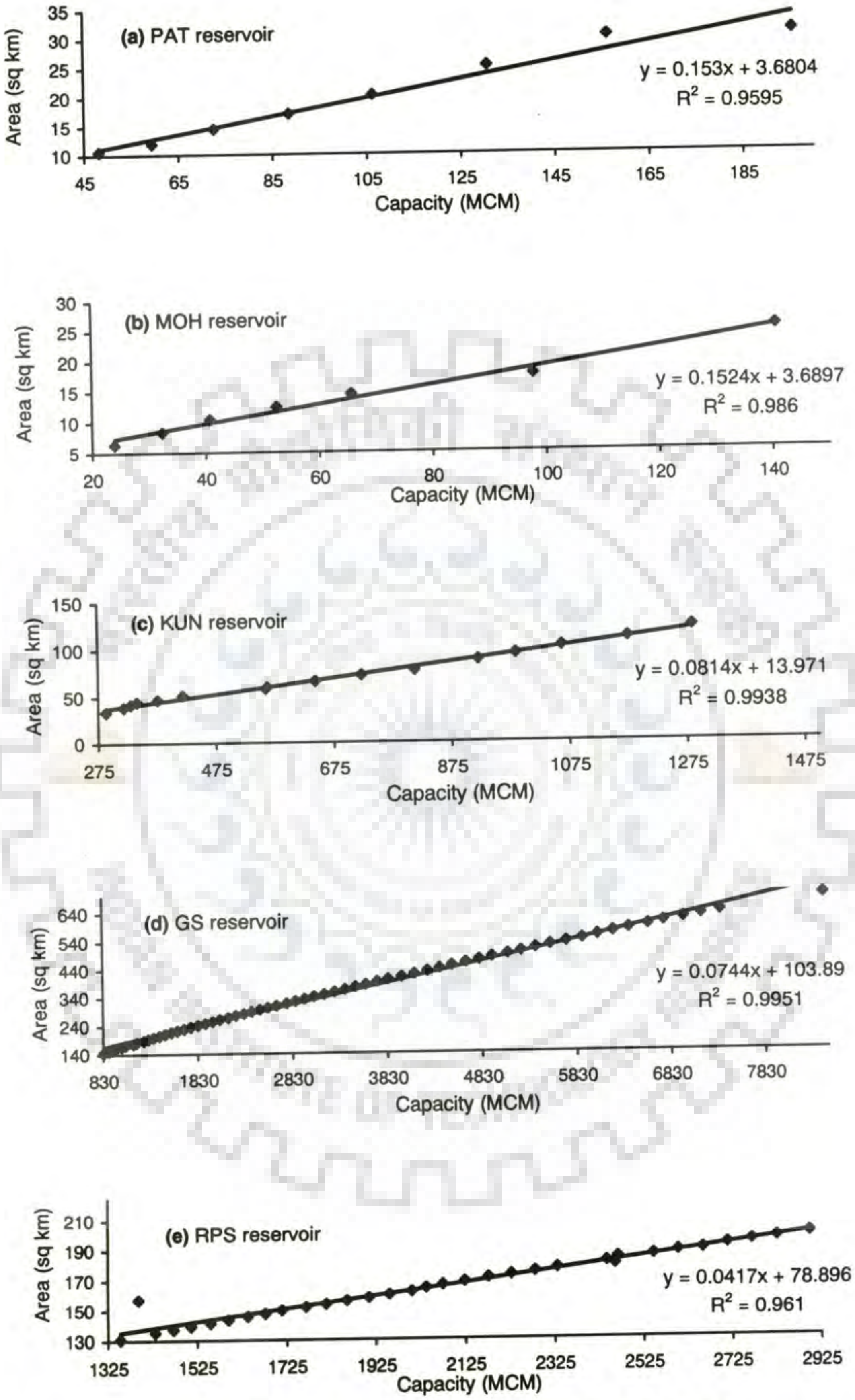

**Figure 8.2** Storage-area curve linearised above dead storage

### 8.2.2.2 The within year continuity equation for the modeled critical year

The within year continuity equation estimates within the year storage capacity requirements. This may be required if the distribution of within year yields differs from the distribution of within year inflows. In the yield model, the within year continuity equation is written for within year periods for only one year (the modeled critical year) to reduce the number of equations and thus the size of the model. It is assumed that the total inflow to the reservoir in the critical year is equal to the total yearly yield from the reservoir, so that the reservoir neither fills nor empties during the modeled critical year. In yield model, inflow at time period t is assumed equal to $\beta_{i,t}$ times the annual yield including evaporation, where $\sum_{t} \beta_{i,t} = 1$. A good choice for $\beta_{i,t}$ is the ratio of the inflow in period t of the driest year of the record to the total inflow in that year. Each $\beta_{i,t}$ thus reflects the relative proportion of the critical year's inflow that is likely to occur in period t (Loucks et al., 1981).

Stedinger et al. (1983) compared the results of yield model with simulation for a three-reservoir water supply system. They tried $\beta_{i,t}$ value based on average monthly flows, on the driest year of record and finally adopted the $\beta_{i,t}$ values based on the average of within the year inflows in the driest and fifth driest years of record. They state that, "A conservative choice is to select the within year flows corresponding to the driest year of record. Modifications of the modeled within year inflows or of the $\beta_{i,t}$'s, in the light of simulation experience, can provide system designs that more nearly meet desired release reliability targets in a cost efficient manner".

Dandy et al. (1997) conducted a study on methods for yield assessment of multiple reservoir systems. They evaluated the yield model with $\beta_{i,t}$ values for the driest and the second driest year. They pointed out that though the second driest year following the driest year appeared to be the critical year from their previous results, the value of system annual reservoir yield that is closest to that obtained with full (complete) optimization model is given by the $\beta_{i,t}$ values of the driest year. They have further mentioned that the selection of the critical year could require some trial-and-error runs of the yield model.

Dahe (2001) compared the results of the yield model with simulation for eight reservoirs in the Narmada river basin in India. He tried $\beta_{i,t}$'s based on (a) average monthly flows (b) the driest year of record, and (c) on flows of the second driest year of record. The comparison of results indicates that out of eight reservoirs, five reservoirs gave better results with $\beta_{i,t}$'s based on the average monthly flows, and for one reservoir, better results were obtained with $\beta_{i,t}$'s based on the flows of the driest year of record. Dahe (2001) stated that, (a) the values of parameter $\beta_{i,t}$ primarily determines the reliability of the identified designs, (b) $\beta_{i,t}$ depends on the nature of inflows as well as the quantity of annual reservoir yield to be delivered and its within year distribution, (c) some trials with the yield model are useful in deciding the values of $\beta_{i,t}$ 's to be adopted, and (d) comparison with simulation results is recommended to select the values of $\beta_{i,t}$ 's.

In light of the above discussions, it is decided to apply the IGPYM to PAT reservoir to select an appropriate set of $\beta_{i,t}$ values. For this purpose, the following $\beta_{i,t}$ values are tried:

(a) the $\beta_{i,t}$'s based on average monthly flows,

(b) the $\beta_{i,t}$ 's based on the flow of the driest year of record, and

(c) the *mean* of the two $\beta_{i,t}$'s (a) and (b) above.

Simulation analysis is carried out for PAT reservoir and the results are compared with the IGPYM results with different $\beta_{i,t}$ values. The results of the IGPYM for different $\beta_{i,t}$ values and simulation are presented in Tables 8.6 (a) and 8.6 (b).

The IGPYM using the *mean* of the $\beta_{i,t}$ values from the average and driest year's flows gives result closest to the results obtained through simulation, compared to the model results by using other $\beta_{i,t}$ values. So, further it is decided to apply IGPYM to all the reservoirs in the system using *mean* $\beta_{i,t}$ values. The adopted $\beta_{i,t}$ values are shown in Fig. 8.3.

**Table 8.6 (a)** IGPYM results for PAT reservoir with different $\beta_{i,t}$ values

| Target annual water supply release=3 MCM<br>Target annual irrigation release=137 MCM | Average $\beta_{i,t}$ value | Driest year's $\beta_{i,t}$ value | *Mean* of the $\beta_{i,t}$ values from the average and driest year's flows |
|---|---|---|---|
| 1. Annual domestic water supply release (MCM) | 3 | 3 | 3 |
| 2. Annual reliability of domestic water supply release | 94% | 94% | 94% |
| 3. Annual irrigation release (MCM) | 137.00 | 132.97 | 137.00 |
| 4. Maximum annual reliability that can be achieved for irrigation | 94% | 94% | 94% |
| 5. Maximum possible annual water export release after meeting the domestic water supply demand and irrigation demand (MCM) | 532.62 | 0.00 | 184.27 |
| 6. Maximum annual reliability of release that can be achieved for water export | 72% | - | 94% |
| 7. Fraction of the annual water export that can be released in a failure year | 0.45 | - | 1.00 |
| 8. Average annual spill (MCM) | 240.11 | 704.47 | 517.21 |

Table 8.6 (b) Simulation results for PAT reservoir

| Water need/Spill | Annual release (MCM) | Annual reliability (%) | Annual allowable failure percentage to achieve highest possible annual reliability, i.e., 94.44% |
|---|---|---|---|
| Domestic water supply | 3 | 94.44 | - |
| Irrigation | 137 | 83.33 | 7 |
| Water export | 74 | 83.33 | 15 |
| Spill | | | |
| (i)Average spill | 620.40 | 55.56 | |
| (ii) Minimum spill | 156.96 | 94.44 | |
| (iii) Maximum spill | 999.53 | 5.56 | |

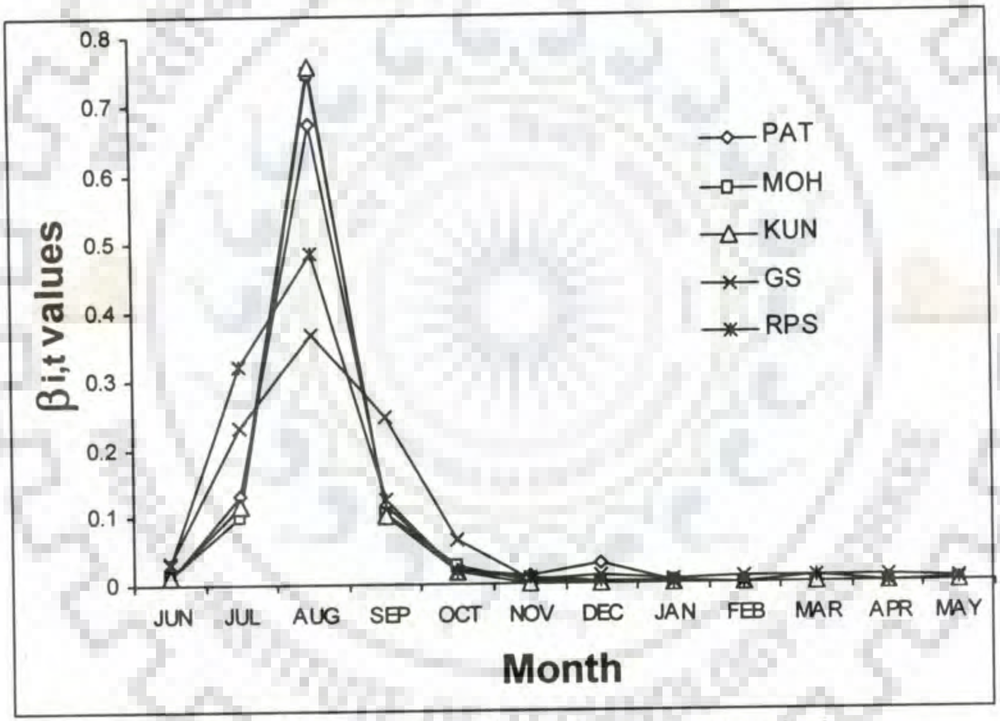

**Figure 8.3** *Mean* $\beta_{i,t}$ values adopted at reservoir sites

### 8.2.2.3 Minimum failure fraction values for priority yields

It is decided that the annual domestic water supply and firm energy demands will be met with maximum possible annual reliability and a minimum annual reliability of 72% (four failure years) will be maintained for irrigation supply, water export and secondary energy generation. Also during irrigation failure years, at least 50% of the target irrigation demand will be met.

As the priority demands for PAT, MOH and KUN reservoirs consist of domestic water supply demand and irrigation demand, the minimum failure fraction for priority yield for these three reservoirs are calculated by the following formula:

For successful years

$\theta_{p1,j} = 1.0$.

For failure years

$\theta_{p1,j}$ = (Domestic water supply demand + 50% of irrigation demand) / (domestic water supply demand + irrigation demand).

For GS reservoir, the priority yield is used for irrigation, so as per the policy adopted, the minimum failure fraction is 0.5 for failure years. For RPS, the priority yield is used for firm energy generation, so no yield failure is allowed, i.e., failure fraction is unity for all the years. The minimum failure fraction values for priority yields, for all the reservoirs are presented in Table 8.7.

**Table 8.7** Minimum failure fraction values for priority yields

| Reservoirs | Minimum failure fraction values for priority yields | |
|---|---|---|
| | Successful years | Failure years |
| PAT | 1 | 0.51 |
| MOH | 1 | 0.51 |
| KUN | 1 | 0.51 |
| GS | 1 | 0.50 |
| RPS | 1 | 1.00 |

### 8.2.3 Formulation of Various Cases for Study

Three cases are formulated to find (i) the maximum water that can be exported with design reservoir capacities after meeting the water supply demand and irrigation demand at desired reliabilities, (ii) the maximum reliabilities that can be achieved for irrigation, water export and secondary energy generation, (iii) the values of failure fractions for priority yields and second yields during failure years, i.e., to know the amount of water each reservoir is capable of supplying for each purpose in a failure year, (iv) the trade-off between reservoir yields for different water needs for design reservoir capacities, (v) the maximum firm and secondary energies, and (vi) alternative reservoir capacities to derive the same benefits as obtained from the design reservoir capacities.

**Case-1:** Reservoir capacities, annual domestic water supply and irrigation demands are known (i.e., design values for reservoir capacities and annual target water demands). Annual water export and energy demands are unknown. The following sub-cases are explored, i.e.,

Case-1 (a): preference is given to increase the volume of irrigation supply over water export during failure years, and

Case-1 (b): preference is given to increase the volume of water export over irrigation supply during failure years.

In India, irrigation is given priority over water export. Case-1 (b) is formulated just to show the flexibility the model is anticipated to offer in enhancing desired yield during failure years, maintaining the same annual yields for all water needs with prespecified reliabilities.

**Case-2** Reservoir capacities and annual domestic demands are known (i.e., design values for reservoir capacities and annual target domestic water supply demands). Both annual priority and second yields are unknown. Preference is given to increase the volume of irrigation supply over water export during failure years.

**Case-3** Reservoir capacities are unknown, annual domestic water supply and irrigation demands are known. The failure fraction values are assumed minimum under the adopted policy of supplying at least 50% of the irrigation target during failure years. For alternative capacity of a proposed reservoir, it is assumed that the increase in its design capacity is either restricted to 10% (Case-3I) or it has no restriction (Case-3II).

Under Case-3I and Case-3II, again two cases are classified, i.e., the total energy benefit is assumed equal to the value as obtained in Case-1 (a) and Case-1 (b); and are termed as Case-3I.1(a) and 3I.1(b), and Case-3II.1(a) and 3II.1(b), respectively.

### 8.2.4 Model Application Methodology, Computations and Results

The IGPYM is applied to each reservoir considering the contributions from the upper/upstream reservoirs either in the form of water export or regenerated flows from water uses. For GS and RPS reservoirs, having hydropower, the model is applied to get the maximum total weighted energy, after applying weightage factors for firm energy and secondary energy. For Case-1 and Case-3, no relationship (like equation 5.61) between priority yield and second yield is required for the reservoirs PAT, MOH, and KUN, as one of the yields is known. Let $\alpha_1$, $\alpha_2$, $\alpha_3$, $\alpha_4$ and $\alpha_5$ represent the desired ratio of priority yield to second yield for PAT, MOH, KUN, GS and RPS, respectively. The $\alpha_5$ value is assumed 2.5 for RPS reservoir for Case-1 and Case-3.

For Case-1 and Case-2, the live reservoir capacities of the proposed reservoirs are assumed equal to their design values. The values of the failure fractions are computed by making trial runs of the model. Initially only the PAT reservoir is considered. The failure fraction value for priority yield is assumed minimum as shown in Table 8.7 and zero for the second yield. The model is run with the objective function of maximizing the second yield for Case-1 and Case-2. As the values of the failure fractions are minimum, the model will give the maximum possible value of second yield for the adopted policy. Then the value of the failure fraction for priority yield is increased for Case-1 (a) and Case-2, in which preference is given to increase the volume of irrigation supply over water export during failure years, to see the changes in the value of second yield. Thus the value of the failure fraction for priority yield is increased till the value of annual second yield does not decrease, to know the maximum possible failure fraction value for priority yield, i.e., the maximum amount of priority yield that can be supplied even during a failure year, without decreasing the value of second yield. When this value of failure fraction for priority yield is reached, trials are made with the value of the failure fraction for second yield. The value of the failure fraction for second yield is increased till the value of annual second yield does not decrease. This value of the failure fraction for second yield indicates the amount of water that can be supplied for second yield during a failure year. It is to be remembered that the maximum possible value of failure fraction is 1.0, and when it is one, it means, there is no failure, i.e., the particular yield's reliability is the maximum possible.

After finding the maximum value of second yield and failure fractions for PAT reservoir, the model is applied for the reservoirs PAT and MOH to find the values of maximum second yield and failure fractions for MOH reservoir. The process is repeated for KUN reservoir, by applying the model to PAT, MOH and KUN reservoirs. For GS reservoir, the objective function is taken to maximize the sum of the firm energy and 0.35 times the secondary energy. The weightage of the secondary energy is reduced only to depict the relative significance of firm and secondary energies. The model is applied for PAT, MOH, KUN and GS reservoirs. The maximum weighted total energy and failure fraction values for both the yields are obtained. Finally the model is applied to all the reservoirs in the system, with the objective function of maximizing the total weighted energy from GS and RPS reservoirs. By trials, the maximum values of failure fractions for priority yield and second yield are obtained. The entire process was carried out for Link Alternative I and Link Alternative II. Selected trial steps for finding the failure fraction values of priority yield and second yield for Case-1 (a), in the order in which they were made, are shown in Table 8.8 (a) to Table 8.8 (c).

In Case-1 (b), preference is given to water export over irrigation supply during failure years after meeting irrigation demand as per adopted policy, i.e., maintaining 50% of the irrigation demand during failure years. Trials are made starting with the minimum values of both the failure fractions. Then preference is given first to increase the value of the failure fraction for the second yield, and when it reaches its maximum value, then trials are made to increase the value of the failure fraction for priority yield. The entire process was done for Link Alternative I and Link Alternative II. Selected trial steps for finding the failure fraction values of priority yield and second yield for Case-1 (b) in the order in which they were made are shown in Table 8.8 (a), Table 8.8 (d) and Table 8.8 (e). The results of the model study for Case-1 are presented in Table 8.9. The results show that in Case-1 (b), when preference is given to the water export over irrigation, an additional weighted energy of 1086 MWhr (i.e., 281586-280500) and 384 MWhr (i.e., 246882-246498) are generated for Link Alternatives I and II, respectively, over and above that obtained in Case-1 (a) at the cost of 20% reduction in the priority yield during failure years at MOH reservoir [$\theta_{p1,j}$ value for MOH reservoir is 1.0 in Case-1 (a) and 0.8 in Case-1 (b)].

**Table 8.8 (a)** Trial steps to find the values of failure fractions for proposed reservoirs for Case-1 for Link alternatives I and II

| Reservoir | Failure fraction for priority yield $\theta_{p1,j}$ | | Failure fraction for second yield $\theta_{p2,j}$ | | Maximum possible annual second yield (MCM) | | Adopted failure fraction values | |
|---|---|---|---|---|---|---|---|---|
| | Case-1 (a) | Case-1 (b) | Case-1 (a) | Case-1 (b) | Case-1 (a) | Case-1 (b) | Case-1 (a) | Case-1 (b) |
| PAT | 0.51 | 0.51 | 0 | 0 | 184.27 | 184.27 | $\theta_{p1,j}$=1.00 | $\theta_{p1,j}$=1.00 |
| | 1.00 | 1.00 | 0 | 0 | 184.27 | 184.27 | $\theta_{p2,j}$=1.00 | $\theta_{p2,j}$=1.00 |
| | 1.00 | 1.00 | 1.00 | 1.00 | 184.27 | 184.27 | | |
| MOH | 0.51 | 0.51 | 0 | 0 | 201.31 | 201.31 | $\theta_{p1,j}$=1.00 | $\theta_{p1,j}$=0.80 |
| | 1.00 | 0.51 | 0 | 1.00 | 201.31 | 201.31 | $\theta_{p2,j}$=0.85 | $\theta_{p2,j}$=1.00 |
| | 1.00 | 1.00 | 1.00 | 1.00 | 178.85 | 178.85 | | |
| | 1.00 | 0.85 | 0.80 | 1.00 | 201.31 | 196.58 | | |
| | 1.00 | 0.95 | 0.90 | 1.00 | 194.84 | 184.76 | | |
| | 1.00 | 0.80 | 0.85 | 1.00 | 201.31 | 201.31 | | |
| KUN | 0.51 | 0.51 | 0 | 0 | 525.61 | 535.94 | $\theta_{p1,j}$=0.51 | $\theta_{p1,j}$=0.51 |
| | 1.00 | 0.51 | 0 | 1 | 466.93 | 378.9122 | $\theta_{p2,j}$=0.00 | $\theta_{p2,j}$=0.00 |
| | 0.55 | 0.51 | 0 | 0.50 | 521.23 | 452.01 | | |
| | 0.51 | 0.51 | 1.00 | 0.05 | 368.62 | 526.93 | | |
| | 0.51 | 0.55 | 0.05 | 0 | 516.77 | 531.56 | | |

**Table 8.8 (b)** Trial steps to find the values of failure fractions for Case-1 (a) for Gandhi Sagar (GS) Reservoir

| Link Alter-native | Failure fraction for priority yield $\theta_{p1,j}$ | Failure fraction for second yield $\theta_{p2,j}$ | Weighted total annual energy (Annual firm energy+0.35 x annual secondary energy) (MWhr) | Annual firm energy (MWhr) | Annual secondary energy (MWhr) | Total annual energy (MWhr) | Remark Objective function: Maximize weighted annual energy |
|---|---|---|---|---|---|---|---|
| I | 0.50 | 0 | 96625 | 9536 | 248826 | 258362 | Maximum total annual energy=258362<br>Maximum weighted annual energy=143204<br>Adopted failure fraction values $\theta_{p1,j}$ = 0.50, $\theta_{p2,j}$ =1.00 |
| | 1.00 | 0 | 45138 | 19071 | 74478 | 93549 | |
| | 0.80 | 0 | 65824 | 15257 | 144477 | 159734 | |
| | 0.55 | 0 | 91519 | 10489 | 231515 | 242004 | |
| | 0.50 | 1.00 | 143204 | 98345 | 128167 | 226512 | |
| | 0.50 | 0.95 | 141483 | 95049 | 132669 | 227718 | |
| II | 0.50 | 0 | 83415 | 9536 | 211083 | 220618 | Maximum total annual energy=220618<br>Maximum weighted annual energy =115758<br>Adopted failure fraction values $\theta_{p1,j}$ = 0.50, $\theta_{p2,j}$ =1.00 |
| | 1.00 | 0 | 32122 | 19071 | 37287 | 56358 | |
| | 0.55 | 0 | 78309 | 10489 | 193771 | 204261 | |
| | 0.50 | 1.00 | 115758 | 70899 | 128167 | 199066 | |
| | 0.50 | 0.95 | 114545 | 68598 | 131276 | 199874 | |

**Table 8.8** **(c)** Trial steps to find the values of failure fractions for Case-1 (a) for Ranapratap Sagar (RPS) Reservoir

| Link Alternative | Failure fraction for priority yield* | Failure fraction for second yield** | System weighted annual energy (MWhr) | Weighted annual energy from GS (MWhr) | Weighted annual energy from RPS (MWhr) | Gandhi Sagar (GS) |  |  | Ranapratapap Sagar (RPS) |  | Total energy (MWhr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | Annual energy (MWhr) |  | Second yield (MCM) | Annual energy (MWhr) |  |  |
|  |  |  |  |  |  | Firm | Secondary |  | Firm | Secondary |  |
| I | 1 | 0 | 280500 | 141327 | 139172 | 96469 | 128167 | 1141 | 122081 | 48832 | 395549 |
|  | 1 | 1 | 266199 | 143095 | 123104 | 98236 | 128167 | 1164 | 107986 | 43194 | 377583 |
|  | 1 | 0.50 | 273123 | 141505 | 131618 | 96647 | 128167 | 1143 | 115455 | 46182 | 386450 |
|  | 1 | 0.05 | 279778 | 140956 | 138823 | 96097 | 128167 | 1136 | 121774 | 48710 | 394748 |
| II | 1 | 0 | 246498 | 112697 | 133801 | 67838 | 128167 | 765 | 117370 | 46948 | 360322 |
|  | 1 | 1 | 228896 | 108052 | 120844 | 63193 | 128167 | 704 | 106004 | 42401 | 339765 |
|  | 1 | 0.50 | 237276 | 110270 | 127006 | 65412 | 128167 | 733 | 111409 | 44564 | 349551 |
|  | 1 | 0.05 | 245549 | 112451 | 133098 | 67593 | 128167 | 762 | 116753 | 46701 | 359213 |

**Note:** $^{*}\theta_{p1,j}$; $^{**}\theta_{p2,j}$; adopted failure fraction values for both the Link Alternatives are, $\theta_{p1,j}$ =1.0 and $\theta_{p2,j}$ = 0.0.

**Table 8.8 (d)** Trial steps to find the values of failure fractions for Case-1 (b) for Gandhi Sagar (GS) Reservoir

| Link Alter-native | Failure fraction for priority yield $\theta_{p1,j}$ | Failure fraction for second yield $\theta_{p2,j}$ | Weighted total annual energy (Annual firm energy+0.35 x annual secondary energy) (MWhr) | Annual firm energy (MWhr) | Annual secondary energy (MWhr) | Total annual energy (MWhr) | Remark<br>Objective function: Maximize weighted annual energy |
|---|---|---|---|---|---|---|---|
| I | 0.50 | 0 | 96884 | 9536 | 249568 | 259104 | Maximum total annual energy=259104<br>Maximum weighted annual energy =143739<br>Adopted failure fraction values<br>$\theta_{p1,j} = 0.50$, $\theta_{p2,j} = 1.00$ |
| | 1.00 | 0 | 45394 | 19071 | 75209 | 94280 | |
| | 0.55 | 0 | 91779 | 10489 | 232257 | 242746 | |
| | 0.50 | 1.00 | 143739 | 98881 | 128167 | 227047 | |
| | 0.50 | 0.05 | 100027 | 15499 | 241511 | 257009 | |
| | 0.50 | 0.95 | 142008 | 95564 | 132696 | 228261 | |
| II | 0.50 | 0 | 83415 | 9536 | 211083 | 220618 | Maximum total annual energy=220618<br>Maximum weighted annual energy=115758<br>Adopted failure fraction values<br>$\theta_{p1,j} = 0.50$, $\theta_{p2,j} = 1.00$ |
| | 1.00 | 0 | 32122 | 19071 | 37287 | 56358 | |
| | 0.55 | 0 | 78309 | 10489 | 193771 | 204261 | |
| | 0.50 | 1.00 | 115758 | 70899 | 128167 | 199066 | |
| | 0.50 | 0.95 | 114545 | 68598 | 131276 | 199874 | |

**Table 8.8** (e) Trial steps to find the values of failure fractions for Case-1 (b) for Ranapratap Sagar (RPS) Reservoir

| Link Alternative | Failure fraction for priority yield* | Failure fraction for second yield** | System weighted annual energy (MWhr) | Weighted annual energy from GS (MWhr) | Weighted annual energy from RPS (MWhr) | Gandhi Sagar (GS) Annual energy (MWhr) Firm | Gandhi Sagar (GS) Annual energy (MWhr) Secondary | Gandhi Sagar (GS) Second yield (MCM) | Ranapratapap Sagar (RPS) Annual energy (MWhr) Firm | Ranapratapap Sagar (RPS) Annual energy (MWhr) Secondary | Total energy (MWhr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I | 1 | 0 | 281586 | 141888 | 139698 | 97029 | 128167 | 1148 | 122542 | 49017 | 396755 |
| | 1 | 1 | 267236 | 143630 | 123607 | 98772 | 128167 | 1171 | 108427 | 43371 | 378736 |
| | 1 | 0.50 | 274188 | 142032 | 132156 | 97174 | 128167 | 1150 | 115926 | 46370 | 387637 |
| | 1 | 0.05 | 280866 | 141516 | 139350 | 96658 | 128167 | 1143 | 122237 | 48895 | 395956 |
| II | 1 | 0 | 246881 | 112567 | 134315 | 67709 | 128167 | 764 | 117820 | 47128 | 360823 |
| | 1 | 1 | 229186 | 107891 | 121295 | 63032 | 128167 | 702 | 106399 | 42560 | 340158 |
| | 1 | 0.50 | 237608 | 110122 | 127486 | 65264 | 128167 | 731 | 111829 | 44732 | 349992 |
| | 1 | 0.05 | 245912 | 112312 | 133600 | 67453 | 128167 | 760 | 117193 | 46877 | 359690 |

Note: $^{*}\theta_{p1,j}$; $^{**}\theta_{p2,j}$; adopted failure fraction values for both the Link Alternatives are, $\theta_{p1,j}=1.0$ and $\theta_{p2,j}=0.0$.

**Table 8.9** Reservoir releases, failure fractions and yield reliabilities for design capacities (results of Case-1)

| Case | Alternative | Reservoir | Annual Ws release (MCM) | Annual Irr release (MCM) | **Max. annual Exp (MCM)*** / Max. weighted annual energy (MWhr) | $\theta_{p1,j}$ | $\theta_{p2,j}$ | Annual reliability (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Ws | Irr | Exp | FE | SE |
| 1(a) | I & II | PAT | 3 | 137 | **184** | 1.00 | 1.00 | 94 | 94 | 94 | - | - |
| | I & II | MOH | 3 | 141 | **201** | 1.00 | 0.85 | 94 | 94 | 72 | - | - |
| | I & II | KUN | 7.2 | 313 | **526** | 0.51 | 0.00 | 94 | 72 | 72 | - | - |
| | I | GS | - | 3363 | 143204 | 0.50 | 1.00 | - | 72 | - | 94 | 72 |
| | II | GS | - | 3363 | 115758 | 0.50 | 1.00 | - | 72 | - | 94 | 72 |
| | I | RPS | - | - | 139172 | 1.00 | 0.00 | - | - | - | 94 | 72 |
| | II | RPS | - | - | 133801 | 1.00 | 0.00 | - | - | - | 94 | 72 |
| | I | System | 13.2 | 3954 | 280500 | | | | | | | |
| | II | System | 13.2 | 3954 | 246498 | | | | | | | |
| 1(b) | I & II | PAT | 3 | 137 | **184** | 1.00 | 1.00 | 94 | 94 | 94 | - | - |
| | I & II | MOH | 3 | 141 | **201** | 0.80 | 1.00 | 94 | 72 | 94 | - | - |
| | I & II | KUN | 7.2 | 313 | **536** | 0.51 | 0.00 | 94 | 72 | 72 | - | - |
| | I | GS | - | 3363 | 143739 | 0.50 | 1.00 | - | 72 | - | 94 | 72 |
| | II | GS | - | 3363 | 115758 | 0.50 | 1.00 | - | 72 | - | 94 | 72 |
| | I | RPS | - | - | 139698 | 1.00 | 0.00 | - | - | - | 94 | 72 |
| | II | RPS | - | - | 134315 | 1.00 | 0.00 | - | - | - | 94 | 72 |
| | I | System | 13.2 | 3954 | 281586 | | | | | | | |
| | II | System | 13.2 | 3954 | 246882 | | | | | | | |

Note: Ws-domestic water supply, Irr-irrigation, Exp-water export, FE-firm energy, SE-secondary energy. *Bold figures indicate water export.

For Case-2, the model objective function was to find the maximum reservoir yield with design reservoir capacities and known domestic water supply demand. The annual reliability of domestic water supply should be the maximum possible. Here both the priority and second yields are unknown. The failure fraction values adopted and the reliabilities obtained for different yields in all the reservoirs are same as in Case-1 (a). The value of $\alpha_i$ was varied for PAT, MOH, KUN and RPS reservoirs, to know the variations in the annual priority and second yields available from their respective design reservoir capacities. For all the proposed reservoirs, the $\alpha_i$ value was assumed equal to 0.5, 0.75, 1.0 and 1.25. For RPS reservoir, $\alpha_5$ value was assumed equal to 1, 2, 4 and 6. As per the project report of Gandhi Sagar reservoir prepared by the Madhya Pradesh state in respect of sharing of the Chambal waters, 3947 MCM of water is committed from the Gandhi Sagar reservoir to meet the requirements of hydropower generation at Gandhi Sagar, Ranapratap Sagar and Jawahar Sagar reservoirs and for downstream irrigation use. The water requirement for hydropower at Gandhi Sagar is assessed to be 584 MCM by the NWDA. The balance downstream committed use (3363 MCM) for irrigation is considered as known for GS reservoir. So, no relationship equation between priority yield and second yield (like equation 5.61) is applied for GS reservoir. For PAT reservoir, different $\alpha_1$ values were assumed and the trade-off between priority yield and second yield were obtained from the model results. Then for a particular value of $\alpha_2$ for MOH reservoir, $\alpha_1$ values for PAT reservoir were varied. From this trade-off between second yield from PAT reservoir and priority yield from MOH reservoir, and priority and second yields from MOH reservoir were plotted for all the assumed $\alpha_2$ values for MOH reservoir. The process was repeated for KUN reservoir, where for a particular value of $\alpha_3$, the values of $\alpha_1$ and $\alpha_2$ were varied. Trade-off curves were plotted for all the assumed values of $\alpha_3$. Then for a particular value of $\alpha_5$, all values of $\alpha_1$, $\alpha_2$ and $\alpha_3$ were varied.

Finally trade-off between second yield from KUN reservoir, system weighted energy, system firm energy, and system secondary energy were plotted. The trade-off curves are shown in Fig. 8.4 for both the Link Alternatives.

In Case-3, to find the minimum active reservoir capacity required for each reservoir, water demands need to be varied in the model. But the maximum water demands that the reservoir can meet with prescribed reliabilities were calculated (in Case-1) by the model on the basis of the known active reservoir capacity. So, with an objective function of minimizing the active capacity of any individual reservoir in the system for the given yields as calculated in Case-1, the model solution will result in giving the same reservoir capacity as that of in Case-1. The total weighted energy calculated in Case-1 is used as basis for alternative reservoir active capacity calculation. The model is run with the objective function of minimizing the sum of the active capacities of the proposed reservoirs, for meeting the same domestic water supply and irrigation demands from individual reservoirs and for producing the same system weighted energy for the Case-1 (a) or Case-1 (b). The results of the model study for Case-3 are presented in Table 8.10, which show that the capacity of the KUN reservoir can be reduced substantially, by about 10% increase in the capacities of PAT and MOH reservoirs.

The values of productive storage heads are to be substituted externally into the model and are verified after obtaining the solution because of the nonlinear nature of the hydropower generation equation. The process is repeated till the storage's obtained are equivalent to the values of heads and the annual system yield and the annual system hydropower values getting stabilized. This is perhaps the most cumbersome and time-consuming part of the yield model solution process.

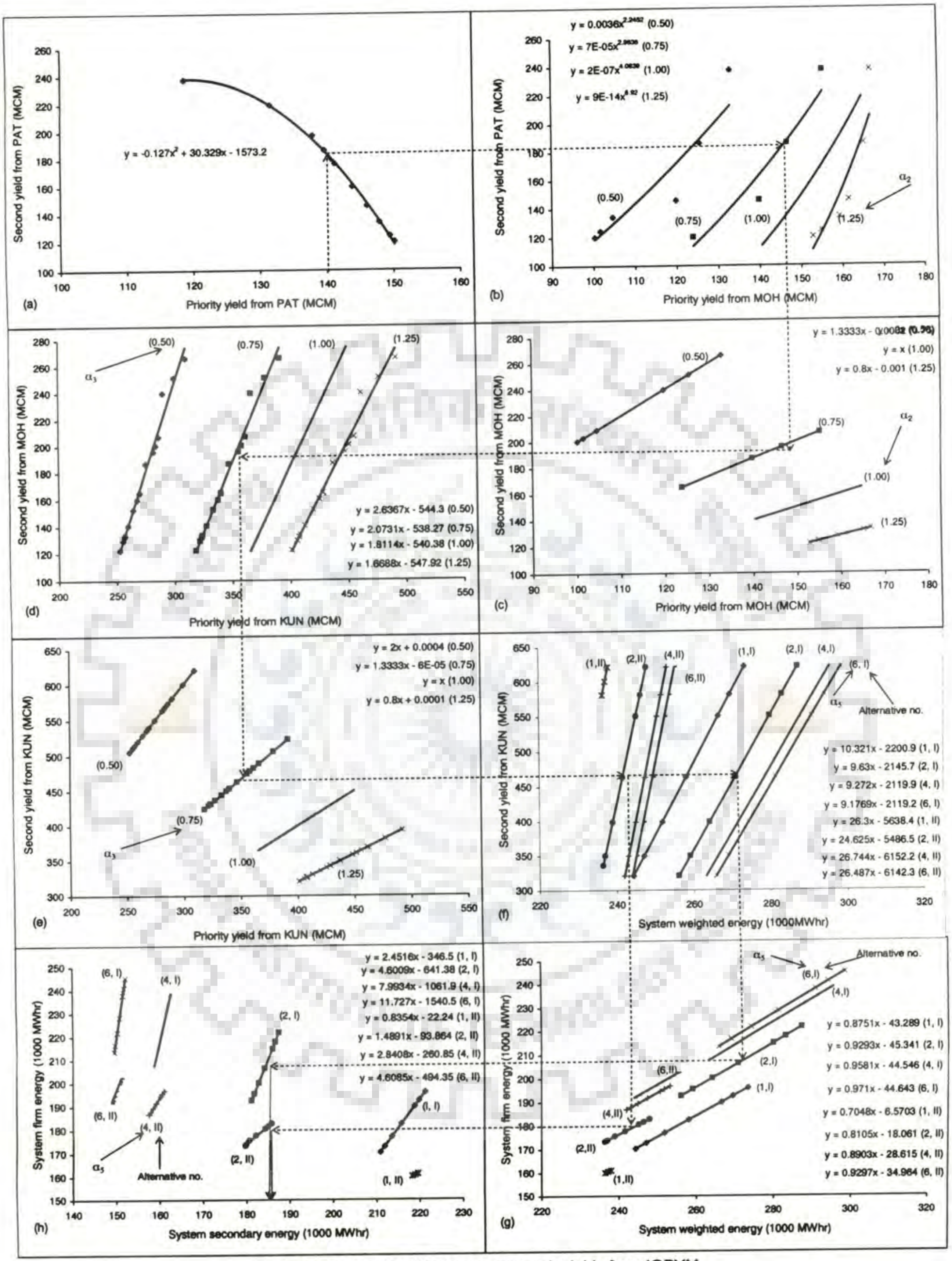

**Figure 8.4** Trade-off between reservoir yields from IGPYM

**Table 8.10** Alternative active reservoir capacities (results of Case-3)

| Reservoir | Design active reservoir capacity (MCM) | Case | Alternative active reservoir capacity (MCM) | Annual priority yield (MCM) | Annual second yield (MCM) |
|---|---|---|---|---|---|
| PAT | 110 | 3I.1(a) | 121.00 | 140.00 | 300.79 |
| | | 3I.1(b) | 121.00 | 140.00 | 300.79 |
| | | 3II.1(a) | 139.59 | 140.00 | 497.75 |
| | | 3II.1(b) | 139.59 | 140.00 | 497.75 |
| MOH | 122 | 3I.1(a) | 134.20 | 144.00 | 327.48 |
| | | 3I.1(b) | 134.20 | 144.00 | 327.48 |
| | | 3II.1(a) | 131.56 | 144.00 | 449.32 |
| | | 3II.1(b) | 134.19 | 144.00 | 459.65 |
| KUN | 1025 | 3I.1(a) | 675.50 | 320.20 | 525.61 |
| | | 3I.1(b) | 719.80 | 320.20 | 535.93 |
| | | 3II.1(a) | 347.20 | 320.20 | 525.61 |
| | | 3II.1(b) | 347.76 | 320.20 | 535.94 |

## 8.3 DYNAMIC PROGRAMMING MODELS APPLICATION

Dynamic Programming (DP) is a mathematical technique for optimization of multistage decision process. It divides the original problem initially into stages and then solves it sequentially until the original problem is finally solved. So, it can be said that the DP approach is particularly appropriate for the type of problems that can be divided into stages. It is an iterative procedure and requires small number of computer instructions. DP can treat non-convex, non-linear, discontinuous objectives and constraint functions. Here the main objective of DP models application during planning stage is to find the design demands at each reservoir.

### 8.3.1 Fixation of Penalty Parameters in CIM and PPM

The penalty values in different stages are important parameters in both CIM and PPM. In CIM, they control the decision variable $O_r$ (what amount of water is required to be used from the current inflow), the changes in storages, the spill and the designed demands. In PPM also, the penalty values in different stages control the decision variable $O_r$ (how much import of water is to be made), changes in storages and the spill.

The purpose of the introduction of these coefficients in the objective functions of the two DP models, namely PPM and CIM, were to indicate priority of execution of a particular function; like storage over spill, domestic water supply over irrigation, irrigation over water export, and spill during monsoon is preferred over spill during non-monsoon period and not for real situation costs (mentioned in Section 6.4 and Section 6.5 under objective function). These coefficients encourage water transfer from a donor reservoir when spare water is available in it, and discourage other wise. They also take care that a reservoir is ready to accommodate in its storage high flows during monsoon periods and conserve water for non-monsoon periods. Once the priority of executions of different functions (jobs) is fixed, the coefficient values are so taken that the model follows the priority of executions. In the model results, the values of the storages, spills, water import or exports at different stages are more important. If the coefficient values are changed but their pattern remains same (according to the accepted priority), the storages, spills, water import or exports at different stages remain same. Results show that this arrangement has worked well. As the models are formulated to minimize the objective functions, the penalty value for a particular function is made larger, if that function is not to be preferred at a particular stage.

#### 8.3.1.1 Penalty data for CIM

The CIM basically calculates the water demands that a reservoir can meet. To meet maximum demands, penalty values or penalty for not meeting a demand (supply deficit penalty,

$CDD_{r,p}$) are kept more as compared to penalty of storage and penalty of spill in a period, so that supply deficit is the least or in other words, maximum possible demand may be always met. Again, among different reservoir purposes, penalty for not meeting domestic water demand is kept largest, then followed by penalty for not meeting irrigation demand, and lastly that for not meeting water export and energy demands, according to the accepted priority of purposes adopted in India. Also a higher storage is preferred over spill, hence penalty of spill is made higher than penalty of end storage in a period. Define p=1 (domestic water supply), p=2 (irrigation) and p=3 (water export or energy). Mathematically, at r stages to go,

$CSR_r < CSP_r < CDD_{r,3} < CDD_{r,2} < CDD_{r,1}$

where $CSR_r$ = penalty of end reservoir storage, and $CSP_r$ = penalty of reservoir spill.

Penalty of not meeting a demand for a particular purpose is kept uniform throughout the year. Spill penalty in non-monsoon period is kept larger as compared to spill penalty in monsoon period to discourage spill during non-monsoon period. Storage penalty at the beginning of monsoon period is kept higher and is reduced with the advancement of the monsoon period to accommodate monsoon flows in a reservoir during the later monsoon period. Storage penalty at the end of the monsoon period is kept least to encourage a higher storage, and the same is maintained during the non-monsoon period also.

The assumed penalty values for the CIM are presented in Table 8.11.

**Table 8.11** Penalty data for CIM

| Month | t | r | $CSR_r$ | $CSP_r$ | $CDD_{r,3}$ | $CDD_{r,2}$ | $CDD_{r,1}$ |
|---|---|---|---|---|---|---|---|
| Jun | 1 | 12 | 25 | 150 | 500 | 1000 | 5000 |
| Jul | 2 | 11 | 12 | 100 | 500 | 1000 | 5000 |
| Aug | 3 | 10 | 6 | 100 | 500 | 1000 | 5000 |
| Sep | 4 | 9 | 3 | 100 | 500 | 1000 | 5000 |
| Oct | 5 | 8 | 2 | 150 | 500 | 1000 | 5000 |
| Nov | 6 | 7 | 2 | 350 | 500 | 1000 | 5000 |
| Dec | 7 | 6 | 2 | 350 | 500 | 1000 | 5000 |
| Jan | 8 | 5 | 2 | 350 | 500 | 1000 | 5000 |
| Feb | 9 | 4 | 2 | 350 | 500 | 1000 | 5000 |
| Mar | 10 | 3 | 2 | 350 | 500 | 1000 | 5000 |
| Apr | 11 | 2 | 2 | 350 | 500 | 1000 | 5000 |
| May | 12 | 1 | 2 | 350 | 500 | 1000 | 5000 |

Note: t-forward period counter, and r-backward period counter. Values are dimensionless.

### 8.3.1.2 Penalty data for PPM

In PPM, water demands are to be fully met, and water is to be imported in case of any shortage. To prepare values of transfer penalty for exporting reservoirs, the values of transfer fractions obtained from the trial run of IGPYM results (Table 8.4) are used. These values are period-wise export fractions from exporting reservoir to importing reservoir. The importing fractions are then taken equal to these exporting fractions. When export fractions are zero indicating no transfer, the values of import penalty in these periods are made very high. When export fraction values are greater than zero, the values of import penalty are distributed between 10 and 100, e.g., for the smallest fraction, the value of import penalty is 100 and for the largest fraction the value of import penalty is 10. The patterns for penalty of end storage and penalty of spill are kept similar to that in CIM.

The assumed values of penalty for the PPM are presented in Table 8.12.

**Table 8.12** Penalty data for PPM

| Month | t | r | MOH | | | KUN | | | GS / RPS | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $CTR_r$ | $CSR_r$ | $CSP_r$ | $CTR_r$ | $CSR_r$ | $CSP_r$ | $CTR_r$ | $CSR_r$ | $CSP_r$ |
| Jun | 1 | 12 | 500 | 25 | 105 | 100 | 25 | 50 | 60 | 25 | 75 |
| Jul | 2 | 11 | 19 | 12 | 25 | 15 | 12 | 15 | 14 | 12 | 15 |
| Aug | 3 | 10 | 10 | 6 | 20 | 10 | 6 | 15 | 10 | 6 | 20 |
| Sep | 4 | 9 | 14 | 3 | 22 | 12 | 3 | 15 | 13 | 3 | 30 |
| Oct | 5 | 8 | 100 | 2 | 20 | 500 | 2 | 20 | 35 | 2 | 65 |
| Nov | 6 | 7 | 500 | 2 | 150 | 500 | 2 | 40 | 74 | 2 | 75 |
| Dec | 7 | 6 | 500 | 2 | 150 | 500 | 2 | 40 | 83 | 2 | 105 |
| Jan | 8 | 5 | 500 | 2 | 150 | 500 | 2 | 40 | 100 | 2 | 105 |
| Feb | 9 | 4 | 500 | 2 | 150 | 500 | 2 | 40 | 500 | 2 | 105 |
| Mar | 10 | 3 | 500 | 2 | 150 | 500 | 2 | 40 | 500 | 2 | 105 |
| Apr | 11 | 2 | 500 | 2 | 150 | 500 | 2 | 40 | 500 | 2 | 105 |
| May | 12 | 1 | 500 | 2 | 150 | 500 | 2 | 40 | 500 | 2 | 105 |

Note: t-forward period counter, and r-backward period counter. Values are dimensionless.

### 8.3.2 Nomenclature of Various Cases

The NWDA has studied three proposed alternative options for link canal capacities as presented in Table 8.13, and has finally suggested 'Option C' as the design link canal capacities with the assumption that an uniform amount of 117.21 MCM water will be exported from KUN reservoir in each month. Two more alternative canal capacity options are considered in the present study for the dynamic programming model application. First, initially unlimited canal capacity is assumed (canal capacity option 'D' in Table 8.14) for all the link canals. From the reservoir operation results, the monthly water exports are obtained for the 72.22% water year annual dependable flows for each water-exporting reservoir. These monthly water exports from each water-exporting reservoir are then compared with the monthly design water exports obtained from the CIM results for that reservoir. The maximum water export, out of these monthly design water exports and monthly water exports obtained from 72.22% water year dependable flows is considered as another alternative for link canal capacities (canal capacity options under 'E' in Table 8.14) from that reservoir. This study proposes to study all these canal capacity options.

**Table 8.13** Design monthly link canal capacities proposed by NWDA

| Option | PAT to MOH | MOH to KUN | KUN to GS/RPS |
|---|---|---|---|
| A | 339.01 | 491.70 | 692.74 |
| B | 697.47 | 802.33 | 1162.10 |
| C | 523.76 | 625.46 | 129.03 |

Note: Unit MCM

The various cases considered in the dynamic model application involve two link alternatives, three sets of reservoir sizes obtained from the IGPYM results (Table 8.10) and thirteen link canal capacity options. For easy reference; some indices are assigned to each link alternative, each set of active reservoir capacities and link canal capacity options as given in Table 8.14. The nomenclatures of the various cases considered are made referring to these indices as explained in the same table.

**Table 8.14** Ready reference for different cases

| Name | Meaning | Index | Description |
|---|---|---|---|
| Link alternative | Water transfer link | I | PAT to MOH, MOH to KUN, and KUN to GS |
| | | II | PAT to MOH, MOH to KUN, and KUN to RPS |
| Reservoir size | Active reservoir capacity (Unit: MCM) | 1 | PAT=110, MOH=122, and KUN=1025 |
| | | 2 | PAT=121, MOH=134, and KUN=675 |
| | | 3 | PAT=140, MOH=132, and KUN=348 |
| Canal size (Option) | Canal capacity (Unit: MCM/month) | A1 | PAT to MOH=339.01<br>MOH to KUN=491.70<br>KUN to GS=692.74 |
| | | A2 | PAT to MOH=339.01<br>MOH to KUN=491.70<br>KUN to RPS=692.74 |
| | | B1 | PAT to MOH=697.47<br>MOH to KUN=802.33<br>KUN to GS=1162.10 |
| | | B2 | PAT to MOH=697.47<br>MOH to KUN=802.33<br>KUN to RPS=1162.10 |
| | | C1 | PAT to MOH=523.76<br>MOH to KUN=625.46<br>KUN to GS=129.03 |
| | | C2 | PAT to MOH=523.76<br>MOH to KUN=625.46<br>KUN to RPS=129.03 |
| | | D | UNLIMITED CANAL CAPACITY |
| | | E1 | PAT to MOH=249.72<br>MOH to KUN=527.67<br>KUN to GS=672.65 |
| | | E2 | PAT to MOH=249.72<br>MOH to KUN=527.67<br>KUN to RPS=806.43 |
| | | E3 | PAT to MOH=238.61<br>MOH to KUN=504.50<br>KUN to GS=668.48 |
| | | E4 | PAT to MOH=238.61<br>MOH to KUN=504.50<br>KUN to RPS=753.10 |
| | | E5 | PAT to MOH=219.40<br>MOH to KUN=487.30<br>KUN to GS=746.78 |
| | | E6 | PAT to MOH=219.40<br>MOH to KUN=487.30<br>KUN to RPS=746.78 |

Note: Odd and even numbers in canal capacity option are for Link Alternative I and II, respectively. Cases are referred in the form Case: I2C1, where I means transfer link corresponding to the Alternative index I, 2 means active capacity of reservoirs corresponding to the size index 2, and C1 means capacity of canals corresponding to the option index C1.

### 8.3.3 Methodology, Computations and Results

For planning, the PPM and CIM are applied using the 72.22% water year dependable inflow on monthly basis. The number of stages is twelve. The initial storages (states) at the start of the water year for PAT, MOH and RPS reservoirs are taken as the dead storage (zero active storage) of respective reservoirs. For KUN and GS reservoirs, the initial storages are taken as the active storage of 50 and 360 MCM, respectively, to make DP model runs feasible. For states during other stages, the model is allowed to take any value within the active storage. The monthly target water demands for domestic water supply and irrigation for each reservoir are taken from Table 3.11. The monthly target hydropower demands are taken from the IGPYM results for GS and RPS reservoirs. The monthly rate of evaporation and the elevation-area-capacity data for each reservoir are taken from Table 3.10 and Annexure-I.

In a DP model, the storage (state) in a reservoir can assume its value only in a fixed increment and the accuracy of these model results depend on this storage increment selected during model application. Less the value of storage increment, more accurate the results are. The curse of dimensionality in DP limits the selection of storage increment. The storage increment defines the number of states in a given stage. The larger the numbers of states, the combinations of discrete states that must be examined at each stage are more. This requires more computer time and storage capacity. The FORTRAN 77 program for PPM and CIM are run on *Fortran Power Station 4.0 (Microsoft Developer Studio)*. The minimum integer, as storage (state) increment for which the dimension of the problem does not exceed the capacity of the software is adopted as storage (state) increment for each reservoir. The values adopted as storage increment for PAT, MOH, KUN, GS and RPS reservoirs are 1, 1, 5, 60 and 10, respectively. In case of DP models, since storages (states) at the beginning and end of any stage are known, the productive storage head at any stage is calculated by taking the average of the water heads at the beginning and end of the stage minus the tail water level.

The following steps are followed.

***Step-1***:

This step finds the import water requirements by the reservoirs having import options, to meet their respective target demands fully. These import water requirements by the importing reservoirs give the target water export demands for the corresponding exporting reservoirs.

The PPM is applied to the last reservoir in the transfer link (i.e., GS for Link Alternative I and RPS for Link Alternative II). In Link Alternative II the last reservoir has an upstream reservoir located on the same river, i.e., GS above RPS. The CIM was first applied to upstream reservoir GS in Link Alternative II to determine its contribution from the regenerated (return) flows of its water uses and spill from reservoir to the downstream RPS reservoir. The PPM determines the import water requirements. The import water requirements for the last reservoirs, i.e., GS and RPS in the Link Alternatives I and II, respectively, are determined and are considered as water export demands from the exporting reservoir (i.e., KUN in both the Link Alternatives) in the links. The application of PPM is repeated for KUN reservoir to determine its import water requirements from MOH reservoir; and so on for MOH reservoir to determine its import water requirements from PAT reservoir; for both the Link Alternatives. The PPM is not applied to the first reservoir, i.e., PAT, as it does not have any import option. The results are shown in Table 8.15 (a) and Table 8.15 (b).

**Table 8.15 (a)** Amount of import water requirements in MCM for reservoirs obtained from PPM

| Case: | Month | GS | KUN | MOH | Case: | Month | RPS | KUN | MOH |
|---|---|---|---|---|---|---|---|---|---|
| | Jun | 0.00 | 0.00 | 0.00 | | Jun | 141.15 | 130.77 | 90.05 |
| I1A1; | Jul | 598.30 | 587.05 | 524.49 | II1A2; | Jul | 0.00 | 0.00 | 0.00 |
| | Aug | 2.83 | 0.00 | 0.00 | | Aug | 0.00 | 2.07 | 0.00 |
| I1B1; | Sep | 1175.81 | 1097.44 | 1011.11 | II1B2; | Sep | 1071.64 | 973.24 | 886.91 |
| I1D | Oct | 0.00 | 0.00 | 0.00 | II1D | Oct | 0.00 | 0.00 | 0.00 |
| | Nov | 0.00 | 0.00 | 0.00 | | Nov | 0.00 | 0.13 | 0.00 |
| and | Dec | 0.00 | 0.00 | 0.00 | and | Dec | 1.20 | 0.00 | 0.00 |
| | Jan | 10.35 | 0.00 | 0.00 | | Jan | 0.00 | 0.00 | 0.00 |
| I1E1 | Feb | 0.00 | 0.00 | 0.00 | II2E4 | Feb | 0.00 | 0.00 | 0.00 |
| | Mar | 0.00 | 0.00 | 0.00 | | Mar | 0.00 | 0.00 | 0.00 |
| | Apr | 0.00 | 0.00 | 0.00 | | Apr | 0.00 | 0.00 | 0.00 |
| | May | 0.00 | 0.00 | 0.00 | | May | 0.00 | 0.00 | 0.00 |
| | Total | 1787.29 | 1684.49 | 1535.60 | | Total | 1213.99 | 1106.21 | 976.96 |
| | Jun | 0.00 | 0.00 | 0.00 | | Jun | 141.15 | 130.77 | 90.05 |
| I2A1; | Jul | 598.30 | 587.05 | 524.49 | II2A2; | Jul | 0.00 | 0.00 | 0.00 |
| | Aug | 2.83 | 0.00 | 0.00 | | Aug | 0.00 | 2.07 | 0.00 |
| I2B1; | Sep | 1175.81 | 1097.44 | 999.24 | II2B2; | Sep | 1071.64 | 973.24 | 875.04 |
| I2D | Oct | 0.00 | 0.00 | 0.00 | II 2D | Oct | 0.00 | 0.00 | 0.00 |
| | Nov | 0.00 | 0.00 | 0.00 | | Nov | 0.00 | 0.13 | 0.00 |
| and | Dec | 0.00 | 0.00 | 0.00 | and | Dec | 1.20 | 0.00 | 0.00 |
| | Jan | 10.35 | 0.00 | 0.00 | | Jan | 0.00 | 0.00 | 0.00 |
| I2E3 | Feb | 0.00 | 0.00 | 0.00 | II2E4 | Feb | 0.00 | 0.00 | 0.00 |
| | Mar | 0.00 | 0.00 | 0.00 | | Mar | 0.00 | 0.00 | 0.00 |
| | Apr | 0.00 | 0.00 | 0.00 | | Apr | 0.00 | 0.00 | 0.00 |
| | May | 0.00 | 0.00 | 0.00 | | May | 0.00 | 0.00 | 0.00 |
| | Total | 1787.29 | 1684.49 | 1523.73 | | Total | 1213.99 | 1106.21 | 965.09 |
| | Jun | 0.00 | 0.00 | 0.00 | | Jun | 141.15 | 130.77 | 90.05 |
| I3A1; | Jul | 598.30 | 587.05 | 524.49 | II3A2; | Jul | 0.00 | 0.00 | 0.00 |
| | Aug | 2.83 | 0.00 | 0.00 | | Aug | 0.00 | 1.06 | 0.00 |
| I3B1; | Sep | 1175.81 | 1086.41 | 990.19 | II3B2; | Sep | 1071.63 | 968.21 | 871.99 |
| I3D | Oct | 0.00 | 0.00 | 0.00 | II3D | Oct | 0.00 | 0.00 | 0.00 |
| | Nov | 0.00 | 0.00 | 0.00 | | Nov | 0.00 | 0.00 | 0.00 |
| and | Dec | 0.00 | 0.00 | 0.00 | and | Dec | 1.20 | 0.00 | 0.00 |
| | Jan | 10.35 | 0.00 | 0.00 | | Jan | 0.00 | 0.00 | 0.00 |
| I3E5 | Feb | 0.00 | 0.00 | 0.00 | II3E6 | Feb | 0.00 | 0.00 | 0.00 |
| | Mar | 0.00 | 0.00 | 0.00 | | Mar | 0.00 | 0.00 | 0.00 |
| | Apr | 0.00 | 0.00 | 0.00 | | Apr | 0.00 | 0.00 | 0.00 |
| | May | 0.00 | 0.36 | 0.00 | | May | 0.00 | 0.36 | 0.00 |
| | Total | 1787.29 | 1673.82 | 1514.68 | | Total | 1213.98 | 1100.40 | 962.04 |

**Table 8.15 (b)** Amount of import water requirements in MCM for reservoirs obtained from PPM

| Month | Cases: I1C1 and II1C2 | | Cases: I2C1 and II2C2 | | Cases: I3C1 and II3C2 | |
|---|---|---|---|---|---|---|
| | KUN | MOH | KUN | MOH | KUN | MOH |
| Jun | 96.79 | 56.07 | 96.79 | 56.07 | 96.79 | 56.07 |
| Jul | 125.91 | 101.72 | 125.91 | 101.72 | 125.91 | 101.72 |
| Aug | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sep | 926.78 | 867.73 | 575.28 | 516.49 | 245.78 | 186.95 |
| Oct | 1.36 | 8.23 | 2.69 | 9.80 | 1.92 | 8.99 |
| Nov | 0.87 | 0.71 | 3.67 | 0.65 | 0.00 | 0.00 |
| Dec | 2.35 | 0.07 | 0.81 | 0.63 | 86.25 | 0.68 |
| Jan | 4.62 | 0.01 | 3.11 | 0.63 | 166.93 | 169.63 |
| Feb | 1.94 | 0.19 | 89.58 | 32.66 | 164.46 | 184.83 |
| Mar | 4.33 | 0.56 | 131.65 | 136.80 | 131.65 | 136.80 |
| Apr | 10.61 | 0.55 | 129.75 | 133.67 | 129.75 | 133.67 |
| May | 131.51 | 119.17 | 131.51 | 135.70 | 131.51 | 135.70 |
| Total | 1307.07 | 1155.01 | 1290.75 | 1124.82 | 1280.95 | 1115.04 |

Note: It is assumed that an uniform amount of 117.21 MCM water will be exported from KUN reservoir.

### *Step-2*:

This step finds the annual design demands at all the reservoirs for their respective water uses and known reservoir capacities. The CIM is applied to the first reservoir, i.e., PAT in both the links. The import water requirements of the second reservoir, i.e., MOH in both the links are considered as the target export demands from PAT reservoir. The CIM revises the annual target demands and gives the annual design demands. If there is spill at a stage, then this spill can be exported (i.e., additional water export), if required, over and above the actual export requirements and can be added to the design water exports of PAT reservoir. The CIM is then applied to the second reservoir, i.e., MOH in both the links. The total inflow to MOH reservoir includes natural inflow to reservoir and the design import water to MOH reservoir (i.e., design export water from PAT reservoir). The target demands for MOH reservoir include demands for all the water uses from MOH and the export water demands to KUN reservoir obtained through PPM in step 1. This process is repeated up to the last reservoir in the links for both the Link Alternatives. The results (design demands) are given in Table 8.16 (a) and Table 8.16 (b) for all the cases.

**Table 8.16 (a)** Design demands for domestic water supply, irrigation, water export and hydropower

| CASE: | Month | PAT | | | MOH | | | KUN | | | GS | | RPS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | WS | IRR | EXPORT | WS | IRR | EXPORT | WS | IRR | EXPORT | IRR | POWER | POWER |
| I1A1; I1B1; I1D and I1E1 | Jun | 0.25 | 9.59 | 0.00 | 0.25 | 9.57 | 0.00 | 0.60 | 21.91 | 0.00 | 96.26 | **6713** | **1734** |
| | Jul | 0.25 | 21.92 | 139.86 | 0.25 | 22.56 | 203.41 | 0.60 | 50.08 | 214.66 | 516.92 | **36051** | **14033** |
| | Aug | 0.25 | 15.07 | 249.72 | 0.25 | 15.51 | 292.67 | 0.60 | 34.26 | 0.00 | 1340.35 | **50370** | **13741** |
| | Sep | 0.25 | 9.59 | 170.09 | 0.25 | 9.87 | 263.49 | 0.60 | 21.91 | 670.62 | 973.60 | **50370** | **13693** |
| | Oct | 0.25 | 6.00 | 0.00 | 0.25 | 7.05 | 0.00 | 0.60 | 13.29 | 0.00 | 136.87 | **16033** | **13846** |
| | Nov | 0.25 | 9.59 | 0.00 | 0.25 | 9.53 | 0.00 | 0.60 | 21.83 | 0.00 | 51.12 | **7389** | **13676** |
| | Dec | 0.25 | 15.07 | 0.00 | 0.25 | 15.12 | 0.00 | 0.60 | 31.41 | 0.00 | 30.94 | **8112** | **13713** |
| | Jan | 0.25 | 20.01 | 0.00 | 0.25 | 21.00 | 0.00 | 0.60 | 46.95 | 4.38 | 27.91 | **7825** | **13528** |
| | Feb | 0.25 | 18.27 | 0.00 | 0.25 | 18.89 | 0.00 | 0.60 | 41.10 | 0.00 | 20.85 | **6788** | **5581** |
| | Mar | 0.25 | 3.51 | 0.00 | 0.25 | 3.73 | 0.00 | 0.60 | 9.39 | 0.00 | 29.59 | **6561** | **772** |
| | Apr | 0.25 | 2.74 | 0.00 | 0.25 | 2.64 | 0.00 | 0.60 | 3.59 | 0.00 | 32.62 | **2816** | **279** |
| | May | 0.25 | 2.33 | 0.00 | 0.25 | 2.52 | 0.00 | 0.60 | 6.26 | 0.00 | 27.58 | **5706** | **686** |
| | Total | 3.00 | 133.69 | 559.67 | 3.00 | 137.99 | 759.57 | 7.20 | 301.98 | 889.66 | 3284.61 | **204734** | **105281** |
| I2A1; I2B1; I2D and I2E3 | Jun | 0.25 | 9.59 | 0.00 | 0.25 | 9.57 | 0.00 | 0.60 | 21.91 | 0.00 | 96.26 | 6713 | **1734** |
| | Jul | 0.25 | 21.92 | 139.86 | 0.25 | 22.56 | 203.41 | 0.60 | 50.08 | 214.66 | 516.92 | 36051 | **14033** |
| | Aug | 0.25 | 15.07 | 238.61 | 0.25 | 15.51 | 269.50 | 0.60 | 34.43 | 1.72 | 1342.07 | 50370 | **13756** |
| | Sep | 0.25 | 9.59 | 180.96 | 0.25 | 9.87 | 286.24 | 0.60 | 21.91 | 668.48 | 971.46 | 50370 | **13674** |
| | Oct | 0.25 | 6.00 | 0.00 | 0.25 | 7.05 | 0.00 | 0.60 | 13.29 | 0.00 | 136.87 | 16033 | **13846** |
| | Nov | 0.25 | 9.59 | 0.00 | 0.25 | 9.53 | 0.00 | 0.60 | 21.83 | 0.00 | 51.12 | 7389 | **13676** |
| | Dec | 0.25 | 15.07 | 0.00 | 0.25 | 15.12 | 0.00 | 0.60 | 31.41 | 0.00 | 30.94 | 8112 | **13713** |
| | Jan | 0.25 | 20.01 | 0.00 | 0.25 | 21.00 | 0.00 | 0.60 | 46.95 | 4.38 | 27.91 | 7825 | **13528** |
| | Feb | 0.25 | 18.27 | 0.00 | 0.25 | 18.89 | 0.00 | 0.60 | 41.10 | 0.00 | 20.85 | 6788 | **5580** |
| | Mar | 0.25 | 3.51 | 0.00 | 0.25 | 3.73 | 0.00 | 0.60 | 9.39 | 0.00 | 29.59 | 6561 | **772** |
| | Apr | 0.25 | 2.74 | 0.00 | 0.25 | 2.64 | 0.00 | 0.60 | 3.59 | 0.00 | 32.62 | 2816 | **279** |
| | May | 0.25 | 2.33 | 0.00 | 0.25 | 2.52 | 0.00 | 0.60 | 6.26 | 0.00 | 27.58 | 5706 | **686** |
| | Total | 3.00 | 133.69 | 559.43 | 3.00 | 137.99 | 759.15 | 7.20 | 302.15 | 889.24 | 3284.19 | 204734 | **105277** |
| I3A1; I3B1; I3D and I3E5 | Jun | 0.25 | 9.59 | 0.00 | 0.25 | 9.57 | 0.00 | 0.60 | 21.91 | 0.00 | 96.26 | 6713 | **1734** |
| | Jul | 0.25 | 21.92 | 139.86 | 0.25 | 22.56 | 203.41 | 0.60 | 50.08 | 214.66 | 516.92 | 36051 | **14033** |
| | Aug | 0.25 | 15.07 | 219.40 | 0.25 | 15.51 | 252.30 | 0.60 | 34.43 | 227.13 | 1326.47 | **50370** | **13617** |
| | Sep | 0.25 | 9.59 | 199.74 | 0.25 | 9.87 | 303.04 | 0.60 | 21.91 | 442.43 | 984.03 | 50370 | **13785** |
| | Oct | 0.25 | 6.00 | 0.00 | 0.25 | 7.05 | 0.00 | 0.60 | 15.29 | 0.00 | 136.87 | 16033 | **13846** |
| | Nov | 0.25 | 9.59 | 0.00 | 0.25 | 9.53 | 0.00 | 0.60 | 20.83 | 0.00 | 51.12 | 7389 | **13676** |
| | Dec | 0.25 | 15.07 | 0.00 | 0.25 | 15.12 | 0.00 | 0.60 | 34.41 | 0.00 | 30.94 | 8112 | **13713** |
| | Jan | 0.25 | 20.01 | 0.00 | 0.25 | 21.00 | 0.00 | 0.60 | 46.95 | 1.39 | 27.91 | 7616 | **13263** |
| | Feb | 0.25 | 18.27 | 0.00 | 0.25 | 18.89 | 0.00 | 0.60 | 42.10 | 0.00 | 20.85 | 6788 | **5580** |
| | Mar | 0.25 | 3.51 | 0.00 | 0.25 | 3.73 | 0.00 | 0.60 | 8.79 | 0.00 | 29.59 | 6561 | **772** |
| | Apr | 0.25 | 2.74 | 0.00 | 0.25 | 2.64 | 0.00 | 0.60 | 5.59 | 0.00 | 32.62 | 2816 | **279** |
| | May | 0.25 | 2.33 | 0.00 | 0.25 | 2.52 | 0.00 | 0.60 | 5.90 | 0.00 | 27.58 | 5706 | **686** |
| | Total | 3.00 | 133.69 | 559.00 | 3.00 | 137.99 | 758.75 | 7.20 | 308.19 | 885.61 | 3281.16 | 204525 | **104985** |
| I1C1 | Jun | 0.25 | 9.59 | 17.61 | 0.25 | 9.87 | 58.33 | 0.60 | 21.91 | 78.75 | 53.27 | 3716 | **1353** |
| | Jul | 0.25 | 21.92 | 122.99 | 0.25 | 22.56 | 147.18 | 0.60 | 50.08 | 113.41 | 534.76 | 37295 | **14191** |
| | Aug | 0.25 | 15.07 | 249.72 | 0.25 | 15.51 | 292.67 | 0.60 | 34.43 | 114.99 | 1334.83 | **50370** | **13691** |
| | Sep | 0.25 | 9.59 | 165.03 | 0.25 | 9.87 | 256.41 | 0.60 | 21.91 | 111.99 | 996.12 | 50370 | **13892** |
| | Oct | 0.25 | 6.85 | 0.05 | 0.25 | 7.05 | 0.90 | 0.60 | 15.65 | 115.36 | 136.87 | 16102 | **13934** |
| | Nov | 0.25 | 9.59 | 0.15 | 0.25 | 9.67 | 0.00 | 0.60 | 21.91 | 113.52 | 51.12 | 7152 | **13375** |
| | Dec | 0.25 | 15.05 | 0.00 | 0.25 | 15.51 | 0.60 | 0.60 | 34.43 | 111.97 | 30.94 | 7659 | **14025** |
| | Jan | 0.25 | 20.55 | 0.42 | 0.25 | 21.15 | 0.26 | 0.60 | 46.95 | 104.26 | 27.91 | **6457** | **10935** |
| | Feb | 0.25 | 19.18 | 0.05 | 0.25 | 19.74 | 0.19 | 0.60 | 43.82 | 2.36 | 20.85 | 6952 | **5790** |
| | Mar | 0.25 | 4.11 | 0.37 | 0.25 | 4.10 | 0.00 | 0.60 | 9.39 | 0.37 | 29.59 | 6587 | **805** |
| | Apr | 0.25 | 2.74 | 0.04 | 0.25 | 2.82 | 0.88 | 0.60 | 6.26 | 3.20 | 32.62 | 3039 | **562** |
| | May | 0.25 | 2.74 | 0.57 | 0.25 | 2.12 | 0.00 | 0.60 | 6.26 | 0.64 | 27.58 | 5751 | **743** |
| | Total | 3.00 | 136.98 | 557.00 | 3.00 | 139.97 | 757.42 | 7.20 | 313.00 | 870.82 | 3276.46 | **201450** | **103296** |
| I2C1 | Jun | 0.25 | 9.59 | 17.61 | 0.25 | 9.87 | 58.33 | 0.60 | 21.91 | 78.75 | 53.27 | 3716 | **1353** |
| | Jul | 0.25 | 21.92 | 122.99 | 0.25 | 22.56 | 147.18 | 0.60 | 50.08 | 113.41 | 534.76 | 37295 | **14191** |
| | Aug | 0.25 | 15.07 | 238.61 | 0.25 | 15.51 | 269.50 | 0.60 | 34.43 | 116.88 | 1336.72 | 50370 | **13708** |
| | Sep | 0.25 | 9.59 | 175.90 | 0.25 | 9.87 | 279.16 | 0.60 | 21.91 | 114.91 | 996.12 | 50370 | **14232** |
| | Oct | 0.25 | 6.85 | 0.05 | 0.25 | 7.05 | 0.90 | 0.60 | 15.65 | 115.42 | 136.87 | 16106 | **13927** |
| | Nov | 0.25 | 9.59 | 0.15 | 0.25 | 9.87 | 0.80 | 0.60 | 21.91 | 114.34 | 51.12 | 7209 | **13438** |
| | Dec | 0.25 | 15.05 | 0.00 | 0.25 | 15.11 | 0.00 | 0.60 | 34.43 | 116.40 | 30.94 | 7968 | **9082** |
| | Jan | 0.25 | 20.55 | 0.42 | 0.25 | 21.15 | 0.26 | 0.60 | 46.95 | 94.29 | 27.91 | 5762 | **13617** |
| | Feb | 0.25 | 19.18 | 0.05 | 0.25 | 19.74 | 0.19 | 0.60 | 43.82 | 2.36 | 20.85 | 6952 | **9318** |
| | Mar | 0.25 | 4.11 | 0.37 | 0.25 | 4.10 | 0.00 | 0.60 | 9.39 | 0.37 | 29.59 | 6587 | **805** |
| | Apr | 0.25 | 2.74 | 0.04 | 0.25 | 2.82 | 0.88 | 0.60 | 6.26 | 3.20 | 32.62 | 3039 | **563** |
| | May | 0.25 | 2.74 | 0.57 | 0.25 | 2.12 | 0.00 | 0.60 | 6.26 | 0.64 | 27.58 | 5751 | **743** |
| | Total | 3.00 | 136.98 | 556.76 | 3.00 | 139.77 | 757.20 | 7.20 | 313.00 | 870.97 | 3278.35 | 201125 | **104977** |
| I3C1 | Jun | 0.25 | 9.59 | 17.61 | 0.25 | 9.87 | 58.33 | 0.60 | 21.91 | 78.75 | 53.27 | 3716 | **1353** |
| | Jul | 0.25 | 21.92 | 122.99 | 0.25 | 22.56 | 147.18 | 0.60 | 50.08 | 129.03 | 550.38 | 38385 | **13483** |
| | Aug | 0.25 | 15.07 | 219.40 | 0.25 | 15.51 | 252.30 | 0.60 | 34.43 | 129.03 | 1343.18 | 50370 | **13761** |
| | Sep | 0.25 | 9.59 | 185.57 | 0.25 | 9.87 | 244.40 | 0.60 | 21.91 | 117.82 | 996.12 | **50370** | **13887** |
| | Oct | 0.25 | 6.85 | 7.93 | 0.25 | 7.05 | 1.87 | 0.60 | 15.65 | 115.15 | 136.87 | **16087** | **13909** |
| | Nov | 0.25 | 9.59 | 0.14 | 0.25 | 9.04 | 0.00 | 0.60 | 21.91 | 54.97 | 51.12 | **7278** | **13532** |
| | Dec | 0.25 | 15.04 | 0.00 | 0.25 | 15.51 | 48.42 | 0.60 | 34.43 | 0.54 | 30.94 | **4138** | **1560** |
| | Jan | 0.25 | 20.55 | 1.41 | 0.25 | 21.15 | 0.25 | 0.60 | 46.95 | 1.62 | 27.91 | **3588** | **214** |
| | Feb | 0.25 | 19.18 | 0.05 | 0.25 | 19.74 | 0.18 | 0.60 | 43.82 | 0.41 | 20.85 | **2757** | **359** |
| | Mar | 0.25 | 4.11 | 0.37 | 0.25 | 4.23 | 0.86 | 0.60 | 9.39 | 0.25 | 29.59 | **2539** | **823** |
| | Apr | 0.25 | 2.74 | 0.04 | 0.25 | 2.82 | 0.88 | 0.60 | 6.26 | 0.20 | 32.62 | **2986** | **6574** |
| | May | 0.25 | 2.74 | 0.57 | 0.25 | 2.12 | 0.00 | 0.60 | 6.26 | 1.63 | 24.56 | **1713** | **153** |
| | Total | 3.00 | 136.97 | 556.08 | 3.00 | 139.47 | 754.67 | 7.20 | 313.00 | 629.40 | 3297.41 | **183927** | **79609** |

Note: All values for domestic water supply (WS), irrigation (IRR) and water export (EXPORT) are in MCM.
Energy values (in bold figures) are in MWhr (Mega Watt hour).

**Table 8.16 (b)** Design demands for domestic water supply, irrigation, water export and hydropower

| CASE: | Month | PAT | | | MOH | | | KUN | | | GS | | RPS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | WS | IRR | EXPORT | WS | IRR | EXPORT | WS | IRR | EXPORT | IRR | POWER | POWER |
| II1A2; II1B2; II1D and II1E2 | Jun | 0.25 | 9.59 | 17.61 | 0.25 | 9.87 | 58.33 | 0.60 | 21.91 | 78.75 | 35.21 | **2456** | **13418** |
| | Jul | 0.25 | 21.92 | 122.99 | 0.25 | 22.56 | 147.18 | 0.60 | 50.08 | 2.66 | 361.84 | **25236** | **8980** |
| | Aug | 0.25 | 15.07 | 249.72 | 0.25 | 15.51 | 292.67 | 0.60 | 32.98 | 0.00 | 1340.35 | **50370** | **13579** |
| | Sep | 0.25 | 9.59 | 170.09 | 0.25 | 9.87 | 263.49 | 0.60 | 21.91 | 805.04 | 785.76 | **50370** | **13093** |
| | Oct | 0.25 | 6.00 | 0.00 | 0.25 | 7.05 | 0.00 | 0.60 | 13.29 | 0.00 | 115.52 | **8057** | **13116** |
| | Nov | 0.25 | 9.59 | 0.00 | 0.25 | 9.53 | 0.00 | 0.60 | 21.83 | 0.00 | 49.39 | **3445** | **13055** |
| | Dec | 0.25 | 15.07 | 0.00 | 0.25 | 15.12 | 0.00 | 0.60 | 34.43 | 1.20 | 30.94 | **4101** | **13006** |
| | Jan | 0.25 | 20.01 | 0.00 | 0.25 | 21.00 | 0.00 | 0.60 | 46.35 | 0.00 | 27.91 | **3475** | **13287** |
| | Feb | 0.25 | 18.27 | 0.00 | 0.25 | 18.89 | 0.00 | 0.60 | 41.10 | 0.00 | 20.85 | **2728** | **7388** |
| | Mar | 0.25 | 3.51 | 0.00 | 0.25 | 3.73 | 0.00 | 0.60 | 9.39 | 0.00 | 29.59 | **2522** | **801** |
| | Apr | 0.25 | 2.74 | 0.00 | 0.25 | 2.64 | 0.00 | 0.60 | 3.59 | 0.00 | 32.62 | **2972** | **6556** |
| | May | 0.25 | 2.33 | 0.00 | 0.25 | 2.52 | 0.00 | 0.60 | 6.26 | 0.00 | 22.93 | **1599** | **138** |
| | Total | 3.00 | 133.69 | 560.41 | 3.00 | 138.29 | 761.67 | 7.20 | 303.12 | 887.65 | 2852.91 | **157329** | **116419** |
| II2A2; II2B2; II2D and II2E4 | Jun | 0.25 | 9.59 | 17.61 | 0.25 | 9.87 | 58.33 | 0.60 | 21.91 | 78.75 | 35.21 | **2456** | **8167** |
| | Jul | 0.25 | 21.92 | 122.99 | 0.25 | 22.56 | 147.18 | 0.60 | 50.08 | 53.20 | 361.84 | **25236** | **13128** |
| | Aug | 0.25 | 15.07 | 238.61 | 0.25 | 15.51 | 269.50 | 0.60 | 34.43 | 0.00 | 1340.35 | **50370** | **12833** |
| | Sep | 0.25 | 9.59 | 180.96 | 0.25 | 9.87 | 286.24 | 0.60 | 21.91 | 753.10 | 785.76 | **50370** | **12972** |
| | Oct | 0.25 | 6.00 | 0.00 | 0.25 | 7.05 | 0.00 | 0.60 | 13.29 | 0.00 | 115.52 | **8057** | **12984** |
| | Nov | 0.25 | 9.59 | 0.00 | 0.25 | 9.53 | 0.00 | 0.60 | 21.83 | 0.00 | 49.39 | **3445** | **12922** |
| | Dec | 0.25 | 15.07 | 0.00 | 0.25 | 15.12 | 0.00 | 0.60 | 34.43 | 1.20 | 30.94 | **4101** | **12883** |
| | Jan | 0.25 | 20.01 | 0.00 | 0.25 | 21.00 | 0.00 | 0.60 | 46.35 | 0.00 | 27.91 | **3475** | **13171** |
| | Feb | 0.25 | 18.27 | 0.00 | 0.25 | 18.89 | 0.00 | 0.60 | 41.10 | 0.00 | 20.85 | **2728** | **13458** |
| | Mar | 0.25 | 3.51 | 0.00 | 0.25 | 3.73 | 0.00 | 0.60 | 9.39 | 0.00 | 29.59 | **2522** | **13055** |
| | Apr | 0.25 | 2.74 | 0.00 | 0.25 | 2.64 | 0.00 | 0.60 | 3.59 | 0.00 | 32.62 | **2972** | **13590** |
| | May | 0.25 | 2.33 | 0.00 | 0.25 | 2.52 | 0.00 | 0.60 | 6.26 | 0.00 | 22.93 | **1599** | **138** |
| | Total | 3.00 | 133.69 | 560.17 | 3.00 | 138.29 | 761.25 | 7.20 | 304.57 | 886.25 | 2852.91 | **157329** | **139300** |
| II3A2; II3B2; II3D and II3E6 | Jun | 0.25 | 9.59 | 17.61 | 0.25 | 9.87 | 58.33 | 0.60 | 21.91 | 78.75 | 35.21 | **2456** | **8167** |
| | Jul | 0.25 | 21.92 | 122.99 | 0.25 | 22.56 | 147.18 | 0.60 | 50.08 | 138.48 | 361.84 | **25236** | **13569** |
| | Aug | 0.25 | 15.07 | 219.40 | 0.25 | 15.51 | 252.30 | 0.60 | 34.43 | 227.13 | 1340.35 | **50370** | **13393** |
| | Sep | 0.25 | 9.59 | 199.74 | 0.25 | 9.87 | 303.04 | 0.60 | 21.91 | 444.43 | 785.76 | **50370** | **13025** |
| | Oct | 0.25 | 6.00 | 0.00 | 0.25 | 7.05 | 0.00 | 0.60 | 15.30 | 0.00 | 115.52 | **8057** | **12986** |
| | Nov | 0.25 | 9.59 | 0.00 | 0.25 | 9.53 | 0.00 | 0.60 | 20.84 | 0.00 | 49.39 | **3445** | **12926** |
| | Dec | 0.25 | 15.07 | 0.00 | 0.25 | 15.12 | 0.00 | 0.60 | 34.43 | 0.00 | 30.94 | **4101** | **13667** |
| | Jan | 0.25 | 20.01 | 0.00 | 0.25 | 21.00 | 0.00 | 0.60 | 46.34 | 0.00 | 27.91 | **3475** | **13179** |
| | Feb | 0.25 | 18.27 | 0.00 | 0.25 | 18.89 | 0.00 | 0.60 | 42.10 | 0.00 | 20.85 | **2728** | **13467** |
| | Mar | 0.25 | 3.51 | 0.00 | 0.25 | 3.73 | 0.00 | 0.60 | 8.79 | 0.00 | 29.59 | **2522** | **13074** |
| | Apr | 0.25 | 2.74 | 0.00 | 0.25 | 2.64 | 0.00 | 0.60 | 5.59 | 0.00 | 32.62 | **2972** | **11832** |
| | May | 0.25 | 2.33 | 0.00 | 0.25 | 2.52 | 0.00 | 0.60 | 5.90 | 0.00 | 22.93 | **1599** | **138** |
| | Total | 3.00 | 133.69 | 559.74 | 3.00 | 138.29 | 760.85 | 7.20 | 307.62 | 888.79 | 2852.91 | **157329** | **139424** |
| II1C2 | Jun | 0.25 | 9.59 | 17.61 | 0.25 | 9.87 | 58.33 | 0.60 | 21.91 | 78.75 | 35.21 | **2456** | **13418** |
| | Jul | 0.25 | 21.92 | 122.99 | 0.25 | 22.56 | 147.18 | 0.60 | 50.08 | 113.41 | 361.84 | **25236** | **13219** |
| | Aug | 0.25 | 15.07 | 249.72 | 0.25 | 15.51 | 292.67 | 0.60 | 34.43 | 114.99 | 1340.35 | **50370** | **13151** |
| | Sep | 0.25 | 9.59 | 165.03 | 0.25 | 9.87 | 256.41 | 0.60 | 21.91 | 111.99 | 785.76 | **50370** | **12905** |
| | Oct | 0.25 | 6.85 | 0.05 | 0.25 | 7.05 | 0.90 | 0.60 | 15.65 | 115.36 | 115.52 | **8057** | **12969** |
| | Nov | 0.25 | 9.59 | 0.15 | 0.25 | 9.67 | 0.00 | 0.60 | 21.91 | 113.52 | 49.39 | **3445** | **13517** |
| | Dec | 0.25 | 15.05 | 0.00 | 0.25 | 15.51 | 0.60 | 0.60 | 34.43 | 111.97 | 30.94 | **4101** | **13169** |
| | Jan | 0.25 | 20.55 | 0.42 | 0.25 | 21.15 | 0.26 | 0.60 | 46.95 | 104.26 | 27.91 | **3475** | **12829** |
| | Feb | 0.25 | 19.18 | 0.05 | 0.25 | 19.74 | 0.19 | 0.60 | 43.82 | 2.36 | 20.85 | **2728** | **2298** |
| | Mar | 0.25 | 4.11 | 0.37 | 0.25 | 4.10 | 0.00 | 0.60 | 9.39 | 0.37 | 29.59 | **2522** | **834** |
| | Apr | 0.25 | 2.74 | 0.04 | 0.25 | 2.82 | 0.88 | 0.60 | 6.26 | 3.20 | 32.62 | **2972** | **6840** |
| | May | 0.25 | 2.74 | 0.57 | 0.25 | 2.12 | 0.00 | 0.60 | 6.26 | 0.64 | 22.93 | **1599** | **195** |
| | Total | 3.00 | 136.98 | 557.00 | 3.00 | 139.97 | 757.42 | 7.20 | 313.00 | 870.82 | 2852.91 | **157329** | **115344** |
| II2C2 | Jun | 0.25 | 9.59 | 17.61 | 0.25 | 9.87 | 58.33 | 0.60 | 21.91 | 78.75 | 35.21 | **2456** | **8167** |
| | Jul | 0.25 | 21.92 | 122.99 | 0.25 | 22.56 | 147.18 | 0.60 | 50.08 | 113.41 | 361.84 | **25236** | **13127** |
| | Aug | 0.25 | 15.07 | 238.61 | 0.25 | 15.51 | 269.50 | 0.60 | 34.43 | 116.88 | 1340.35 | **50370** | **13396** |
| | Sep | 0.25 | 9.59 | 175.90 | 0.25 | 9.87 | 279.16 | 0.60 | 21.91 | 114.91 | 785.76 | **50370** | **13215** |
| | Oct | 0.25 | 6.85 | 0.05 | 0.25 | 7.05 | 0.90 | 0.60 | 15.65 | 115.42 | 115.52 | **8057** | **13680** |
| | Nov | 0.25 | 9.59 | 0.15 | 0.25 | 9.87 | 0.80 | 0.60 | 21.91 | 114.34 | 49.39 | **3445** | **13446** |
| | Dec | 0.25 | 15.05 | 0.00 | 0.25 | 15.11 | 0.00 | 0.60 | 34.43 | 116.40 | 30.94 | **4101** | **13429** |
| | Jan | 0.25 | 20.55 | 0.42 | 0.25 | 21.15 | 0.26 | 0.60 | 46.95 | 94.29 | 27.91 | **3475** | **13587** |
| | Feb | 0.25 | 19.18 | 0.05 | 0.25 | 19.74 | 0.19 | 0.60 | 43.82 | 2.36 | 20.85 | **2728** | **13689** |
| | Mar | 0.25 | 4.11 | 0.37 | 0.25 | 4.10 | 0.00 | 0.60 | 9.39 | 0.37 | 29.59 | **2522** | **13137** |
| | Apr | 0.25 | 2.74 | 0.04 | 0.25 | 2.82 | 0.88 | 0.60 | 6.26 | 3.20 | 32.62 | **2972** | **9477** |
| | May | 0.25 | 2.74 | 0.57 | 0.25 | 2.12 | 0.00 | 0.60 | 6.26 | 0.64 | 22.93 | **1599** | **195** |
| | Total | 3.00 | 136.98 | 556.76 | 3.00 | 139.77 | 757.20 | 7.20 | 313.00 | 870.97 | 2852.91 | **157329** | **138545** |
| II3C2 | Jun | 0.25 | 9.59 | 17.61 | 0.25 | 9.87 | 58.33 | 0.60 | 21.91 | 78.75 | 35.21 | **2456** | **8167** |
| | Jul | 0.25 | 21.92 | 122.99 | 0.25 | 22.56 | 147.18 | 0.60 | 50.08 | 129.03 | 361.84 | **25236** | **13621** |
| | Aug | 0.25 | 15.07 | 219.40 | 0.25 | 15.51 | 252.30 | 0.60 | 34.43 | 129.03 | 1340.35 | **50370** | **13582** |
| | Sep | 0.25 | 9.59 | 185.57 | 0.25 | 9.87 | 244.40 | 0.60 | 21.91 | 117.82 | 785.76 | **50370** | **13464** |
| | Oct | 0.25 | 6.85 | 7.93 | 0.25 | 7.05 | 1.87 | 0.60 | 15.65 | 115.15 | 115.52 | **8057** | **13646** |
| | Nov | 0.25 | 9.59 | 0.14 | 0.25 | 9.04 | 0.00 | 0.60 | 21.91 | 54.97 | 49.39 | **3445** | **13506** |
| | Dec | 0.25 | 15.04 | 0.00 | 0.25 | 15.51 | 48.42 | 0.60 | 34.43 | 0.54 | 30.94 | **4101** | **12948** |
| | Jan | 0.25 | 20.55 | 1.41 | 0.25 | 21.15 | 0.25 | 0.60 | 46.95 | 1.62 | 27.91 | **3475** | **13431** |
| | Feb | 0.25 | 19.18 | 0.05 | 0.25 | 19.74 | 0.18 | 0.60 | 43.82 | 0.41 | 20.85 | **2728** | **7424** |
| | Mar | 0.25 | 4.11 | 0.37 | 0.25 | 4.23 | 0.86 | 0.60 | 9.39 | 0.25 | 29.59 | **2522** | **823** |
| | Apr | 0.25 | 2.74 | 0.04 | 0.25 | 2.82 | 0.88 | 0.60 | 6.26 | 0.20 | 32.62 | **2972** | **6574** |
| | May | 0.25 | 2.74 | 0.57 | 0.25 | 2.12 | 0.00 | 0.60 | 6.26 | 1.63 | 22.93 | **1599** | **283** |
| | Total | 3.00 | 136.97 | 556.08 | 3.00 | 139.47 | 754.67 | 7.20 | 313.00 | 629.40 | 2852.91 | **157329** | **117468** |

Note: All values for domestic water supply (WS), irrigation (IRR) and water export (EXPORT) are in MCM.
Energy values (in bold figures) are in MWhr (Mega Watt hour).

## 8.4 DISCUSSION

(1) The results of IGPYM application for Case-1 show that the annual target domestic water supply and irrigation demands can be met for all the reservoirs for both the Link Alternatives, with reliabilities equal or above the target annual reliabilities. In Case-1 (a), the annual reliability achieved for irrigation supply and water export for MOH reservoir are 94% and 72%, respectively (Table 8.9). In Case-1 (b), water export was given preference over irrigation, just to show the flexibility offered by the model in enhancing desired yield during failure years, maintaining the same annual yields for all water needs with prespecified reliabilities. In Case-1 (b), the annual reliabilities achieved for irrigation supply and water export are 72% and 94%, respectively. Thus in Case-1 (b), annual water export from MOH reservoir is increased by an amount 30.20 MCM at the cost of 28.20 MCM of irrigation supply during failure years. In Case-1 (b), the increase in the water export resulted in an increase in the system-weighted energy by an amount 1086 MWhr for Link Alternative I and 384 MWhr in Link Alternative II. For KUN reservoir, it is observed that an increase in the minimum value of any failure fraction decreases the annual water export from the reservoir. Thus the annual maximum water export obtained from KUN reservoir is vulnerable to an attempt to increase water export during failure years, with the specified export release fractions.

The trade-off curves (Fig. 8.4) for reservoir yields obtained through the solution of Case-2 can be very useful during the planning stages in deriving information about the possible relative variations in reservoir yields from different reservoirs in the system. A planner can use a path like that shown by dashed line in Fig. 8.4. Corresponding to a particular value of priority yield from PAT reservoir [Fig. 8.4 (a)], the planner will get different values of priority yields from MOH reservoir [Fig. 8.4 (b)]. He has to select a desired value of priority yield from MOH reservoir and Fig.8.4 (c) will give him the second yield from MOH reservoir. Corresponding to this second yield from MOH reservoir, the planner will again get different values of priority yield from KUN reservoir. Selection of a particular value of priority yield from KUN reservoir will give a definite value of second yield from KUN reservoir. This second yield from KUN reservoir will give different possible system weighted energy. These system weighted energy are again corresponding to some definite system firm and secondary energies. The planner has to select a particular system weighted energy that satisfies the firm and secondary system energy requirements. In this process, the planner will select some definite values of desired ratio of priority yield to second yield, i.e., $\alpha_1$, $\alpha_2$, $\alpha_3$ and $\alpha_5$ which will govern the yield relations between priority yield and second yield at PAT, MOH, KUN and RPS reservoirs.

Solution of Case-3 (Table 8.10) shows that by marginal increase in capacities for PAT and MOH reservoirs, the required capacity for KUN reservoir can be reduced substantially by an amount of 305.2 MCM [for Case-3I.1(b)] to 677.8 MCM [for Case-3II.1(a)] in meeting the same domestic water supply and irrigation demands as from individual reservoirs with design capacities and for producing the same system weighted energy.

(2) The PPM application results show that when the model is allowed to run freely, i.e., except in canal capacity options C1 and C2, where export release from KUN reservoir are prefixed, the water exports are mainly confined to monsoon period, when excess water is generally available in a donor reservoir.

The CIM application results show that amount of import water required by the importing reservoirs to meet their annual target demands are high in some months as compared to the amount of water that they can receive from the exporting reservoirs. The annual target domestic water supply demands in all the time periods can be met, but the target irrigation and export demands in some months cannot be met, i.e., the design demands in these months are less than the target demands. The power generation in case of Alternative I is higher than that obtained in Alternative II.

## NOTATION

$NER_i$ = number of water exporting reservoirs to reservoir i; and

$SSWB_i^{75D}$ = surplus surface water balance at 75% water year dependability of the catchments area of reservoir i.

All other notations are same as mentioned in Chapter 5 and Chapter 6.

# RESERVOIR OPERATION AND EVALUATION OF SYSTEM PERFORMANCE

## 9.1 INTRODUCTION

The monthly design water demands are estimated by the *controlled input model* (CIM) in Chapter 8. It is felt that CIM also has the potential of simulation, and in this Chapter reservoir operation is done by the CIM. The objective is to find the reservoir yields for different water uses corresponding to different reliabilities. The multi reservoir simulation model presented in Chapter 7 is then applied to test the results of CIM. The reservoir capacities and design water demands obtained in Chapter 8 are adopted for both the models. These models were run using monthly inflows of 17 years data. The results obtained by the two models are compared to see the feasibility of CIM in reservoir planning and operation. Based on these reservoir operation results, the most promising cases are identified in terms of meeting annual demands. The consequences of the adoption of selected cases are highlighted in terms of increase or decrease in system parameters (capacities of proposed reservoirs and link canals above or below design values proposed by NWDA) and the resulting increase or decrease in reservoir yields for different water uses with respect to the yields from the system with design values of reservoir capacities and canal capacities

## 9.2 RESERVOIR OPERATION BY CIM

In planning, the CIM basically provides annual design demands, i.e., the demands that may be actually met by a reservoir, from the input target demands to the model for different water uses. In reservoir operation by CIM, the design demands obtained in planning stage are fed as input to the model. The model determines the portion of the design demands for each water use that can be fully met in each time period. These model releases for each water use in each time period are considered as reservoir releases for the corresponding water use in that time period. If there is any spill in a period, and if the link canal capacity allows to transfer a part or total volume of this spill along with the water export release, then this additional volume is considered as an additional water export, and is added as an import to the importing reservoir to maximize the utilization of water. The GS and RPS reservoirs are in series. Before applying CIM to RPS reservoir, the spill and regenerated flows from upstream uses of GS reservoir are determined, and added to inflow of RPS reservoir. Various reservoir releases are then compared with their respective design demands and shortage, if any, in meeting these design demands are estimated for all water uses at each time period. These estimated shortages define the annual reliabilities of releases for each of the water use purposes.

Reservoir operation is performed for all the cases referred in Table 8.14. The results show that the domestic water supply demands can be fully met in each case in all the time periods. The amounts of annual releases for all the water uses are also calculated. These annual yields for irrigation, water export and hydropower generation are arranged in descending order of magnitude to calculate the annual yields corresponding to different annual reliabilities. The achieved annual yields for irrigation, water export and hydropower generation obtained for different reliabilities for different reservoirs are presented in Table 9.1 (a) to Table 9.1 (i). The canal capacity option 'D' is for unlimited canal capacity, and hence can be discarded for future study. The NWDA has suggested two canal capacity options C1 and C2 out of A1, A2, B1, B2, C1 and C2. The canal capacities corresponding to options B1 and B2 are too high like that in option D. The cases corresponding to canal capacity options A1 and A2 give almost similar results as in the cases corresponding to canal capacity options E1 to E6. For clarity of graphical presentation, the annual irrigation yield, annual hydropower release and annual water export for different reliabilities from individual reservoirs are presented only for the cases related to canal capacity options C1, C2, E1, E2, E3, E4, E5 and E6 in Fig. 9.1 (a) to Fig. 9.1 (r).

The annual system yields for irrigation and hydropower for each case are obtained by adding the year-wise yield for the particular water use from each reservoir. These system yields for irrigation and hydropower are arranged in descending order of magnitude to calculate the annual yields corresponding to different reliabilities. The achieved annual system yields for irrigation and hydropower obtained for different reliabilities for different cases are presented in Table 9.2 and Table 9.3, respectively. The system annual irrigation yields for different reliabilities for the cases related to canal capacity options C1, C2, E1, E2, E3, E4, E5 and E6 are exhibited in Fig. 9.2 (a) and Fig. 9.2 (b) for Link Alternatives I and II, respectively. The system annual hydropower yields for different reliabilities for the cases related to canal capacity options C1, C2, E1, E2, E3, E4, E5 and E6 are exhibited in Fig. 9.3 (a) and Fig. 9.3 (b) for Link Alternatives I and II, respectively.

**Table 9.1 (a)** Achieved annual yield for irrigation from PAT reservoir obtained for different reliabilities through reservoir operation by CIM

| Reli. (%) | Achieved annual yield for irrigation from PAT reservoir (MCM) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CASES | | | | | | | | | | | | | | |
| | I1A1 | I1B1 | I1C1 | I1D | I1E1 | I2A1 | I2B1 | I2C1 | I2D | I2E3 | I3A1 | I3B1 | I3C1 | I3D | I3E5 |
| 6 | 133.38 | 133.38 | 136.27 | 133.38 | 133.38 | 133.12 | 133.12 | 136.98 | 133.12 | 133.12 | 133.12 | 133.12 | 136.64 | 133.12 | 133.12 |
| 11 | 133.12 | 133.12 | 136.18 | 133.12 | 133.12 | 132.91 | 132.91 | 136.74 | 132.91 | 132.91 | 132.96 | 132.96 | 136.60 | 132.96 | 132.96 |
| 17 | 132.94 | 132.94 | 136.09 | 132.94 | 132.94 | 132.87 | 132.87 | 136.37 | 132.87 | 132.87 | 132.91 | 132.91 | 136.45 | 132.91 | 132.91 |
| 22 | 132.91 | 132.91 | 136.04 | 132.91 | 132.91 | 132.73 | 132.73 | 136.18 | 132.73 | 132.73 | 132.87 | 132.87 | 136.38 | 132.87 | 132.87 |
| 28 | 132.87 | 132.87 | 136.01 | 132.87 | 132.87 | 132.71 | 132.71 | 136.09 | 132.71 | 132.71 | 132.86 | 132.86 | 136.34 | 132.86 | 132.86 |
| 33 | 132.84 | 132.84 | 135.91 | 132.84 | 132.84 | 132.70 | 132.70 | 136.04 | 132.70 | 132.70 | 132.84 | 132.84 | 136.26 | 132.84 | 132.84 |
| 39 | 132.70 | 132.70 | 135.78 | 132.70 | 132.70 | 132.61 | 132.61 | 136.01 | 132.61 | 132.61 | 132.70 | 132.70 | 136.25 | 132.70 | 132.70 |
| 44 | 132.61 | 132.61 | 135.75 | 132.61 | 132.61 | 132.57 | 132.57 | 135.91 | 132.57 | 132.57 | 132.61 | 132.61 | 136.24 | 132.61 | 132.61 |
| 50 | 132.54 | 132.54 | 135.72 | 132.54 | 132.54 | 132.54 | 132.54 | 135.87 | 132.54 | 132.54 | 132.57 | 132.57 | 136.21 | 132.57 | 132.57 |
| 56 | 132.48 | 132.48 | 135.57 | 132.48 | 132.48 | 132.54 | 132.54 | 135.78 | 132.54 | 132.54 | 132.54 | 132.54 | 136.15 | 132.54 | 132.54 |
| 61 | 132.32 | 132.32 | 135.50 | 132.32 | 132.32 | 132.41 | 132.41 | 135.72 | 132.41 | 132.41 | 132.49 | 132.49 | 136.13 | 132.49 | 132.49 |
| 67 | 132.03 | 132.03 | 135.48 | 132.03 | 132.03 | 132.32 | 132.32 | 135.57 | 132.32 | 132.32 | 132.38 | 132.38 | 136.08 | 132.38 | 132.38 |
| 72 | 131.60 | 131.60 | 134.60 | 131.60 | 131.60 | 132.14 | 132.14 | 135.51 | 132.14 | 132.14 | 132.03 | 132.03 | 135.75 | 132.03 | 132.03 |
| 78 | 131.52 | 131.52 | 134.56 | 131.52 | 131.52 | 132.03 | 132.03 | 135.48 | 132.03 | 132.03 | 131.60 | 131.60 | 135.41 | 131.60 | 131.60 |
| 83 | 131.33 | 131.33 | 134.32 | 131.33 | 131.33 | 131.60 | 131.60 | 134.56 | 131.60 | 131.60 | 131.52 | 131.52 | 135.35 | 131.52 | 131.52 |
| 89 | 130.95 | 130.95 | 134.23 | 130.95 | 130.95 | 131.52 | 131.52 | 134.32 | 131.52 | 131.52 | 131.13 | 131.13 | 135.06 | 131.13 | 131.13 |
| 94 | 130.67 | 130.67 | 131.69 | 130.67 | 130.67 | 130.95 | 130.95 | 134.23 | 130.95 | 130.95 | 130.95 | 130.95 | 134.33 | 130.95 | 130.95 |
| Reli. (%) | II1A2 | II1B2 | II1C2 | II1D | II1E2 | II2A2 | II2B2 | II2C2 | II2D | II2E4 | II3A2 | II3B2 | II3C2 | II3D | II3E6 |
| 6 | 132.54 | 133.69 | 136.27 | 133.69 | 133.69 | 133.57 | 133.57 | 136.98 | 133.57 | 133.57 | 133.32 | 133.32 | 136.64 | 133.32 | 133.32 |
| 11 | 132.68 | 133.64 | 136.18 | 133.64 | 133.64 | 133.32 | 133.32 | 136.74 | 133.32 | 133.32 | 133.13 | 133.13 | 136.60 | 133.13 | 133.13 |
| 17 | 132.61 | 133.32 | 136.09 | 133.32 | 133.32 | 133.12 | 133.12 | 136.37 | 133.12 | 133.12 | 133.12 | 133.12 | 136.45 | 133.12 | 133.12 |
| 22 | 133.12 | 133.12 | 136.04 | 133.12 | 133.12 | 132.89 | 132.89 | 136.18 | 132.89 | 132.89 | 132.96 | 132.96 | 136.38 | 132.96 | 132.96 |
| 28 | 132.42 | 132.94 | 136.01 | 132.94 | 132.94 | 132.85 | 132.85 | 136.09 | 132.85 | 132.85 | 132.89 | 132.89 | 136.34 | 132.89 | 132.89 |
| 33 | 132.89 | 132.89 | 135.91 | 132.89 | 132.89 | 132.84 | 132.84 | 136.04 | 132.84 | 132.84 | 132.86 | 132.86 | 136.26 | 132.86 | 132.86 |
| 39 | 133.69 | 132.84 | 135.78 | 132.84 | 132.84 | 132.80 | 132.80 | 136.01 | 132.80 | 132.80 | 132.84 | 132.84 | 136.25 | 132.84 | 132.84 |
| 44 | 131.84 | 132.80 | 135.75 | 132.80 | 132.80 | 132.73 | 132.73 | 135.91 | 132.73 | 132.73 | 132.80 | 132.80 | 136.24 | 132.80 | 132.80 |
| 50 | 130.67 | 132.68 | 135.72 | 132.68 | 132.68 | 132.71 | 132.71 | 135.87 | 132.71 | 132.71 | 132.69 | 132.69 | 136.21 | 132.69 | 132.69 |
| 56 | 132.80 | 132.61 | 135.57 | 132.61 | 132.61 | 132.68 | 132.68 | 135.78 | 132.68 | 132.68 | 132.68 | 132.68 | 136.15 | 132.68 | 132.68 |
| 61 | 131.52 | 132.54 | 135.50 | 132.54 | 132.54 | 132.61 | 132.61 | 135.72 | 132.61 | 132.61 | 132.61 | 132.61 | 136.13 | 132.61 | 132.61 |
| 67 | 132.50 | 132.50 | 135.48 | 132.50 | 132.50 | 132.54 | 132.54 | 135.57 | 132.54 | 132.54 | 132.54 | 132.54 | 136.08 | 132.54 | 132.54 |
| 72 | 133.32 | 132.42 | 134.60 | 132.42 | 132.42 | 132.50 | 132.50 | 135.51 | 132.50 | 132.50 | 132.50 | 132.50 | 135.75 | 132.50 | 132.50 |
| 78 | 132.94 | 131.84 | 134.56 | 131.84 | 131.84 | 132.42 | 132.42 | 135.48 | 132.42 | 132.42 | 132.42 | 132.42 | 135.41 | 132.42 | 132.42 |
| 83 | 132.84 | 131.52 | 134.32 | 131.52 | 131.52 | 132.37 | 132.37 | 134.56 | 132.37 | 132.37 | 132.28 | 132.28 | 135.35 | 132.28 | 132.28 |
| 89 | 131.18 | 131.18 | 134.23 | 131.18 | 131.18 | 131.52 | 131.52 | 134.32 | 131.52 | 131.52 | 131.52 | 131.52 | 135.06 | 131.52 | 131.52 |
| 94 | 133.64 | 130.67 | 131.69 | 130.67 | 130.67 | 131.18 | 131.18 | 134.23 | 131.18 | 131.18 | 131.18 | 131.18 | 134.33 | 131.18 | 131.18 |

**Table 9.1 (b)** Achieved annual yield for irrigation from MOH reservoir obtained for different reliabilities through reservoir operation by CIM

| Reli. (%) | Achieved annual yield for irrigation from MOH reservoir (MCM) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CASES | | | | | | | | | | | | | | |
| | I1A1 | I1B1 | I1C1 | I1D | I1E1 | I2A1 | I2B1 | I2C1 | I2D | I2E3 | I3A1 | I3B1 | I3C1 | I3D | I3E5 |
| 6 | 137.43 | 137.43 | 137.62 | 137.43 | 137.43 | 137.43 | 137.43 | 139.64 | 137.43 | 137.43 | 137.69 | 137.69 | 139.47 | 137.69 | 137.69 |
| 11 | 137.40 | 137.40 | 137.59 | 137.40 | 137.40 | 137.29 | 137.29 | 139.55 | 137.29 | 137.29 | 137.43 | 137.43 | 139.45 | 137.43 | 137.43 |
| 17 | 137.14 | 137.14 | 137.58 | 137.14 | 137.14 | 137.20 | 137.20 | 139.49 | 137.20 | 137.20 | 136.89 | 136.89 | 139.12 | 136.89 | 136.89 |
| 22 | 136.96 | 136.96 | 137.55 | 136.96 | 136.96 | 137.14 | 137.14 | 139.36 | 137.14 | 137.14 | 136.88 | 136.88 | 139.00 | 136.88 | 136.88 |
| 28 | 136.89 | 136.89 | 137.43 | 136.89 | 136.89 | 136.89 | 136.89 | 139.14 | 136.89 | 136.89 | 136.73 | 136.73 | 138.98 | 136.73 | 136.73 |
| 33 | 136.80 | 136.80 | 137.26 | 136.80 | 136.80 | 136.78 | 136.78 | 139.02 | 136.78 | 136.78 | 136.70 | 136.70 | 138.88 | 136.70 | 136.70 |
| 39 | 136.73 | 136.73 | 137.19 | 136.73 | 136.73 | 136.73 | 136.73 | 138.90 | 136.73 | 136.73 | 136.70 | 136.70 | 138.85 | 136.70 | 136.70 |
| 44 | 136.70 | 136.70 | 136.87 | 136.70 | 136.70 | 136.70 | 136.70 | 138.78 | 136.70 | 136.70 | 136.68 | 136.68 | 138.79 | 136.68 | 136.68 |
| 50 | 136.70 | 136.70 | 136.81 | 136.70 | 136.70 | 136.70 | 136.70 | 138.73 | 136.70 | 136.70 | 136.62 | 136.62 | 138.75 | 136.62 | 136.62 |
| 56 | 136.62 | 136.62 | 136.55 | 136.62 | 136.62 | 136.60 | 136.60 | 138.55 | 136.60 | 136.60 | 136.60 | 136.60 | 138.60 | 136.60 | 136.60 |
| 61 | 136.60 | 136.60 | 136.46 | 136.60 | 136.60 | 136.60 | 136.60 | 138.53 | 136.60 | 136.60 | 136.46 | 136.46 | 138.34 | 136.46 | 136.46 |
| 67 | 136.52 | 136.52 | 136.38 | 136.52 | 136.52 | 136.54 | 136.54 | 138.46 | 136.54 | 136.54 | 136.42 | 136.42 | 138.34 | 136.42 | 136.42 |
| 72 | 136.46 | 136.46 | 136.33 | 136.46 | 136.46 | 136.52 | 136.52 | 138.33 | 136.52 | 136.52 | 136.40 | 136.40 | 138.32 | 136.40 | 136.40 |
| 78 | 136.42 | 136.42 | 136.30 | 136.42 | 136.42 | 136.46 | 136.46 | 138.30 | 136.46 | 136.46 | 136.09 | 136.09 | 138.32 | 136.09 | 136.09 |
| 83 | 136.01 | 136.01 | 136.23 | 136.01 | 136.01 | 136.42 | 136.42 | 138.16 | 136.42 | 136.42 | 135.98 | 135.98 | 138.19 | 135.98 | 135.98 |
| 89 | 135.97 | 135.97 | 134.91 | 135.97 | 135.97 | 135.97 | 135.97 | 138.07 | 135.97 | 135.97 | 135.97 | 135.97 | 138.15 | 135.97 | 135.97 |
| 94 | 134.09 | 134.09 | 131.56 | 134.09 | 134.09 | 134.09 | 134.09 | 133.10 | 134.09 | 134.09 | 134.09 | 134.09 | 138.05 | 134.09 | 134.09 |
| Reli. (%) | II1A2 | II1B2 | II1C2 | II1D | II1E2 | II2A2 | II2B2 | II2C2 | II2D | II2E4 | II3A2 | II3B2 | II3C2 | II3D | II3E6 |
| 6 | 137.98 | 137.98 | 137.62 | 137.98 | 137.98 | 137.98 | 137.98 | 139.64 | 138.09 | 137.98 | 137.98 | 137.98 | 139.47 | 137.98 | 137.98 |
| 11 | 137.93 | 137.93 | 137.59 | 137.93 | 137.93 | 137.93 | 137.93 | 139.55 | 137.98 | 137.93 | 137.93 | 137.93 | 139.45 | 137.93 | 137.93 |
| 17 | 137.69 | 137.69 | 137.58 | 137.69 | 137.69 | 137.88 | 137.88 | 139.49 | 137.93 | 137.88 | 137.69 | 137.69 | 139.12 | 137.69 | 137.69 |
| 22 | 137.58 | 137.58 | 137.55 | 137.58 | 137.58 | 137.69 | 137.69 | 139.36 | 137.69 | 137.69 | 137.59 | 137.59 | 139.00 | 137.59 | 137.59 |
| 28 | 137.50 | 137.50 | 137.43 | 137.50 | 137.50 | 137.58 | 137.58 | 139.14 | 137.58 | 137.58 | 137.58 | 137.58 | 138.98 | 137.58 | 137.58 |
| 33 | 137.44 | 137.44 | 137.26 | 137.44 | 137.44 | 137.50 | 137.50 | 139.02 | 137.50 | 137.50 | 137.50 | 137.50 | 138.88 | 137.50 | 137.50 |
| 39 | 137.42 | 137.42 | 137.19 | 137.42 | 137.42 | 137.44 | 137.44 | 138.90 | 137.44 | 137.44 | 137.17 | 137.17 | 138.85 | 137.17 | 137.17 |
| 44 | 137.17 | 137.17 | 136.87 | 137.17 | 137.17 | 137.36 | 137.36 | 138.78 | 137.17 | 137.36 | 137.13 | 137.13 | 138.79 | 137.13 | 137.13 |
| 50 | 137.13 | 137.13 | 136.81 | 137.13 | 137.13 | 137.17 | 137.17 | 138.73 | 137.13 | 137.17 | 137.08 | 137.08 | 138.75 | 137.08 | 137.08 |
| 56 | 137.08 | 137.08 | 136.55 | 137.08 | 137.08 | 137.08 | 137.08 | 138.55 | 137.08 | 137.08 | 137.06 | 137.06 | 138.60 | 137.06 | 137.06 |
| 61 | 137.06 | 137.06 | 136.46 | 137.06 | 137.06 | 136.83 | 136.83 | 138.53 | 137.08 | 136.83 | 136.82 | 136.82 | 138.34 | 136.82 | 136.82 |
| 67 | 136.92 | 136.92 | 136.38 | 136.92 | 136.92 | 136.82 | 136.82 | 138.46 | 137.06 | 136.82 | 136.71 | 136.71 | 138.34 | 136.71 | 136.71 |
| 72 | 136.82 | 136.82 | 136.33 | 136.82 | 136.82 | 136.71 | 136.71 | 138.33 | 137.06 | 136.71 | 136.70 | 136.70 | 138.32 | 136.70 | 136.70 |
| 78 | 136.71 | 136.71 | 136.30 | 136.71 | 136.71 | 136.64 | 136.64 | 138.30 | 136.84 | 136.64 | 136.61 | 136.61 | 138.32 | 136.61 | 136.61 |
| 83 | 136.50 | 136.50 | 136.23 | 136.50 | 136.50 | 136.52 | 136.52 | 138.16 | 136.82 | 136.52 | 136.55 | 136.55 | 138.19 | 136.55 | 136.55 |
| 89 | 136.40 | 136.40 | 134.91 | 136.40 | 136.40 | 136.40 | 136.40 | 138.07 | 136.71 | 136.40 | 136.44 | 136.44 | 138.15 | 136.44 | 136.44 |
| 94 | 136.31 | 136.31 | 131.56 | 136.31 | 136.31 | 135.48 | 135.48 | 133.10 | 136.40 | 135.48 | 136.40 | 136.40 | 138.05 | 136.40 | 136.40 |

**Table 9.1 (c)** Achieved annual yield for irrigation from KUN reservoir obtained for different reliabilities through reservoir operation by CIM

| Reli. (%) | Achieved annual yield for irrigation from KUN reservoir (MCM) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CASES | | | | | | | | | | | | | | |
| | I1A1 | I1B1 | I1C1 | I1D | I1E1 | I2A1 | I2B1 | I2C1 | I2D | I2E3 | I3A1 | I3B1 | I3C1 | I3D | I3E5 |
| 6 | 301.95 | 301.97 | 313.00 | 301.97 | 301.95 | 301.92 | 302.15 | 313.00 | 302.15 | 301.92 | 308.18 | 308.18 | 313.00 | 308.18 | 308.18 |
| 11 | 301.61 | 301.75 | 313.00 | 301.68 | 301.61 | 300.67 | 301.92 | 313.00 | 301.92 | 300.67 | 305.84 | 305.84 | 312.79 | 305.84 | 305.84 |
| 17 | 300.95 | 301.68 | 313.00 | 301.61 | 300.58 | 300.35 | 300.67 | 313.00 | 300.67 | 300.35 | 305.33 | 305.33 | 312.43 | 305.33 | 305.33 |
| 22 | 300.56 | 301.23 | 313.00 | 301.23 | 300.49 | 300.05 | 300.35 | 313.00 | 300.35 | 300.05 | 305.28 | 305.28 | 310.95 | 305.28 | 305.28 |
| 28 | 300.49 | 300.67 | 313.00 | 300.67 | 299.98 | 299.91 | 300.05 | 313.00 | 300.05 | 299.84 | 304.94 | 304.94 | 310.61 | 304.94 | 304.94 |
| 33 | 300.42 | 300.49 | 313.00 | 300.49 | 299.97 | 299.84 | 299.84 | 313.00 | 299.84 | 299.72 | 301.29 | 301.29 | 310.13 | 301.29 | 301.29 |
| 39 | 300.36 | 300.46 | 313.00 | 300.42 | 299.07 | 299.49 | 299.49 | 313.00 | 299.49 | 299.49 | 300.64 | 300.64 | 309.92 | 300.64 | 300.64 |
| 44 | 300.12 | 300.04 | 313.00 | 300.04 | 298.98 | 299.40 | 299.40 | 313.00 | 299.40 | 299.40 | 299.83 | 299.83 | 309.68 | 299.83 | 299.83 |
| 50 | 299.19 | 299.96 | 313.00 | 299.96 | 298.70 | 298.86 | 298.86 | 313.00 | 298.86 | 298.86 | 299.02 | 299.02 | 309.34 | 299.02 | 299.02 |
| 56 | 298.45 | 299.19 | 313.00 | 299.19 | 296.46 | 298.54 | 298.54 | 313.00 | 298.54 | 298.54 | 298.76 | 298.76 | 308.75 | 298.76 | 298.76 |
| 61 | 296.34 | 298.45 | 312.72 | 298.45 | 295.51 | 298.38 | 298.38 | 313.00 | 298.38 | 298.38 | 298.36 | 298.36 | 307.71 | 298.36 | 298.36 |
| 67 | 295.54 | 295.87 | 312.72 | 295.87 | 294.82 | 296.06 | 295.91 | 312.72 | 295.91 | 296.06 | 298.23 | 298.23 | 307.66 | 298.23 | 298.23 |
| 72 | 295.51 | 295.35 | 312.72 | 295.35 | 294.50 | 294.67 | 294.31 | 312.01 | 294.31 | 294.67 | 298.21 | 298.21 | 307.42 | 298.21 | 298.21 |
| 78 | 294.19 | 294.07 | 312.17 | 294.07 | 294.07 | 294.31 | 293.86 | 311.67 | 293.86 | 294.31 | 297.95 | 297.95 | 307.28 | 297.95 | 297.95 |
| 83 | 294.07 | 293.54 | 312.16 | 293.54 | 293.58 | 293.70 | 293.70 | 310.12 | 293.70 | 293.70 | 297.77 | 297.77 | 307.25 | 297.77 | 297.77 |
| 89 | 293.54 | 293.44 | 311.78 | 293.44 | 293.49 | 293.48 | 293.48 | 309.62 | 293.48 | 293.48 | 296.79 | 296.79 | 306.78 | 296.79 | 296.79 |
| 94 | 292.77 | 292.77 | 311.24 | 292.77 | 292.77 | 292.15 | 292.15 | 309.58 | 292.15 | 292.15 | 296.60 | 296.60 | 306.51 | 296.60 | 296.60 |
| Reli. (%) | II1A2 | II1B2 | II1C2 | II1D | II1E2 | II2A2 | II2B2 | II2C2 | II2D | II2E4 | II3A2 | II3B2 | II3C2 | II3D | II3E6 |
| 6 | 303.08 | 303.12 | 313.00 | 303.12 | 303.08 | 304.41 | 304.41 | 313.00 | 304.57 | 304.41 | 307.44 | 307.44 | 313.00 | 307.44 | 307.62 |
| 11 | 303.04 | 303.08 | 313.00 | 303.08 | 303.04 | 303.68 | 303.68 | 313.00 | 304.47 | 303.68 | 306.88 | 306.88 | 312.79 | 306.88 | 307.44 |
| 17 | 302.87 | 303.04 | 313.00 | 303.04 | 302.42 | 303.68 | 303.68 | 313.00 | 304.39 | 303.68 | 306.78 | 306.78 | 312.43 | 306.78 | 306.78 |
| 22 | 302.82 | 302.42 | 313.00 | 302.42 | 301.82 | 303.50 | 303.50 | 313.00 | 303.99 | 303.50 | 305.36 | 305.36 | 310.95 | 305.36 | 305.36 |
| 28 | 302.42 | 302.41 | 313.00 | 302.41 | 301.77 | 303.38 | 303.38 | 313.00 | 303.69 | 303.38 | 301.23 | 301.23 | 310.61 | 301.23 | 301.23 |
| 33 | 301.77 | 302.05 | 313.00 | 302.05 | 301.12 | 303.27 | 303.09 | 313.00 | 303.68 | 303.09 | 301.20 | 301.20 | 310.13 | 301.20 | 301.20 |
| 39 | 300.87 | 300.89 | 313.00 | 300.89 | 300.87 | 303.09 | 303.02 | 313.00 | 303.40 | 303.02 | 300.57 | 300.57 | 309.92 | 300.57 | 300.57 |
| 44 | 300.46 | 300.87 | 313.00 | 300.87 | 300.40 | 303.02 | 302.24 | 313.00 | 302.26 | 302.97 | 300.57 | 300.57 | 309.68 | 300.57 | 300.57 |
| 50 | 300.09 | 300.46 | 313.00 | 300.46 | 300.09 | 302.24 | 301.85 | 313.00 | 301.81 | 302.57 | 300.18 | 300.18 | 309.34 | 300.18 | 300.18 |
| 56 | 299.76 | 300.09 | 313.00 | 300.09 | 299.76 | 301.66 | 301.66 | 313.00 | 301.66 | 302.24 | 299.95 | 299.95 | 308.75 | 299.95 | 299.95 |
| 61 | 298.68 | 299.76 | 312.72 | 299.76 | 299.47 | 299.85 | 299.85 | 313.00 | 299.14 | 299.85 | 299.00 | 299.00 | 307.71 | 299.00 | 299.00 |
| 67 | 298.61 | 298.68 | 312.72 | 298.68 | 298.84 | 298.98 | 298.98 | 312.72 | 298.83 | 298.98 | 298.77 | 298.77 | 307.66 | 298.77 | 298.77 |
| 72 | 298.54 | 298.54 | 312.72 | 298.54 | 298.69 | 298.79 | 298.79 | 312.01 | 298.76 | 298.79 | 297.70 | 297.70 | 307.42 | 297.70 | 297.70 |
| 78 | 298.40 | 298.34 | 312.17 | 298.34 | 298.40 | 298.76 | 298.76 | 311.67 | 298.32 | 298.76 | 297.65 | 297.65 | 307.28 | 297.65 | 297.65 |
| 83 | 298.34 | 297.33 | 312.16 | 297.33 | 297.31 | 298.60 | 298.60 | 310.12 | 298.19 | 298.32 | 296.49 | 296.49 | 307.25 | 296.49 | 296.49 |
| 89 | 297.31 | 297.31 | 311.78 | 297.31 | 295.82 | 296.79 | 296.79 | 309.62 | 297.10 | 296.79 | 296.41 | 296.41 | 306.78 | 296.41 | 296.41 |
| 94 | 295.10 | 295.10 | 311.24 | 295.10 | 294.32 | 294.97 | 294.97 | 309.58 | 296.09 | 294.97 | 292.04 | 292.04 | 306.51 | 292.04 | 292.04 |

**Table 9.1 (d)** Achieved annual yield for irrigation from GS reservoir obtained for different reliabilities through reservoir operation by CIM

| Reli. (%) | Achieved annual yield for irrigation from GS reservoir (MCM) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CASES | | | | | | | | | | | | | | |
| | I1A1 | I1B1 | I1C1 | I1D | I1E1 | I2A1 | I2B1 | I2C1 | I2D | I2E3 | I3A1 | I3B1 | I3C1 | I3D | I3E5 |
| 6 | 3284.61 | 3284.61 | 3276.46 | 3284.61 | 3284.61 | 3284.19 | 3284.19 | 3278.35 | 3284.19 | 3284.19 | 3281.16 | 3281.16 | 3297.41 | 3281.16 | 3281.16 |
| 11 | 3284.61 | 3284.61 | 3276.46 | 3284.61 | 3284.61 | 3284.19 | 3284.19 | 3278.35 | 3284.19 | 3284.19 | 3281.16 | 3281.16 | 3297.41 | 3281.16 | 3281.16 |
| 17 | 3284.61 | 3284.61 | 3276.46 | 3284.61 | 3284.61 | 3284.19 | 3284.19 | 3278.35 | 3284.19 | 3284.19 | 3281.16 | 3281.16 | 3297.41 | 3281.16 | 3281.16 |
| 22 | 3284.61 | 3284.61 | 3276.46 | 3284.61 | 3284.61 | 3284.19 | 3284.19 | 3278.35 | 3284.19 | 3284.19 | 3281.16 | 3281.16 | 3297.41 | 3281.16 | 3281.16 |
| 28 | 3284.61 | 3284.61 | 3276.46 | 3284.61 | 3284.61 | 3284.19 | 3284.19 | 3278.35 | 3284.19 | 3284.19 | 3281.16 | 3281.16 | 3296.97 | 3281.16 | 3281.16 |
| 33 | 3284.61 | 3284.61 | 3276.46 | 3284.61 | 3284.61 | 3284.19 | 3284.19 | 3278.35 | 3284.19 | 3284.19 | 3281.16 | 3281.16 | 3296.53 | 3281.16 | 3281.16 |
| 39 | 3284.61 | 3284.61 | 3276.46 | 3284.61 | 3284.61 | 3284.19 | 3284.19 | 3278.35 | 3284.19 | 3284.19 | 3281.16 | 3281.16 | 3295.41 | 3281.16 | 3281.16 |
| 44 | 3284.61 | 3284.61 | 3276.46 | 3284.61 | 3284.61 | 3284.19 | 3284.19 | 3278.35 | 3284.19 | 3284.19 | 3281.09 | 3281.16 | 3294.32 | 3281.16 | 3281.16 |
| 50 | 3284.61 | 3284.61 | 3276.46 | 3284.61 | 3284.47 | 3284.19 | 3284.19 | 3278.35 | 3284.19 | 3284.19 | 3280.32 | 3281.16 | 3294.27 | 3281.16 | 3281.16 |
| 56 | 3284.61 | 3284.61 | 3276.03 | 3284.61 | 3284.37 | 3284.19 | 3284.05 | 3278.35 | 3284.05 | 3282.72 | 3279.71 | 3281.16 | 3294.17 | 3281.16 | 3281.16 |
| 61 | 3284.47 | 3284.61 | 3272.82 | 3284.61 | 3282.69 | 3284.19 | 3283.76 | 3277.29 | 3283.76 | 3281.53 | 3279.23 | 3279.23 | 3293.37 | 3279.23 | 3281.10 |
| 67 | 3283.97 | 3284.47 | 3272.09 | 3284.47 | 3280.99 | 3282.48 | 3283.57 | 3277.11 | 3283.57 | 3280.56 | 3279.17 | 3279.17 | 3291.98 | 3279.17 | 3281.09 |
| 72 | 3283.82 | 3283.63 | 3271.28 | 3283.63 | 3278.37 | 3281.53 | 3281.53 | 3276.78 | 3281.53 | 3278.90 | 3277.91 | 3277.91 | 3288.48 | 3277.91 | 3279.17 |
| 78 | 3278.37 | 3279.71 | 3267.85 | 3279.71 | 3277.61 | 3279.85 | 3280.11 | 3273.05 | 3280.11 | 3276.58 | 3277.09 | 3277.09 | 3283.62 | 3277.09 | 3277.09 |
| 83 | 3276.31 | 3279.36 | 3266.81 | 3279.36 | 3277.33 | 3278.09 | 3280.04 | 3272.15 | 3279.85 | 3275.72 | 3275.56 | 3274.60 | 3282.21 | 3274.60 | 3274.28 |
| 89 | 3274.14 | 3278.37 | 3266.23 | 3278.37 | 3274.14 | 3276.83 | 3279.85 | 3271.74 | 3278.72 | 3263.11 | 3274.10 | 3266.17 | 3277.17 | 3274.12 | 3274.10 |
| 94 | 3260.17 | 3274.14 | 3249.46 | 3274.14 | 3260.17 | 3263.11 | 3278.19 | 3269.28 | 3278.19 | 3259.41 | 3266.17 | 3263.68 | 3246.62 | 3266.17 | 3266.17 |
| Reli. (%) | II1A2 | II1B2 | II1C2 | II1D | II1E2 | II2A2 | II2B2 | II2C2 | II2D | II2E4 | II3A2 | II3B2 | II3C2 | II3D | II3E6 |
| 6 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 |
| 11 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 |
| 17 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 |
| 22 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 |
| 28 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 | 2852.91 |
| 33 | 2851.12 | 2851.12 | 2851.12 | 2851.12 | 2851.12 | 2851.12 | 2851.12 | 2851.12 | 2851.12 | 2851.12 | 2851.12 | 2851.12 | 2851.12 | 2851.12 | 2851.12 |
| 39 | 2851.09 | 2851.09 | 2851.09 | 2851.09 | 2851.09 | 2851.09 | 2851.09 | 2851.09 | 2851.09 | 2851.09 | 2851.09 | 2851.09 | 2851.09 | 2851.09 | 2851.09 |
| 44 | 2850.22 | 2850.22 | 2850.22 | 2850.22 | 2850.22 | 2850.22 | 2850.22 | 2850.22 | 2850.22 | 2850.22 | 2850.22 | 2850.22 | 2850.22 | 2850.22 | 2850.22 |
| 50 | 2850.17 | 2850.17 | 2850.17 | 2850.17 | 2850.17 | 2850.17 | 2850.17 | 2850.17 | 2850.17 | 2850.17 | 2850.17 | 2850.17 | 2850.17 | 2850.17 | 2850.17 |
| 56 | 2849.41 | 2849.41 | 2849.41 | 2849.41 | 2849.41 | 2849.41 | 2849.41 | 2849.41 | 2849.41 | 2849.41 | 2849.41 | 2849.41 | 2849.41 | 2849.41 | 2849.41 |
| 61 | 2847.83 | 2847.83 | 2847.83 | 2847.83 | 2847.83 | 2847.83 | 2847.83 | 2847.83 | 2847.83 | 2847.83 | 2847.83 | 2847.83 | 2847.83 | 2847.83 | 2847.83 |
| 67 | 2845.62 | 2845.62 | 2845.62 | 2845.62 | 2845.62 | 2845.62 | 2845.62 | 2845.62 | 2845.62 | 2845.62 | 2845.62 | 2845.62 | 2845.62 | 2845.62 | 2845.62 |
| 72 | 2844.14 | 2844.14 | 2844.14 | 2844.14 | 2844.14 | 2844.14 | 2844.14 | 2844.14 | 2844.14 | 2844.14 | 2844.14 | 2844.14 | 2844.14 | 2844.14 | 2844.14 |
| 78 | 2843.02 | 2843.02 | 2843.02 | 2843.02 | 2843.02 | 2843.02 | 2843.02 | 2843.02 | 2843.02 | 2843.02 | 2843.02 | 2843.02 | 2843.02 | 2843.02 | 2843.02 |
| 83 | 2835.12 | 2835.12 | 2835.12 | 2835.12 | 2835.12 | 2835.12 | 2835.12 | 2835.12 | 2835.12 | 2835.12 | 2835.12 | 2835.12 | 2835.12 | 2835.12 | 2835.12 |
| 89 | 2828.05 | 2828.05 | 2828.05 | 2828.05 | 2828.05 | 2828.05 | 2828.05 | 2828.05 | 2828.05 | 2828.05 | 2828.05 | 2828.05 | 2828.05 | 2828.05 | 2828.05 |
| 94 | 2802.70 | 2802.70 | 2802.70 | 2802.70 | 2802.70 | 2802.70 | 2802.70 | 2802.70 | 2802.70 | 2802.70 | 2802.70 | 2802.70 | 2802.70 | 2802.70 | 2802.70 |

**Table 9.1 (e)** Achieved annual yield for water export from PAT reservoir obtained for different reliabilities through reservoir operation by CIM

| Reli. (%) | Achieved annual yield for water export from PAT reservoir (MCM) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CASES | | | | | | | | | | | | | | |
| | I1A1 | I1B1 | I1C1 | I1D | I1E1 | I2A1 | I2B1 | I2C1 | I2D | I2E3 | I3A1 | I3B1 | I3C1 | I3D | I3E5 |
| 6 | 862.84 | 1063.50 | 996.99 | 1063.50 | 738.72 | 851.18 | 1069.68 | 991.65 | 1069.68 | 715.97 | 835.28 | 1060.63 | 980.27 | 1060.63 | 661.62 |
| 11 | 784.18 | 996.69 | 988.59 | 996.69 | 632.97 | 790.36 | 984.59 | 985.60 | 984.59 | 621.86 | 781.31 | 965.91 | 969.75 | 965.91 | 610.57 |
| 17 | 735.72 | 945.67 | 884.83 | 945.67 | 619.44 | 734.72 | 945.43 | 874.08 | 945.43 | 608.09 | 735.23 | 962.79 | 852.85 | 963.96 | 588.45 |
| 22 | 722.26 | 884.72 | 869.03 | 884.72 | 605.60 | 722.26 | 873.06 | 858.34 | 873.06 | 589.56 | 730.18 | 855.16 | 834.40 | 855.16 | 548.51 |
| 28 | 709.52 | 867.72 | 801.36 | 867.72 | 566.69 | 709.27 | 855.92 | 801.19 | 855.92 | 548.94 | 708.84 | 835.21 | 800.87 | 835.21 | 547.69 |
| 33 | 681.15 | 817.89 | 780.50 | 817.89 | 557.14 | 669.35 | 816.90 | 780.49 | 816.90 | 548.13 | 652.65 | 813.15 | 785.18 | 813.15 | 542.09 |
| 39 | 638.47 | 797.97 | 763.72 | 797.97 | 549.18 | 649.34 | 797.73 | 763.46 | 797.73 | 543.78 | 648.64 | 797.29 | 779.77 | 797.29 | 504.85 |
| 44 | 604.79 | 781.40 | 733.51 | 781.40 | 548.37 | 604.55 | 781.40 | 754.05 | 781.40 | 533.92 | 611.97 | 781.27 | 762.22 | 781.27 | 503.31 |
| 50 | 555.11 | 767.96 | 696.92 | 767.96 | 514.60 | 576.32 | 767.71 | 715.93 | 767.71 | 503.75 | 604.33 | 767.28 | 733.59 | 767.28 | 496.01 |
| 56 | 548.37 | 715.90 | 688.91 | 715.90 | 504.01 | 548.13 | 725.49 | 699.78 | 725.49 | 503.26 | 574.16 | 739.24 | 717.23 | 739.24 | 492.36 |
| 61 | 534.41 | 680.12 | 677.91 | 680.12 | 465.82 | 545.28 | 679.88 | 677.67 | 679.88 | 475.92 | 564.06 | 679.45 | 676.42 | 679.45 | 483.83 |
| 67 | 520.50 | 653.32 | 648.48 | 653.32 | 445.12 | 541.20 | 653.08 | 648.24 | 653.08 | 444.88 | 547.69 | 652.65 | 647.27 | 652.65 | 454.55 |
| 72 | 507.57 | 548.37 | 542.48 | 548.37 | 431.21 | 518.44 | 548.13 | 542.24 | 548.13 | 440.80 | 537.21 | 547.69 | 541.52 | 547.69 | 444.45 |
| 78 | 504.01 | 504.01 | 502.43 | 504.01 | 418.28 | 503.75 | 503.75 | 502.18 | 503.75 | 418.04 | 503.31 | 503.31 | 500.95 | 503.31 | 417.60 |
| 83 | 437.76 | 437.76 | 434.01 | 437.76 | 349.72 | 437.52 | 437.52 | 433.78 | 437.52 | 349.48 | 437.25 | 437.25 | 431.92 | 437.25 | 349.21 |
| 89 | 249.17 | 249.17 | 246.16 | 249.17 | 249.17 | 249.17 | 249.17 | 246.16 | 249.17 | 249.17 | 249.08 | 249.08 | 245.98 | 249.08 | 249.08 |
| 94 | 229.69 | 229.69 | 228.09 | 229.69 | 229.69 | 229.69 | 229.69 | 228.09 | 229.69 | 229.69 | 229.69 | 229.69 | 227.95 | 229.69 | 229.69 |
| Reli. (%) | II1A2 | II1B2 | II1C2 | II1D | II1E2 | II2A2 | II2B2 | II2C2 | II2D | II2E4 | II3A2 | II3B2 | II3C2 | II3D | II3E6 |
| 6 | 863.34 | 1063.50 | 996.99 | 1063.50 | 739.22 | 863.34 | 1063.50 | 991.65 | 1069.60 | 717.00 | 835.78 | 1061.13 | 980.27 | 1061.13 | 678.93 |
| 11 | 784.18 | 997.37 | 988.59 | 997.37 | 633.47 | 784.18 | 997.37 | 985.60 | 985.27 | 622.36 | 781.81 | 966.59 | 969.75 | 966.59 | 611.07 |
| 17 | 736.40 | 945.76 | 884.83 | 945.76 | 615.05 | 736.40 | 945.76 | 874.08 | 945.52 | 592.83 | 735.91 | 964.26 | 852.85 | 964.26 | 584.05 |
| 22 | 722.76 | 885.22 | 869.03 | 885.22 | 605.60 | 722.76 | 885.22 | 858.34 | 873.56 | 583.38 | 730.68 | 855.66 | 834.40 | 855.66 | 544.56 |
| 28 | 705.13 | 878.41 | 801.36 | 878.41 | 577.38 | 705.13 | 878.41 | 801.19 | 866.61 | 555.16 | 704.44 | 845.90 | 800.87 | 845.90 | 542.59 |
| 33 | 691.84 | 817.86 | 780.50 | 817.86 | 557.82 | 691.84 | 817.86 | 780.49 | 817.40 | 535.60 | 659.33 | 813.14 | 785.18 | 813.14 | 541.00 |
| 39 | 634.53 | 801.94 | 763.72 | 801.94 | 545.24 | 634.53 | 801.94 | 763.46 | 801.70 | 534.13 | 648.70 | 801.26 | 779.77 | 801.26 | 515.54 |
| 44 | 622.65 | 781.90 | 733.51 | 781.90 | 541.67 | 622.65 | 781.90 | 754.05 | 781.90 | 530.56 | 622.40 | 781.77 | 762.22 | 781.77 | 502.60 |
| 50 | 555.08 | 763.57 | 696.92 | 763.57 | 532.46 | 555.08 | 763.57 | 715.93 | 763.31 | 510.24 | 611.96 | 762.88 | 733.59 | 762.88 | 501.90 |
| 56 | 541.67 | 716.35 | 688.91 | 716.35 | 503.27 | 541.67 | 716.35 | 699.78 | 725.66 | 492.98 | 574.66 | 739.74 | 717.23 | 739.74 | 496.69 |
| 61 | 534.72 | 680.43 | 677.91 | 680.43 | 465.79 | 534.72 | 680.43 | 677.67 | 680.19 | 454.68 | 564.37 | 679.76 | 676.42 | 679.76 | 492.35 |
| 67 | 520.95 | 649.38 | 648.48 | 649.38 | 445.43 | 520.95 | 649.38 | 648.24 | 649.14 | 434.32 | 541.18 | 648.70 | 647.27 | 648.70 | 455.05 |
| 72 | 511.54 | 541.67 | 542.48 | 541.67 | 431.66 | 511.54 | 541.67 | 542.24 | 541.43 | 420.55 | 541.00 | 541.00 | 541.52 | 541.00 | 444.76 |
| 78 | 503.27 | 503.27 | 502.43 | 503.27 | 422.25 | 503.27 | 503.27 | 502.18 | 503.02 | 411.14 | 502.60 | 502.60 | 500.95 | 502.60 | 421.57 |
| 83 | 423.75 | 423.75 | 434.01 | 423.75 | 335.71 | 423.75 | 423.75 | 433.78 | 423.62 | 324.60 | 423.39 | 423.39 | 431.92 | 423.39 | 335.35 |
| 89 | 250.71 | 250.71 | 246.16 | 250.71 | 250.71 | 250.71 | 250.71 | 246.16 | 250.71 | 250.71 | 250.62 | 250.62 | 245.98 | 250.62 | 250.62 |
| 94 | 233.69 | 233.69 | 228.09 | 233.69 | 233.69 | 233.69 | 233.69 | 228.09 | 233.69 | 233.69 | 233.69 | 233.69 | 227.95 | 233.69 | 233.69 |

**Table 9.1 (f)** Achieved annual yield for water export from MOH reservoir obtained for different reliabilities through reservoir operation by CIM

| Reli. (%) | Achieved annual yield for water export from MOH reservoir (MCM) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CASES | | | | | | | | | | | | | | |
| | I1A1 | I1B1 | I1C1 | I1D | I1E1 | I2A1 | I2B1 | I2C1 | I2D | I2E3 | I3A1 | I3B1 | I3C1 | I3D | I3E5 |
| 6 | 1344.91 | 1956.59 | 1611.89 | 2032.97 | 1386.72 | 1346.17 | 1967.43 | 1615.19 | 2164.18 | 1346.54 | 1357.73 | 1978.99 | 1653.40 | 2169.35 | 1305.84 |
| 11 | 1335.33 | 1767.24 | 1596.29 | 1767.24 | 1361.23 | 1332.21 | 1743.44 | 1583.07 | 2043.81 | 1337.79 | 1332.93 | 1724.97 | 1640.19 | 2048.27 | 1298.54 |
| 17 | 1323.42 | 1686.27 | 1518.90 | 1766.82 | 1302.47 | 1324.59 | 1663.40 | 1497.73 | 1743.95 | 1257.47 | 1325.57 | 1645.48 | 1528.04 | 1726.03 | 1222.33 |
| 22 | 1230.53 | 1601.70 | 1500.59 | 1601.70 | 1291.59 | 1231.87 | 1584.67 | 1495.80 | 1743.44 | 1244.61 | 1231.13 | 1577.56 | 1517.64 | 1724.97 | 1208.92 |
| 28 | 1006.99 | 1312.61 | 1188.24 | 1363.79 | 1037.05 | 1006.55 | 1312.18 | 1186.40 | 1584.67 | 1013.46 | 1006.15 | 1312.38 | 1175.00 | 1577.56 | 996.46 |
| 33 | 1001.98 | 1147.16 | 1059.81 | 1164.61 | 916.91 | 1001.55 | 1188.99 | 1058.72 | 1366.33 | 905.37 | 1001.75 | 1222.53 | 1056.09 | 1367.50 | 907.50 |
| 39 | 980.67 | 1067.05 | 1025.14 | 1074.03 | 898.62 | 993.21 | 1073.60 | 1026.42 | 1073.60 | 898.17 | 996.55 | 1073.20 | 1009.64 | 1073.20 | 897.77 |
| 44 | 978.92 | 1065.43 | 987.79 | 1065.43 | 893.23 | 978.41 | 1064.99 | 1000.01 | 1064.99 | 892.81 | 986.16 | 1064.59 | 1007.42 | 1064.59 | 892.41 |
| 50 | 898.62 | 1046.15 | 961.33 | 1046.15 | 889.63 | 898.17 | 1059.56 | 983.02 | 1059.56 | 891.16 | 911.90 | 1064.29 | 990.42 | 1064.29 | 885.76 |
| 56 | 836.53 | 1038.06 | 931.56 | 1038.06 | 872.50 | 878.36 | 1037.55 | 965.13 | 1037.55 | 878.01 | 897.77 | 1037.25 | 948.68 | 1037.25 | 866.55 |
| 61 | 792.68 | 997.37 | 896.89 | 997.37 | 761.46 | 829.26 | 996.95 | 907.16 | 996.95 | 774.87 | 851.19 | 996.55 | 923.13 | 996.55 | 779.60 |
| 67 | 756.42 | 898.62 | 885.30 | 898.62 | 718.63 | 779.16 | 898.17 | 893.70 | 898.17 | 718.21 | 795.96 | 897.77 | 891.19 | 897.77 | 717.80 |
| 72 | 732.05 | 877.76 | 881.23 | 877.76 | 694.34 | 742.74 | 877.34 | 879.30 | 877.34 | 693.91 | 761.55 | 876.94 | 877.96 | 876.94 | 693.51 |
| 78 | 718.63 | 718.63 | 709.16 | 718.63 | 642.76 | 718.21 | 718.21 | 706.55 | 718.21 | 642.34 | 717.80 | 717.80 | 705.24 | 717.80 | 641.94 |
| 83 | 548.86 | 548.86 | 543.64 | 548.86 | 461.00 | 548.43 | 548.43 | 535.51 | 548.43 | 460.57 | 548.20 | 548.20 | 540.71 | 548.20 | 460.33 |
| 89 | 295.56 | 295.56 | 292.89 | 295.56 | 295.56 | 295.20 | 295.20 | 290.91 | 295.20 | 295.20 | 294.90 | 294.90 | 290.59 | 294.90 | 294.90 |
| 94 | 243.06 | 243.06 | 244.20 | 243.06 | 243.06 | 243.06 | 243.06 | 240.73 | 243.06 | 243.06 | 243.06 | 243.06 | 235.77 | 243.06 | 243.06 |
| Reli. (%) | II1A2 | II1B2 | II1C2 | II1D | II1E2 | II2A2 | II2B2 | II2C2 | II2D | II2E4 | II3A2 | II3B2 | II3C2 | II3D | II3E6 |
| 6 | 1345.29 | 1962.52 | 1611.89 | 2164.57 | 1387.12 | 1332.86 | 1953.74 | 1615.19 | 2164.14 | 1341.54 | 1364.40 | 1975.18 | 1653.40 | 2191.44 | 1307.07 |
| 11 | 1341.26 | 1767.62 | 1596.29 | 2038.90 | 1367.16 | 1332.48 | 1755.19 | 1583.07 | 2045.00 | 1324.10 | 1333.31 | 1725.35 | 1640.19 | 2027.55 | 1285.12 |
| 17 | 1323.82 | 1693.58 | 1518.90 | 1774.13 | 1309.78 | 1323.62 | 1681.90 | 1497.73 | 1751.26 | 1263.85 | 1325.97 | 1652.79 | 1528.04 | 1733.34 | 1229.64 |
| 22 | 1237.84 | 1602.10 | 1500.59 | 1767.62 | 1291.97 | 1238.25 | 1590.80 | 1495.80 | 1743.82 | 1245.26 | 1238.44 | 1562.83 | 1517.64 | 1725.35 | 1209.30 |
| 28 | 1059.08 | 1369.71 | 1188.24 | 1602.10 | 1094.15 | 1058.89 | 1369.52 | 1186.40 | 1579.94 | 1059.68 | 1059.32 | 1369.95 | 1175.00 | 1562.83 | 1054.03 |
| 33 | 1017.09 | 1146.66 | 1059.81 | 1358.26 | 929.65 | 1026.39 | 1178.70 | 1058.72 | 1366.62 | 925.99 | 1032.96 | 1220.65 | 1056.09 | 1360.60 | 928.82 |
| 39 | 1003.42 | 1067.62 | 1025.14 | 1074.60 | 913.34 | 1003.23 | 1074.41 | 1026.42 | 1074.17 | 890.93 | 1002.57 | 1078.06 | 1009.64 | 1078.06 | 905.62 |
| 44 | 929.89 | 1061.86 | 987.79 | 1061.86 | 897.37 | 929.44 | 1061.67 | 1000.01 | 1062.97 | 886.89 | 937.19 | 1073.77 | 1007.42 | 1073.77 | 896.54 |
| 50 | 897.37 | 1045.99 | 961.33 | 1045.99 | 872.00 | 897.18 | 1054.61 | 983.02 | 1061.41 | 880.87 | 910.02 | 1061.01 | 990.42 | 1061.01 | 882.18 |
| 56 | 836.03 | 1033.79 | 931.56 | 1033.79 | 840.60 | 868.07 | 1041.24 | 965.13 | 1033.37 | 829.04 | 896.54 | 1032.96 | 948.68 | 1032.96 | 817.58 |
| 61 | 792.52 | 989.03 | 896.89 | 989.03 | 761.30 | 813.20 | 988.58 | 907.16 | 988.58 | 758.81 | 864.96 | 988.28 | 923.13 | 988.28 | 793.37 |
| 67 | 756.99 | 897.37 | 885.30 | 897.37 | 711.23 | 768.86 | 897.18 | 893.70 | 896.93 | 699.94 | 796.53 | 896.54 | 891.19 | 896.54 | 710.41 |
| 72 | 738.22 | 883.93 | 881.23 | 883.93 | 694.91 | 738.04 | 883.75 | 879.30 | 883.51 | 683.61 | 767.72 | 883.11 | 877.96 | 883.11 | 694.08 |
| 78 | 711.23 | 711.23 | 709.16 | 711.23 | 648.93 | 711.05 | 711.05 | 706.55 | 710.81 | 637.64 | 710.41 | 710.41 | 705.24 | 710.41 | 648.11 |
| 83 | 538.31 | 538.31 | 543.64 | 538.31 | 450.45 | 538.13 | 538.13 | 535.51 | 538.00 | 439.15 | 537.80 | 537.80 | 540.71 | 537.80 | 449.93 |
| 89 | 296.31 | 296.31 | 292.89 | 296.31 | 296.31 | 295.95 | 295.95 | 290.91 | 295.95 | 295.95 | 295.65 | 295.65 | 290.59 | 295.65 | 295.65 |
| 94 | 243.84 | 243.84 | 244.20 | 243.84 | 243.84 | 239.62 | 239.62 | 240.73 | 243.84 | 239.62 | 243.84 | 243.84 | 235.77 | 243.84 | 243.84 |

**Table 9.1 (g)** Achieved annual yield for water export from KUN reservoir obtained for different reliabilities through reservoir operation by CIM

| Reli. (%) | Achieved annual yield for water export from KUN reservoir (MCM) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CASES | | | | | | | | | | | | | | |
| | I1A1 | I1B1 | I1C1 | I1D | I1E1 | I2A1 | I2B1 | I2C1 | I2D | I2E3 | I3A1 | I3B1 | I3C1 | I3D | I3E5 |
| 6 | 1733.23 | 2430.70 | 937.56 | 2695.43 | 1715.57 | 1738.06 | 2441.54 | 857.11 | 2774.20 | 1713.59 | 1663.99 | 2439.00 | 581.27 | 2784.53 | 1673.66 |
| 11 | 1685.20 | 2203.07 | 905.93 | 2211.65 | 1667.26 | 1696.42 | 2200.01 | 851.97 | 2711.39 | 1670.04 | 1642.25 | 2144.50 | 576.04 | 2706.76 | 1670.54 |
| 17 | 1513.92 | 1971.80 | 898.44 | 2035.89 | 1544.60 | 1531.09 | 1869.63 | 845.40 | 2200.01 | 1543.09 | 1537.82 | 2006.19 | 571.04 | 2185.98 | 1592.45 |
| 22 | 1508.63 | 1842.76 | 896.76 | 1971.80 | 1365.80 | 1432.33 | 1841.72 | 840.05 | 2019.06 | 1334.82 | 1388.26 | 1876.54 | 549.83 | 2099.92 | 1408.58 |
| 28 | 1373.40 | 1819.26 | 893.03 | 1777.45 | 1364.09 | 1350.07 | 1819.43 | 834.70 | 1869.63 | 1324.92 | 1355.43 | 1824.79 | 544.36 | 1979.12 | 1384.00 |
| 33 | 989.64 | 1374.62 | 874.86 | 1455.17 | 1007.46 | 1321.58 | 1708.11 | 824.82 | 1788.66 | 1307.67 | 1329.96 | 1799.32 | 543.29 | 1876.54 | 1322.69 |
| 39 | 988.54 | 1035.82 | 872.94 | 1038.31 | 910.65 | 1200.45 | 1258.89 | 824.17 | 1258.89 | 1099.27 | 1280.13 | 1338.57 | 530.72 | 1338.57 | 1159.74 |
| 44 | 895.95 | 1031.33 | 861.91 | 1035.82 | 893.65 | 1140.08 | 1199.22 | 822.54 | 1199.22 | 1036.76 | 1135.59 | 1199.21 | 527.45 | 1199.21 | 1015.98 |
| 50 | 893.34 | 994.96 | 861.19 | 994.96 | 893.18 | 996.64 | 1196.10 | 813.55 | 1196.10 | 996.64 | 1092.70 | 1186.68 | 526.42 | 1186.68 | 1000.63 |
| 56 | 892.49 | 945.62 | 830.47 | 945.62 | 889.68 | 994.97 | 1157.50 | 804.85 | 1157.50 | 911.41 | 1000.63 | 1170.68 | 524.10 | 1170.68 | 988.56 |
| 61 | 886.22 | 939.72 | 830.17 | 939.72 | 886.41 | 965.80 | 998.71 | 804.24 | 998.71 | 894.57 | 986.11 | 1092.70 | 505.19 | 1092.70 | 914.52 |
| 67 | 772.72 | 898.82 | 826.78 | 898.82 | 772.72 | 863.06 | 996.64 | 803.21 | 996.64 | 777.81 | 893.44 | 1000.63 | 486.60 | 1000.63 | 800.06 |
| 72 | 742.80 | 836.61 | 802.37 | 836.61 | 731.73 | 771.96 | 835.95 | 775.26 | 835.95 | 771.96 | 800.06 | 884.06 | 461.64 | 884.06 | 790.99 |
| 78 | 742.28 | 816.91 | 740.52 | 816.91 | 653.29 | 752.58 | 816.15 | 689.99 | 816.15 | 652.86 | 768.95 | 800.06 | 389.03 | 800.06 | 650.22 |
| 83 | 593.03 | 593.03 | 660.49 | 593.03 | 512.51 | 457.86 | 457.86 | 434.79 | 457.86 | 370.52 | 460.10 | 460.10 | 342.82 | 460.10 | 372.75 |
| 89 | 571.08 | 580.89 | 502.77 | 580.89 | 506.18 | 295.16 | 295.16 | 192.75 | 295.16 | 295.16 | 208.80 | 208.80 | 198.84 | 208.80 | 208.80 |
| 94 | 512.51 | 512.51 | 463.23 | 512.51 | 430.86 | 231.62 | 231.62 | 190.91 | 231.62 | 231.62 | 153.80 | 153.80 | 158.36 | 153.80 | 153.80 |
| Reli. (%) | II1A2 | II1B2 | II1C2 | II1D | II1E2 | II2A2 | II2B2 | II2C2 | II2D | II2E4 | II3A2 | II3B2 | II3C2 | II3D | II3E6 |
| 6 | 1769.34 | 2477.58 | 924.71 | 2756.15 | 1996.72 | 1730.10 | 2404.46 | 857.11 | 2850.29 | 1850.82 | 1618.64 | 2383.20 | 581.27 | 2856.18 | 1642.68 |
| 11 | 1730.38 | 2176.09 | 907.51 | 2748.88 | 1956.88 | 1696.51 | 2169.03 | 851.97 | 2618.46 | 1817.22 | 1603.14 | 2090.26 | 576.04 | 2634.05 | 1597.80 |
| 17 | 1468.12 | 2008.80 | 899.92 | 2176.09 | 1688.57 | 1423.92 | 1926.59 | 845.40 | 2109.01 | 1472.27 | 1540.12 | 2008.49 | 571.04 | 2131.74 | 1594.75 |
| 22 | 1420.91 | 1961.29 | 899.46 | 2008.80 | 1435.43 | 1408.04 | 1893.28 | 840.05 | 1951.65 | 1467.63 | 1432.64 | 1902.00 | 549.83 | 2102.22 | 1485.79 |
| 28 | 1241.73 | 1664.12 | 896.88 | 1875.72 | 1389.46 | 1394.92 | 1765.46 | 834.70 | 1914.86 | 1418.63 | 1388.23 | 1876.51 | 544.36 | 1968.45 | 1378.35 |
| 33 | 997.57 | 1419.44 | 879.80 | 1499.99 | 1144.37 | 1345.81 | 1721.49 | 824.82 | 1803.98 | 1368.00 | 1324.31 | 1793.67 | 543.29 | 1876.51 | 1322.66 |
| 39 | 993.06 | 1187.95 | 879.13 | 1187.95 | 1015.91 | 1249.38 | 1330.55 | 824.17 | 1328.58 | 1159.94 | 1306.55 | 1364.99 | 530.72 | 1364.99 | 1186.16 |
| 44 | 865.69 | 1164.43 | 861.93 | 1164.43 | 921.70 | 1071.85 | 1198.28 | 822.54 | 1271.51 | 1028.58 | 1161.92 | 1233.44 | 527.45 | 1233.44 | 1038.10 |
| 50 | 822.01 | 1094.41 | 857.58 | 1094.41 | 901.23 | 1007.58 | 1156.69 | 813.55 | 1157.94 | 982.73 | 1048.48 | 1196.03 | 526.42 | 1196.03 | 968.68 |
| 56 | 810.42 | 1059.11 | 836.36 | 1066.09 | 882.88 | 993.11 | 1143.83 | 804.85 | 1155.87 | 967.32 | 1020.34 | 1161.92 | 524.10 | 1161.92 | 950.83 |
| 61 | 808.01 | 922.91 | 836.11 | 922.91 | 850.12 | 956.87 | 1130.13 | 804.24 | 1109.28 | 902.48 | 968.68 | 1099.57 | 505.19 | 1099.57 | 948.75 |
| 67 | 753.64 | 887.61 | 828.18 | 887.61 | 780.35 | 851.14 | 993.11 | 803.21 | 993.99 | 768.86 | 918.79 | 968.68 | 486.60 | 968.68 | 816.34 |
| 72 | 699.69 | 882.79 | 819.53 | 882.79 | 780.25 | 780.04 | 898.19 | 775.26 | 881.50 | 765.89 | 783.73 | 898.83 | 461.64 | 898.83 | 758.28 |
| 78 | 699.58 | 795.19 | 742.25 | 795.19 | 665.13 | 753.19 | 780.04 | 689.99 | 797.02 | 653.48 | 758.28 | 758.28 | 389.03 | 758.28 | 665.00 |
| 83 | 462.56 | 462.56 | 682.17 | 462.56 | 451.04 | 454.64 | 454.64 | 434.79 | 446.37 | 355.37 | 454.15 | 454.15 | 342.82 | 454.15 | 366.81 |
| 89 | 460.90 | 460.90 | 518.78 | 460.90 | 387.24 | 210.37 | 210.37 | 192.75 | 213.91 | 210.37 | 214.48 | 214.48 | 198.84 | 214.48 | 214.48 |
| 94 | 387.24 | 387.24 | 489.06 | 387.24 | 372.81 | 170.53 | 170.53 | 190.91 | 153.87 | 170.53 | 169.98 | 169.98 | 158.36 | 169.98 | 169.98 |

**Table 9.1 (h)** Achieved annual yield for hydropower from GS reservoir obtained for different reliabilities through reservoir operation by CIM

| Reli. (%) | Achieved annual yield for hydropower from GS reservoir (1000 MWhr) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CASES | | | | | | | | | | | | | | |
| | I1A1 | I1B1 | I1C1 | I1D | I1E1 | I2A1 | I2B1 | I2C1 | I2D | I2E3 | I3A1 | I3B1 | I3C1 | I3D | I3E5 |
| 6 | 204.69 | 204.69 | 201.12 | 204.69 | 204.66 | 204.69 | 204.69 | 200.42 | 204.69 | 204.69 | 204.41 | 204.41 | 183.57 | 204.41 | 204.53 |
| 11 | 204.44 | 204.44 | 198.17 | 204.44 | 204.44 | 203.92 | 203.92 | 200.01 | 203.92 | 203.92 | 204.23 | 203.50 | 183.55 | 203.50 | 204.41 |
| 17 | 203.64 | 203.51 | 197.84 | 203.51 | 204.07 | 203.68 | 203.68 | 198.03 | 203.68 | 203.68 | 203.50 | 203.15 | 183.51 | 203.15 | 204.23 |
| 22 | 203.12 | 203.13 | 197.67 | 203.12 | 203.12 | 203.50 | 203.13 | 197.99 | 203.13 | 203.50 | 203.15 | 203.10 | 183.26 | 203.01 | 203.50 |
| 28 | 202.72 | 202.72 | 197.47 | 202.72 | 202.72 | 202.62 | 203.00 | 197.95 | 203.00 | 202.62 | 202.39 | 202.39 | 182.93 | 202.39 | 203.15 |
| 33 | 202.27 | 202.27 | 196.36 | 202.27 | 202.27 | 202.55 | 202.81 | 197.90 | 202.81 | 202.55 | 202.07 | 202.21 | 182.59 | 202.21 | 202.07 |
| 39 | 201.85 | 202.24 | 196.33 | 202.24 | 201.55 | 202.06 | 202.62 | 197.90 | 202.62 | 201.83 | 202.06 | 201.62 | 182.36 | 201.62 | 201.56 |
| 44 | 201.17 | 200.86 | 195.33 | 200.86 | 201.14 | 202.03 | 202.55 | 197.54 | 202.55 | 201.55 | 201.56 | 201.56 | 182.05 | 201.56 | 200.99 |
| 50 | 200.86 | 200.76 | 194.64 | 200.76 | 200.86 | 201.35 | 202.09 | 196.58 | 202.09 | 201.14 | 200.24 | 200.84 | 181.93 | 200.84 | 200.96 |
| 56 | 200.64 | 200.69 | 194.16 | 200.64 | 200.64 | 200.63 | 202.06 | 195.86 | 202.06 | 200.62 | 199.50 | 199.76 | 181.27 | 200.27 | 200.70 |
| 61 | 200.59 | 200.64 | 194.03 | 200.05 | 200.21 | 200.16 | 200.86 | 195.53 | 200.86 | 199.68 | 199.49 | 199.50 | 180.67 | 199.76 | 200.24 |
| 67 | 199.86 | 199.98 | 193.20 | 199.98 | 199.66 | 199.89 | 199.61 | 195.49 | 199.61 | 199.61 | 199.15 | 199.29 | 179.80 | 199.50 | 199.50 |
| 72 | 199.72 | 199.95 | 193.16 | 199.95 | 199.31 | 199.61 | 199.56 | 195.34 | 199.56 | 198.79 | 197.07 | 199.15 | 179.28 | 199.15 | 199.15 |
| 78 | 199.21 | 199.35 | 192.64 | 199.35 | 199.07 | 197.76 | 199.16 | 194.78 | 198.86 | 198.66 | 195.07 | 199.01 | 178.69 | 199.01 | 198.94 |
| 83 | 198.56 | 199.24 | 192.33 | 199.24 | 198.56 | 197.21 | 198.79 | 193.67 | 198.79 | 198.56 | 193.25 | 198.10 | 178.01 | 198.10 | 194.45 |
| 89 | 195.94 | 198.58 | 184.82 | 198.58 | 195.94 | 194.68 | 198.66 | 193.56 | 198.66 | 197.21 | 191.57 | 193.25 | 175.82 | 193.25 | 193.25 |
| 94 | 193.27 | 197.37 | 182.22 | 197.37 | 195.26 | 194.50 | 195.87 | 191.20 | 195.87 | 194.68 | 190.29 | 191.57 | 174.71 | 191.57 | 191.57 |
| Reli. (%) | II1A2 | II1B2 | II1C2 | II1D | II1E2 | II2A2 | II2B2 | II2C2 | II2D | II2E4 | II3A2 | II3B2 | II3C2 | II3D | II3E6 |
| 6 | 157.29 | 157.29 | 157.29 | 157.29 | 157.29 | 157.29 | 157.29 | 157.29 | 157.29 | 157.29 | 157.29 | 157.29 | 157.29 | 157.29 | 157.29 |
| 11 | 157.26 | 157.26 | 157.26 | 157.26 | 157.26 | 157.26 | 157.26 | 157.26 | 157.26 | 157.26 | 157.26 | 157.26 | 157.26 | 157.26 | 157.26 |
| 17 | 157.07 | 157.07 | 157.07 | 157.07 | 157.07 | 157.07 | 157.07 | 157.07 | 157.07 | 157.07 | 157.07 | 157.07 | 157.07 | 157.07 | 157.07 |
| 22 | 156.20 | 156.20 | 156.20 | 156.20 | 156.20 | 156.20 | 156.20 | 156.20 | 156.20 | 156.20 | 156.20 | 156.20 | 156.20 | 156.20 | 156.20 |
| 28 | 156.01 | 156.01 | 156.01 | 156.01 | 156.01 | 156.01 | 156.01 | 156.01 | 156.01 | 156.01 | 156.01 | 156.01 | 156.01 | 156.01 | 156.01 |
| 33 | 155.58 | 155.58 | 155.58 | 155.58 | 155.58 | 155.58 | 155.58 | 155.58 | 155.58 | 155.58 | 155.58 | 155.58 | 155.58 | 155.58 | 155.58 |
| 39 | 155.51 | 155.51 | 155.51 | 155.51 | 155.51 | 155.51 | 155.51 | 155.51 | 155.51 | 155.51 | 155.51 | 155.51 | 155.51 | 155.51 | 155.51 |
| 44 | 155.49 | 155.49 | 155.49 | 155.49 | 155.49 | 155.49 | 155.49 | 155.49 | 155.49 | 155.49 | 155.49 | 155.49 | 155.49 | 155.49 | 155.49 |
| 50 | 155.24 | 155.24 | 155.24 | 155.24 | 155.24 | 155.24 | 155.24 | 155.24 | 155.24 | 155.24 | 155.24 | 155.24 | 155.24 | 155.24 | 155.24 |
| 56 | 155.19 | 155.19 | 155.19 | 155.19 | 155.19 | 155.19 | 155.19 | 155.19 | 155.19 | 155.19 | 155.19 | 155.19 | 155.19 | 155.19 | 155.19 |
| 61 | 155.12 | 155.12 | 155.12 | 155.12 | 155.12 | 155.12 | 155.12 | 155.12 | 155.12 | 155.12 | 155.12 | 155.12 | 155.12 | 155.12 | 155.12 |
| 67 | 154.85 | 154.85 | 154.85 | 154.85 | 154.85 | 154.85 | 154.85 | 154.85 | 154.85 | 154.85 | 154.85 | 154.85 | 154.85 | 154.85 | 154.85 |
| 72 | 154.84 | 154.84 | 154.84 | 154.84 | 154.84 | 154.84 | 154.84 | 154.84 | 154.84 | 154.84 | 154.84 | 154.84 | 154.84 | 154.84 | 154.84 |
| 78 | 154.34 | 154.34 | 154.34 | 154.34 | 154.34 | 154.34 | 154.34 | 154.34 | 154.34 | 154.34 | 154.34 | 154.34 | 154.34 | 154.34 | 154.34 |
| 83 | 154.09 | 154.09 | 154.09 | 154.09 | 154.09 | 154.09 | 154.09 | 154.09 | 154.09 | 154.09 | 154.09 | 154.09 | 154.09 | 154.09 | 154.09 |
| 89 | 153.76 | 153.76 | 153.76 | 153.76 | 153.76 | 153.76 | 153.76 | 153.76 | 153.76 | 153.76 | 153.76 | 153.76 | 153.76 | 153.76 | 153.76 |
| 94 | 149.18 | 149.18 | 149.18 | 149.18 | 149.18 | 149.18 | 149.18 | 149.18 | 149.18 | 149.18 | 149.18 | 149.18 | 149.18 | 149.18 | 149.18 |

**Table 9.1 (i)** Achieved annual yield for hydropower from RPS reservoir obtained for different reliabilities through reservoir operation by CIM

| Reli. (%) | Achieved annual yield for hydropower from RPS reservoir (1000 MWhr) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CASES | | | | | | | | | | | | | | |
| | I1A1 | I1B1 | I1C1 | I1D | I1E1 | I2A1 | I2B1 | I2C1 | I2D | I2E3 | I3A1 | I3B1 | I3C1 | I3D | I3E5 |
| 6 | 105.27 | 105.27 | 102.95 | 105.28 | 105.27 | 104.96 | 105.26 | 104.88 | 104.96 | 105.07 | 104.75 | 104.84 | 79.48 | 104.84 | 104.75 |
| 11 | 105.27 | 105.27 | 102.94 | 105.27 | 105.27 | 105.07 | 105.07 | 104.83 | 105.26 | 105.03 | 104.71 | 104.75 | 79.39 | 104.75 | 104.71 |
| 17 | 104.98 | 104.98 | 102.84 | 105.14 | 105.08 | 105.03 | 105.03 | 104.75 | 105.07 | 104.96 | 104.71 | 104.75 | 79.29 | 104.71 | 104.71 |
| 22 | 104.93 | 104.95 | 102.78 | 105.13 | 104.93 | 104.95 | 104.96 | 104.66 | 105.03 | 104.95 | 104.67 | 104.71 | 79.18 | 104.71 | 104.67 |
| 28 | 104.89 | 104.81 | 102.74 | 105.07 | 104.88 | 104.89 | 104.94 | 104.59 | 104.94 | 104.89 | 104.65 | 104.71 | 79.06 | 104.67 | 104.64 |
| 33 | 104.89 | 104.81 | 102.61 | 105.07 | 104.85 | 104.66 | 104.90 | 104.57 | 104.90 | 104.85 | 104.64 | 104.67 | 79.01 | 104.67 | 104.52 |
| 39 | 104.89 | 104.80 | 102.57 | 105.05 | 104.79 | 104.63 | 104.66 | 104.54 | 104.70 | 104.71 | 104.52 | 104.64 | 78.99 | 104.64 | 104.52 |
| 44 | 104.85 | 104.74 | 102.54 | 105.04 | 104.76 | 104.53 | 104.56 | 104.49 | 104.66 | 104.63 | 104.52 | 104.52 | 78.85 | 104.52 | 104.30 |
| 50 | 104.77 | 104.62 | 102.53 | 105.01 | 104.72 | 104.50 | 104.54 | 104.29 | 104.56 | 104.54 | 104.51 | 104.33 | 78.80 | 104.33 | 104.03 |
| 56 | 104.73 | 104.53 | 102.47 | 104.95 | 104.68 | 104.31 | 104.53 | 104.29 | 104.53 | 104.53 | 104.08 | 104.19 | 78.78 | 104.03 | 103.94 |
| 61 | 104.56 | 104.41 | 102.20 | 104.94 | 104.53 | 104.21 | 104.31 | 104.27 | 104.52 | 104.47 | 104.03 | 104.03 | 78.67 | 103.96 | 103.91 |
| 67 | 104.55 | 104.39 | 101.89 | 104.89 | 104.42 | 104.19 | 104.24 | 104.23 | 104.31 | 104.24 | 103.93 | 103.96 | 78.60 | 103.93 | 103.85 |
| 72 | 104.49 | 104.19 | 101.83 | 104.81 | 104.39 | 104.17 | 104.21 | 104.22 | 104.24 | 104.10 | 103.82 | 103.93 | 78.46 | 103.70 | 103.74 |
| 78 | 104.39 | 103.87 | 101.75 | 104.78 | 104.11 | 103.96 | 104.19 | 104.15 | 104.19 | 104.05 | 103.76 | 103.56 | 78.45 | 103.56 | 103.29 |
| 83 | 104.11 | 103.81 | 101.56 | 104.74 | 104.02 | 103.71 | 104.09 | 103.22 | 104.09 | 104.04 | 103.43 | 103.53 | 78.33 | 103.53 | 103.27 |
| 89 | 103.85 | 103.77 | 101.48 | 104.33 | 103.87 | 103.44 | 104.04 | 102.87 | 104.04 | 104.01 | 103.12 | 103.26 | 78.14 | 103.26 | 102.67 |
| 94 | 102.09 | 103.50 | 101.46 | 103.76 | 103.79 | 102.81 | 103.60 | 102.61 | 103.60 | 103.87 | 102.39 | 102.65 | 77.61 | 102.65 | 102.41 |
| Reli. (%) | II1A2 | II1B2 | II1C2 | II1D | II1E2 | II2A2 | II2B2 | II2C2 | II2D | II2E4 | II3A2 | II3B2 | II3C2 | II3D | II3E6 |
| 6 | 116.37 | 116.41 | 114.73 | 116.41 | 116.37 | 139.12 | 139.12 | 138.40 | 139.03 | 139.12 | 139.29 | 139.29 | 117.47 | 139.29 | 139.29 |
| 11 | 116.35 | 116.37 | 115.34 | 116.37 | 116.35 | 138.78 | 138.78 | 138.29 | 138.82 | 138.72 | 139.20 | 139.20 | 117.07 | 139.20 | 139.20 |
| 17 | 116.16 | 116.35 | 115.34 | 116.35 | 116.06 | 138.72 | 138.72 | 138.27 | 138.76 | 138.67 | 139.17 | 139.17 | 117.00 | 139.17 | 139.17 |
| 22 | 116.04 | 116.33 | 115.16 | 116.33 | 116.04 | 138.67 | 138.67 | 138.19 | 138.67 | 138.66 | 138.94 | 138.94 | 116.97 | 138.94 | 138.85 |
| 28 | 115.75 | 116.04 | 115.11 | 116.04 | 115.89 | 138.66 | 138.66 | 138.05 | 138.62 | 138.64 | 138.85 | 138.85 | 116.96 | 138.85 | 138.83 |
| 33 | 115.72 | 115.78 | 114.95 | 115.78 | 115.75 | 138.64 | 138.64 | 138.02 | 138.59 | 138.61 | 138.83 | 138.83 | 116.53 | 138.83 | 138.81 |
| 39 | 115.72 | 115.75 | 114.95 | 115.75 | 115.72 | 138.61 | 138.61 | 137.82 | 138.59 | 138.54 | 138.81 | 138.81 | 116.50 | 138.81 | 138.66 |
| 44 | 115.49 | 115.73 | 114.93 | 115.73 | 115.60 | 138.55 | 138.53 | 137.76 | 138.50 | 138.53 | 138.53 | 138.53 | 116.40 | 138.53 | 138.47 |
| 50 | 115.46 | 115.72 | 114.87 | 115.72 | 115.46 | 138.53 | 138.46 | 137.74 | 138.43 | 138.49 | 138.47 | 138.47 | 116.30 | 138.47 | 138.36 |
| 56 | 115.31 | 115.53 | 114.82 | 115.53 | 115.31 | 138.46 | 138.35 | 137.65 | 138.26 | 138.46 | 138.36 | 138.36 | 116.04 | 138.36 | 138.33 |
| 61 | 115.30 | 115.46 | 114.80 | 115.46 | 115.25 | 138.26 | 138.26 | 137.60 | 138.23 | 138.26 | 138.08 | 138.08 | 115.88 | 138.08 | 138.01 |
| 67 | 115.22 | 114.93 | 114.63 | 114.93 | 115.23 | 137.44 | 137.44 | 137.23 | 137.58 | 137.44 | 137.59 | 137.59 | 115.79 | 137.59 | 137.59 |
| 72 | 115.08 | 114.93 | 114.56 | 114.93 | 114.93 | 136.22 | 136.22 | 135.63 | 136.40 | 136.22 | 137.36 | 137.36 | 114.84 | 137.36 | 137.36 |
| 78 | 114.93 | 114.75 | 114.09 | 114.75 | 114.87 | 135.67 | 135.67 | 135.62 | 135.53 | 135.67 | 136.53 | 136.53 | 114.39 | 136.53 | 136.53 |
| 83 | 114.74 | 114.74 | 114.07 | 114.74 | 114.74 | 131.60 | 131.60 | 134.06 | 131.86 | 131.60 | 131.83 | 131.83 | 113.05 | 131.83 | 131.83 |
| 89 | 114.51 | 114.72 | 113.11 | 114.72 | 114.72 | 113.47 | 125.97 | 131.24 | 124.73 | 104.93 | 116.98 | 126.73 | 107.85 | 126.73 | 106.79 |
| 94 | 114.45 | 114.47 | 112.22 | 114.47 | 114.71 | 98.24 | 98.24 | 111.01 | 99.68 | 97.35 | 96.43 | 96.43 | 95.71 | 96.43 | 96.43 |

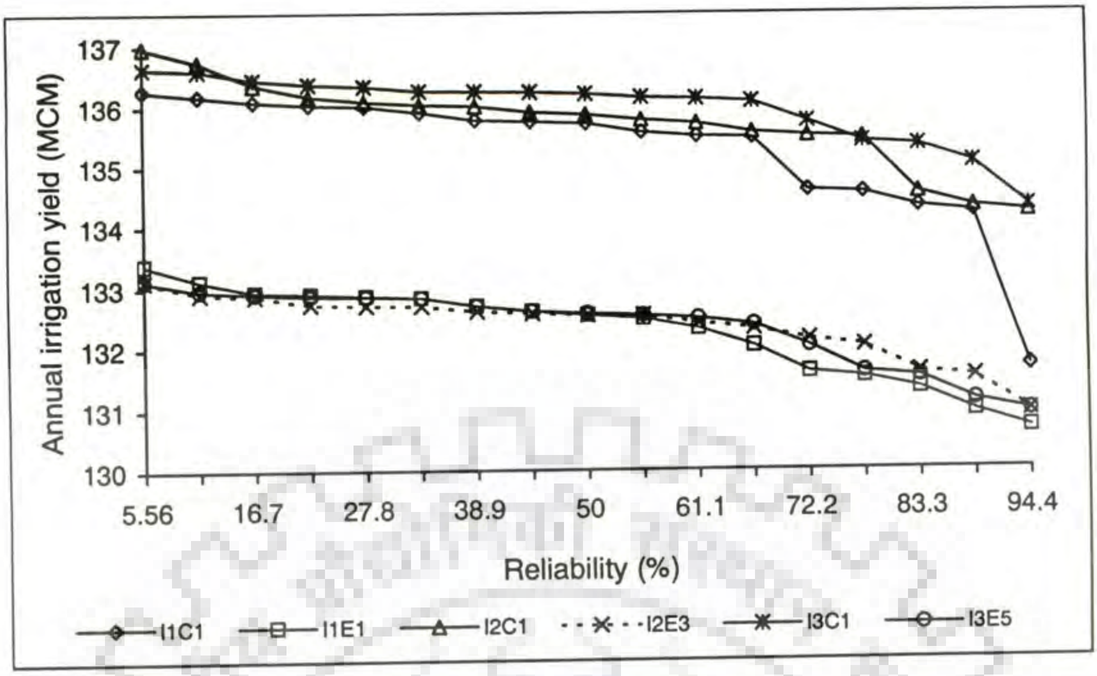

**Figure 9.1 (a)** Achieved annual irrigation yield from PAT reservoir for different reliabilities for Link Alternative I

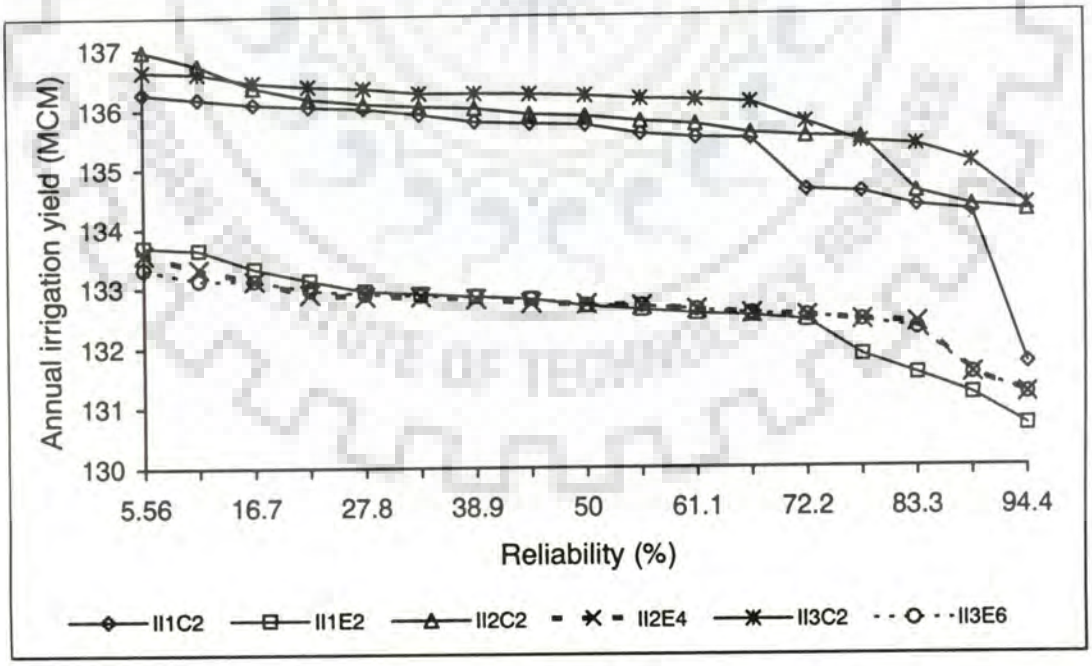

**Figure 9.1 (b)** Achieved annual irrigation yield from PAT reservoir for different reliabilities for Link Alternative II

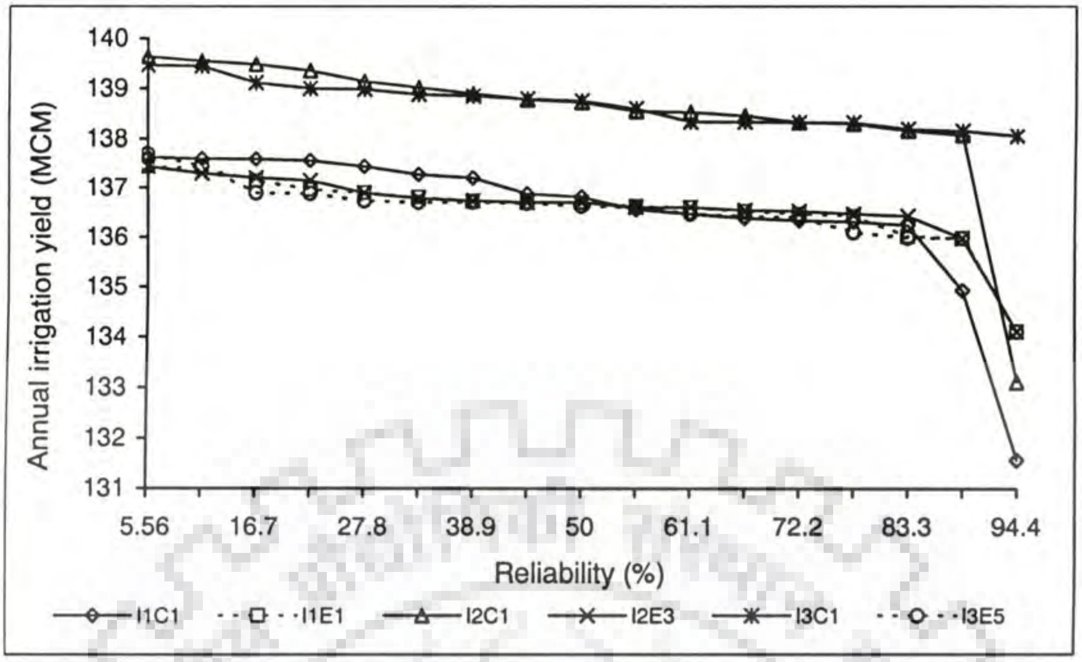

Figure 9.1 (c) Achieved annual irrigation yield from MOH reservoir for different reliabilities for Link Alternative I

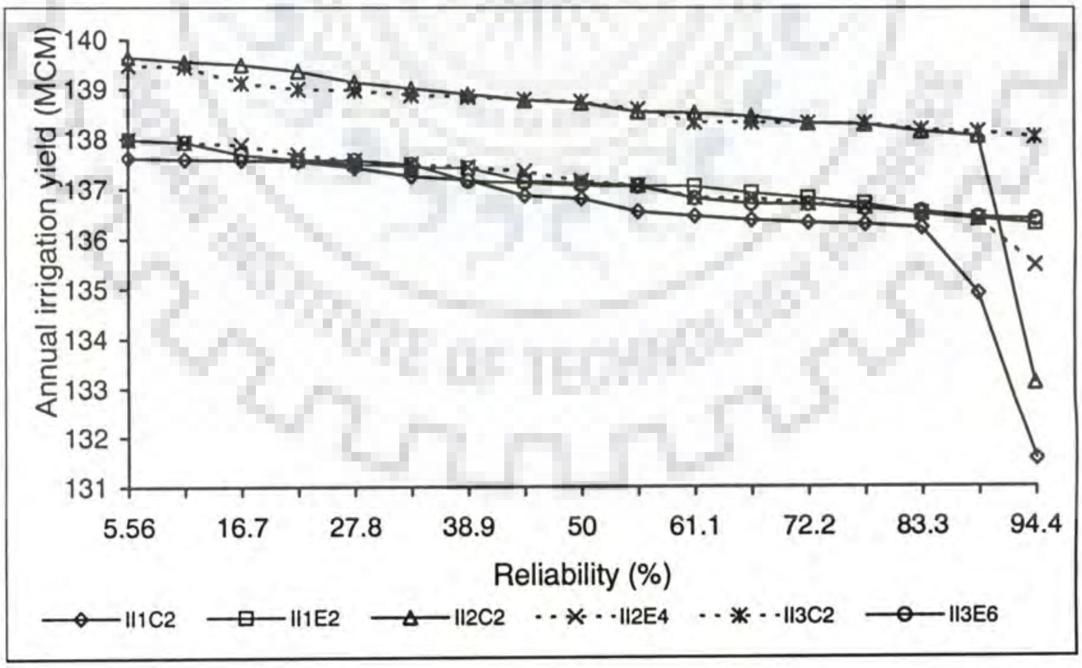

Figure 9.1 (d) Achieved annual irrigation yield from MOH reservoir for different reliabilities for Link Alternative II

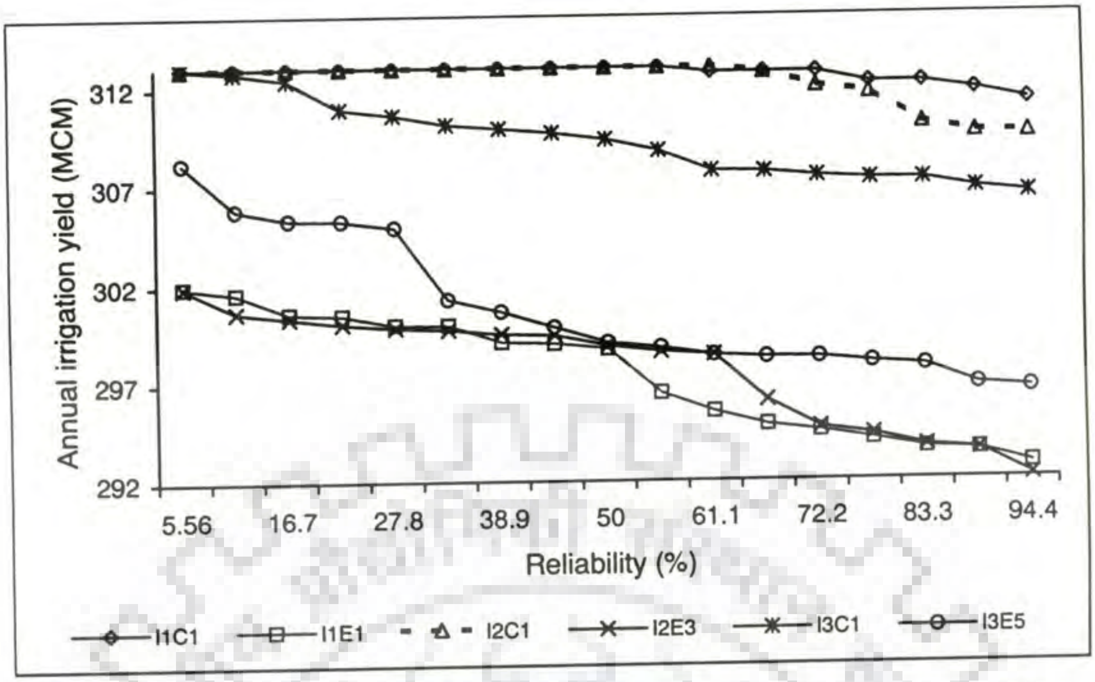

**Figure 9.1 (e)** Achieved annual irrigation yield from KUN reservoir for different reliabilities for Link Alternative I

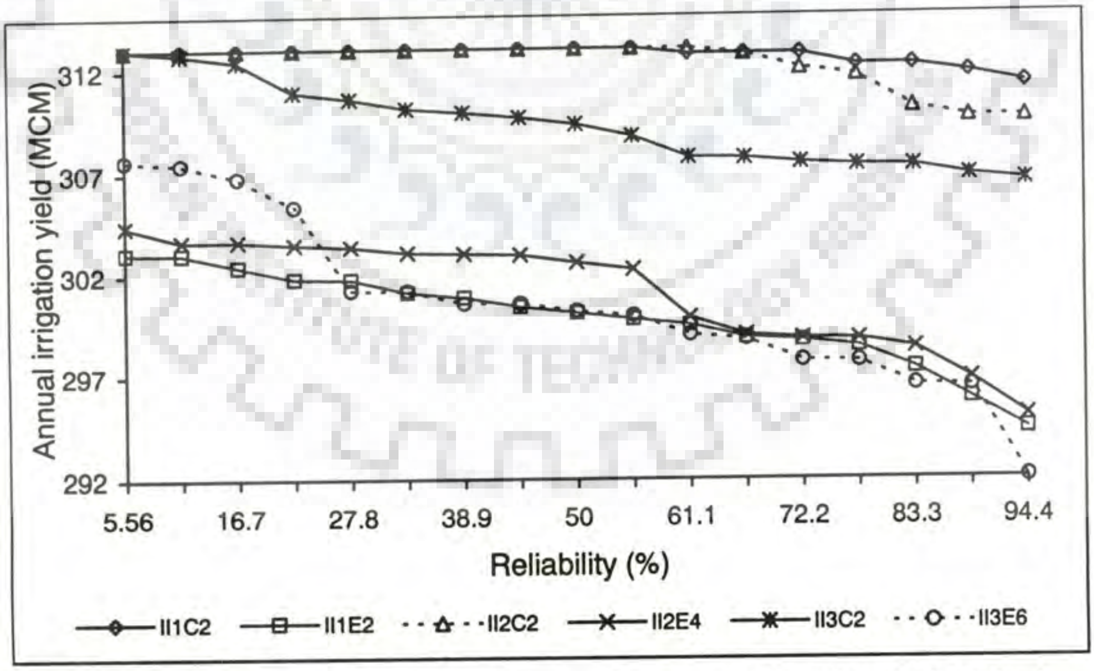

**Figure 9.1 (f)** Achieved annual irrigation yield from KUN reservoir for different reliabilities for Link Alternative II

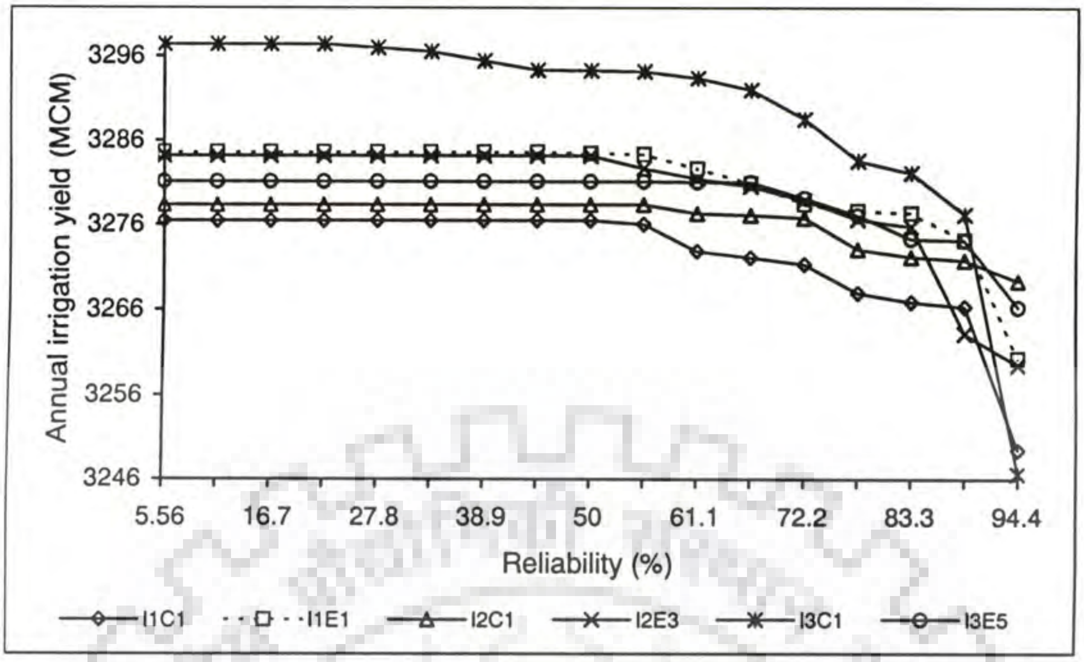

**Figure 9.1** (g) Achieved annual irrigation yield from GS reservoir for different reliabilities for Link Alternative I

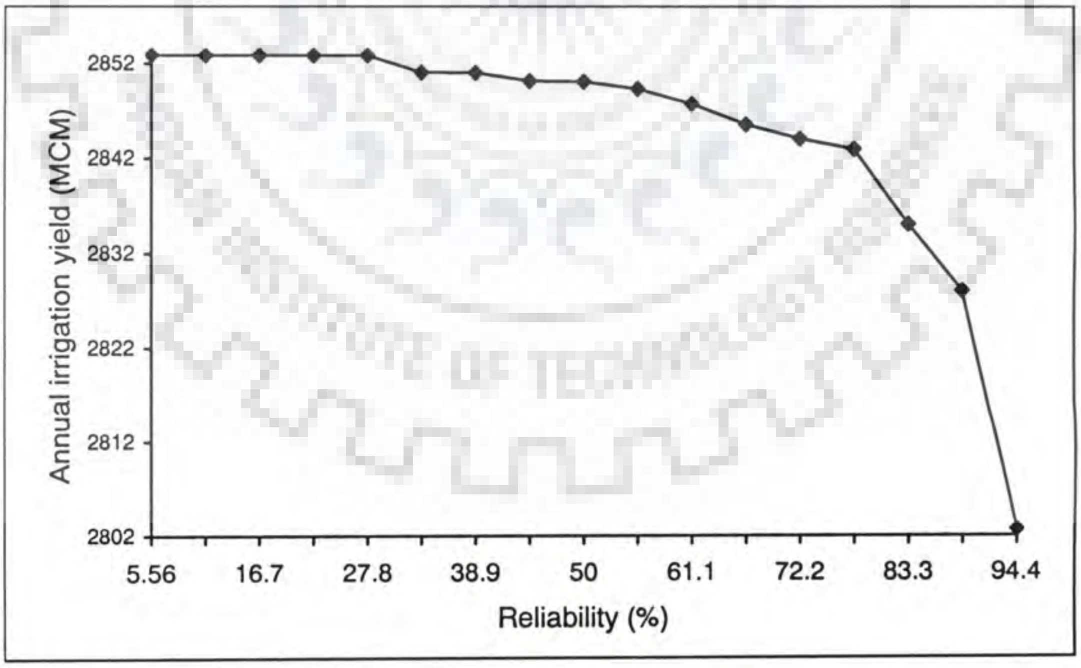

**Figure 9.1** (h) Achieved annual irrigation yield from GS reservoir for different reliabilities for Link Alternative II, for all cases

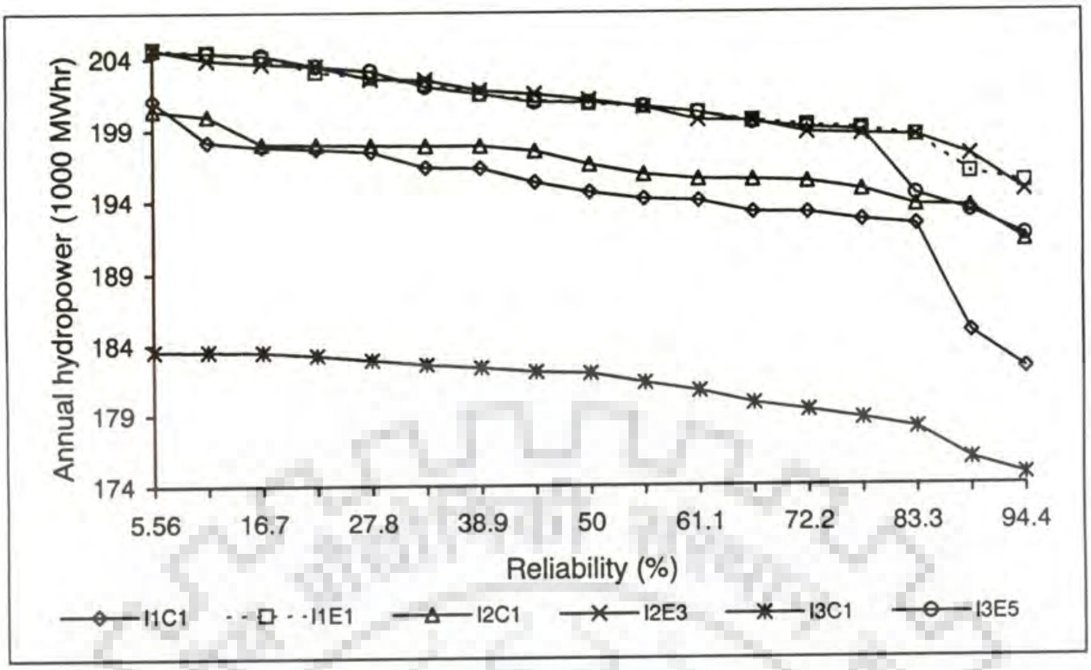

**Figure 9.1 (I)** Achieved annual hydropower yield from GS reservoir for different reliabilities for Link Alternative I

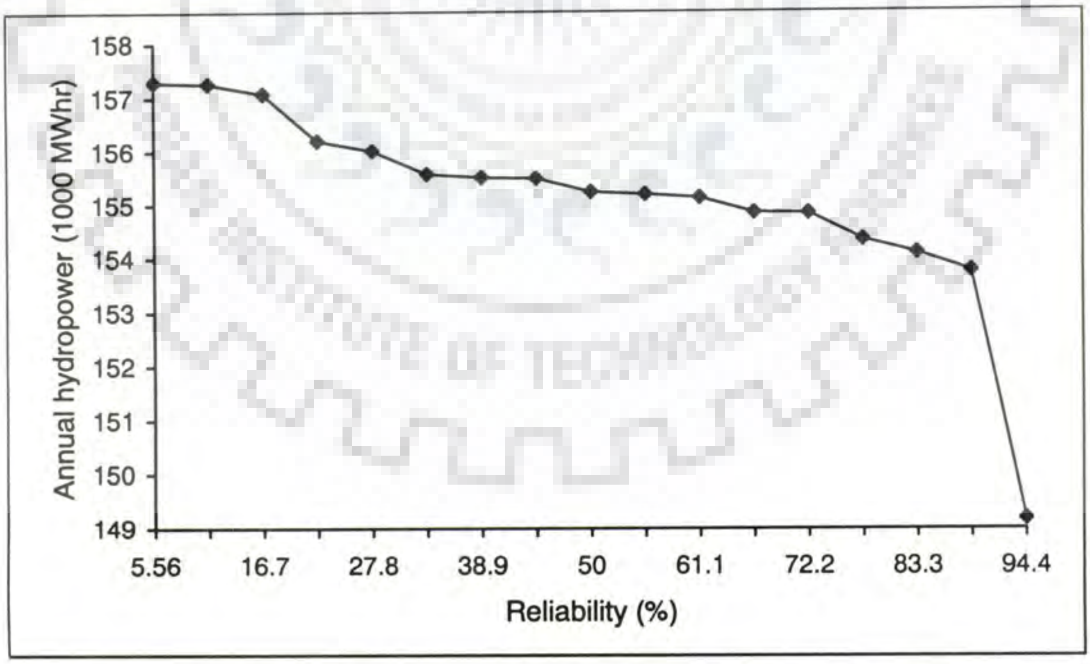

**Figure 9.1 (J)** Achieved annual hydropower yield from GS reservoir for different reliabilities for Link Alternative II, for all cases

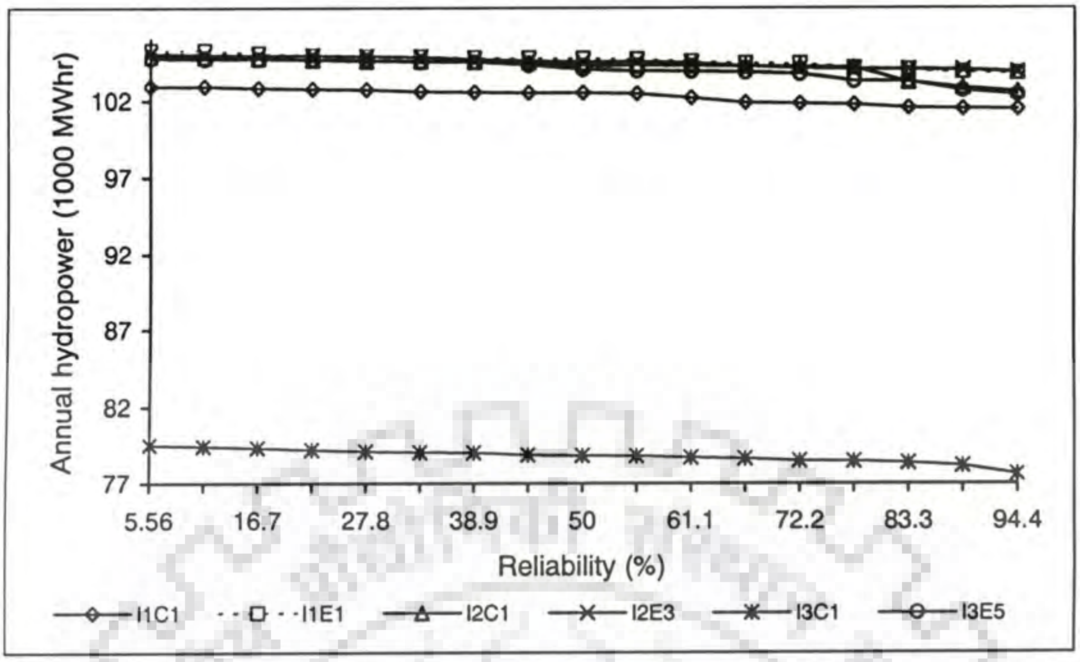

**Figure 9.1 (k)** Achieved annual hydropower yield from RPS reservoir for different reliabilities for Link Alternative I

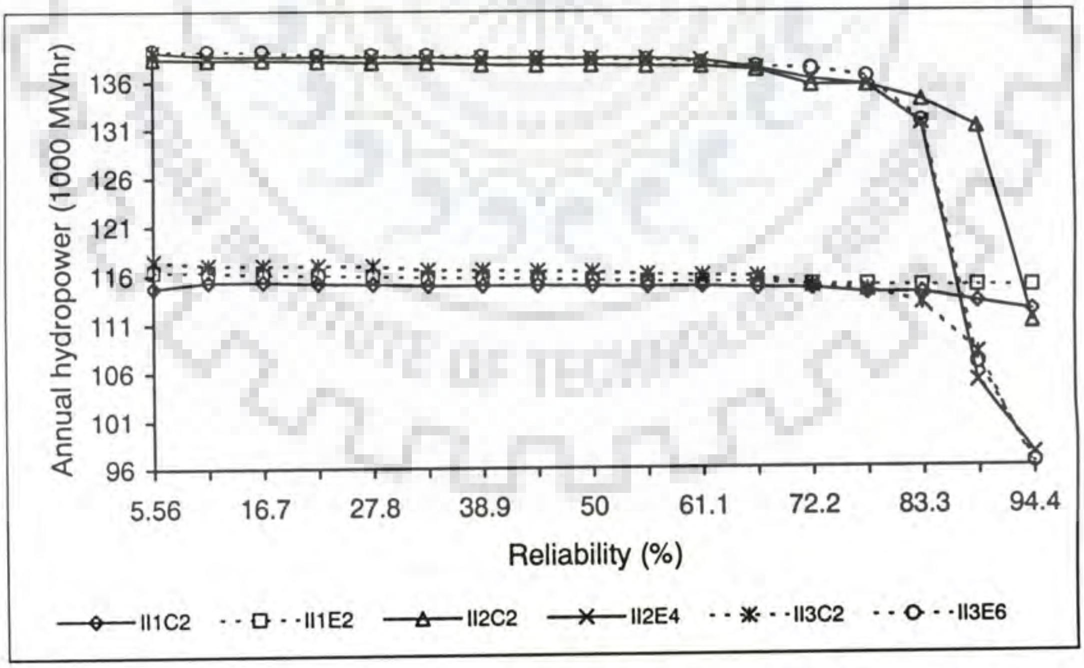

**Figure 9.1 (l)** Achieved annual hydropower yield from RPS reservoir for different reliabilities for Link Alternative II

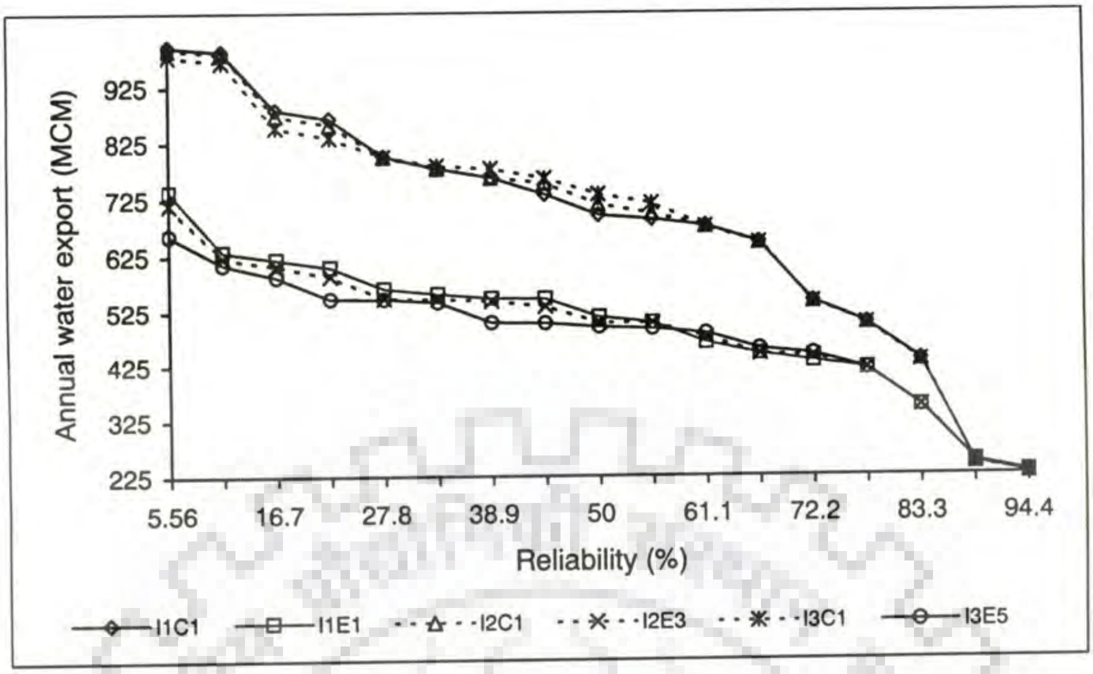

**Figure 9.1 (m)** Achieved annual water export from PAT reservoir for different reliabilities for Link Alternative I

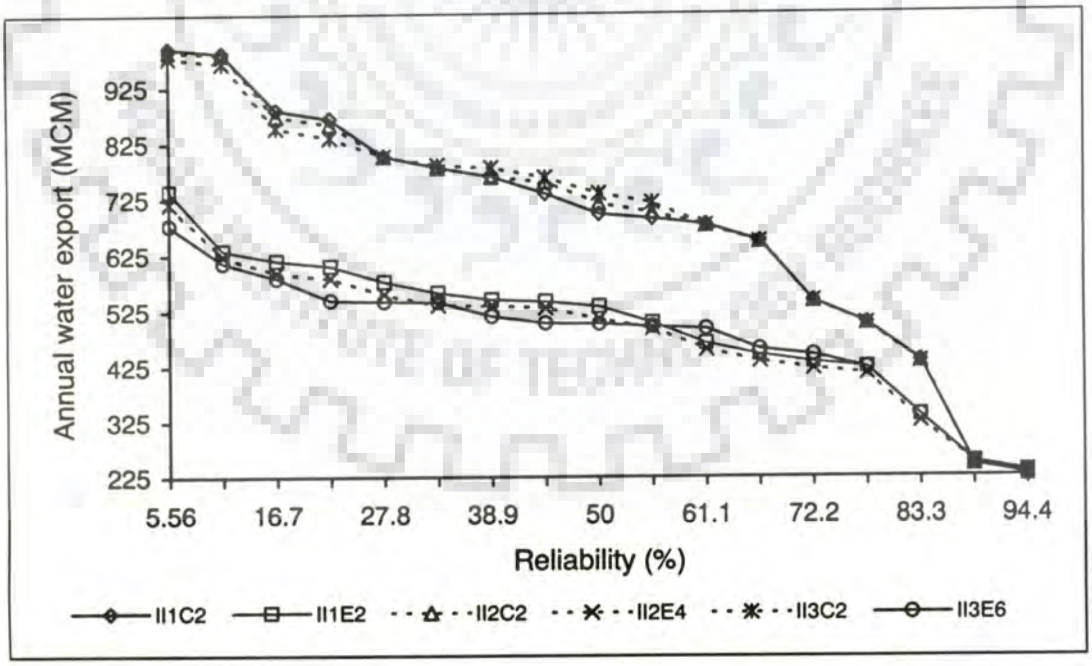

**Figure 9.1 (n)** Achieved annual water export from PAT reservoir for different reliabilities for Link Alternative II

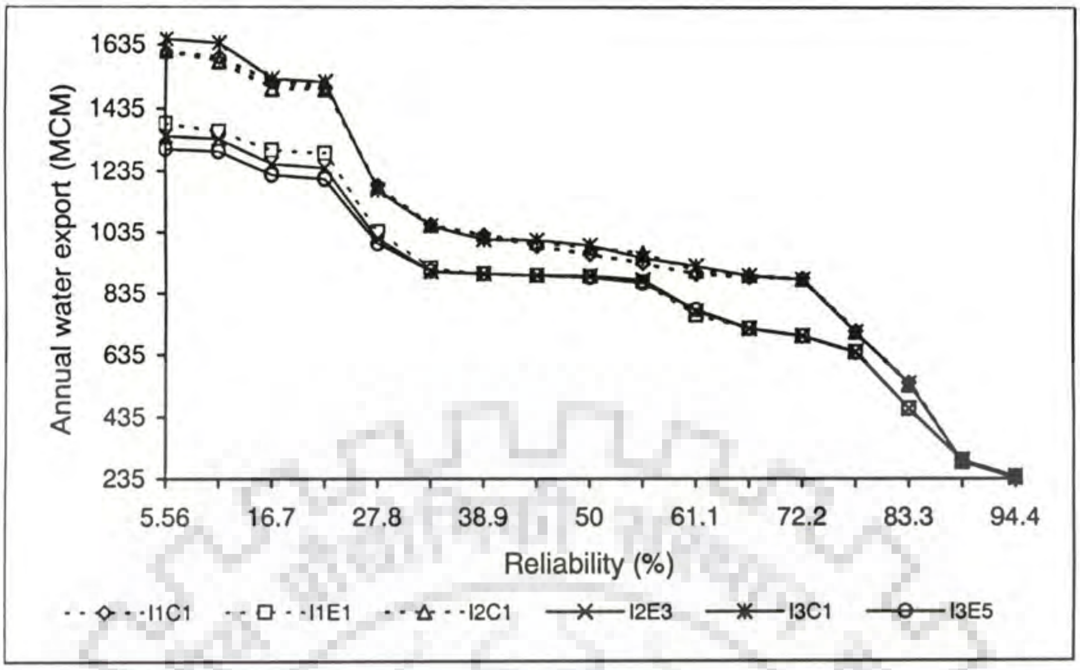

**Figure 9.1 (o)** Achieved annual water export from MOH reservoir for different reliabilities for Link Alternative I

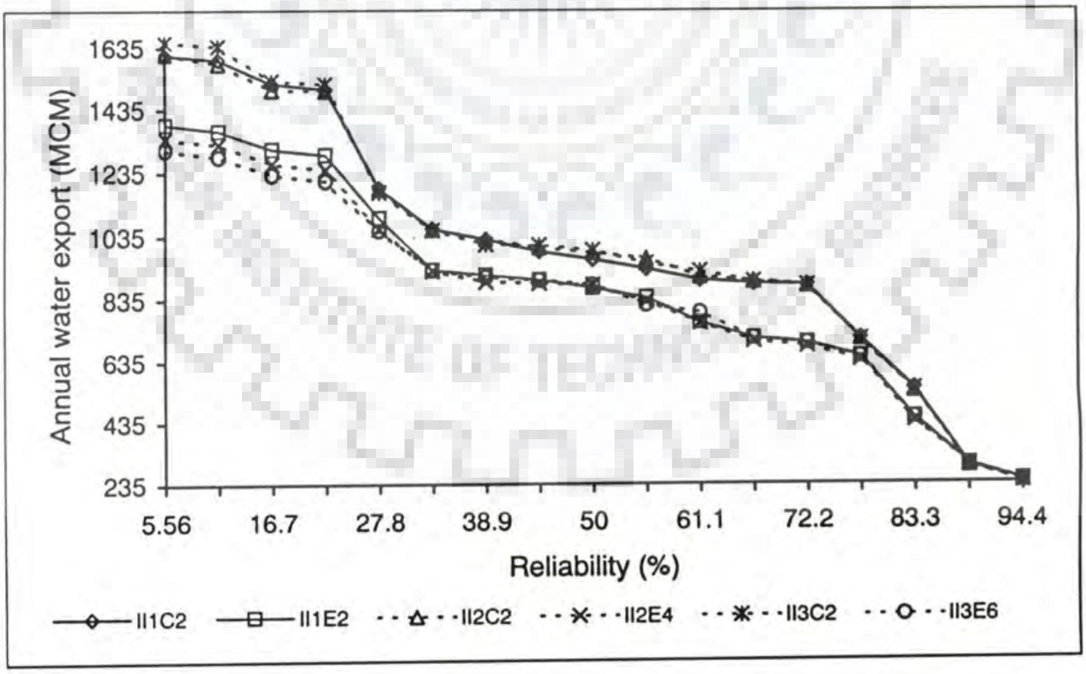

**Figure 9.1 (p)** Achieved annual water export from MOH reservoir for different reliabilities for Link Alternative II

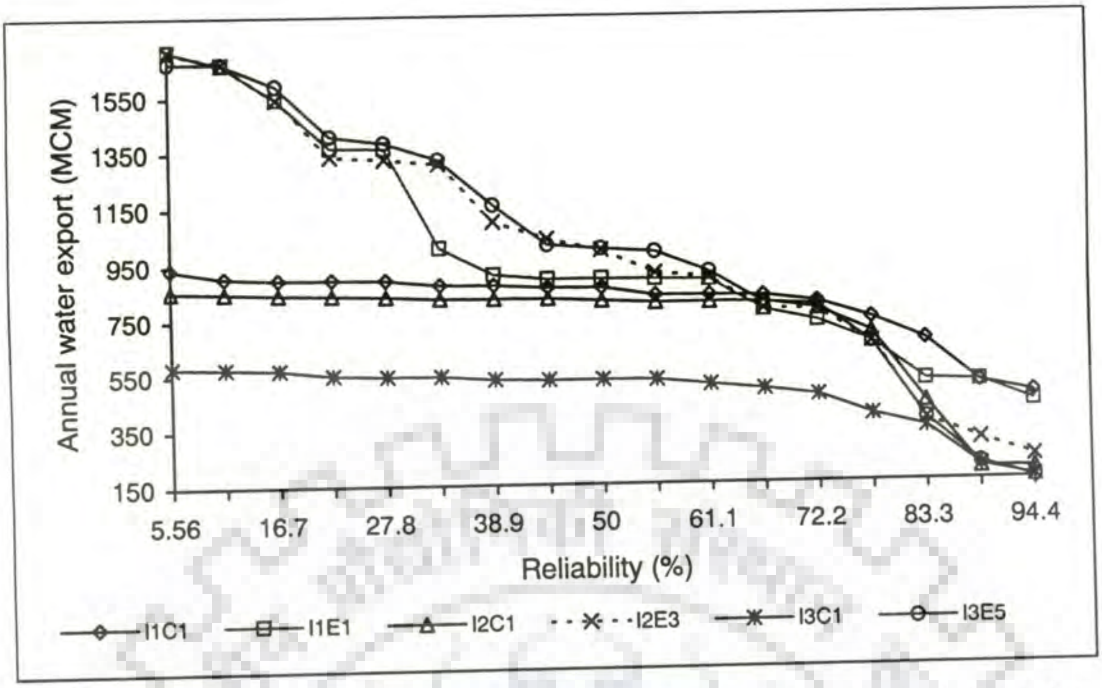

**Figure 9.1 (q)** Achieved annual water export from KUN reservoir for different reliabilities for Link Alternative I

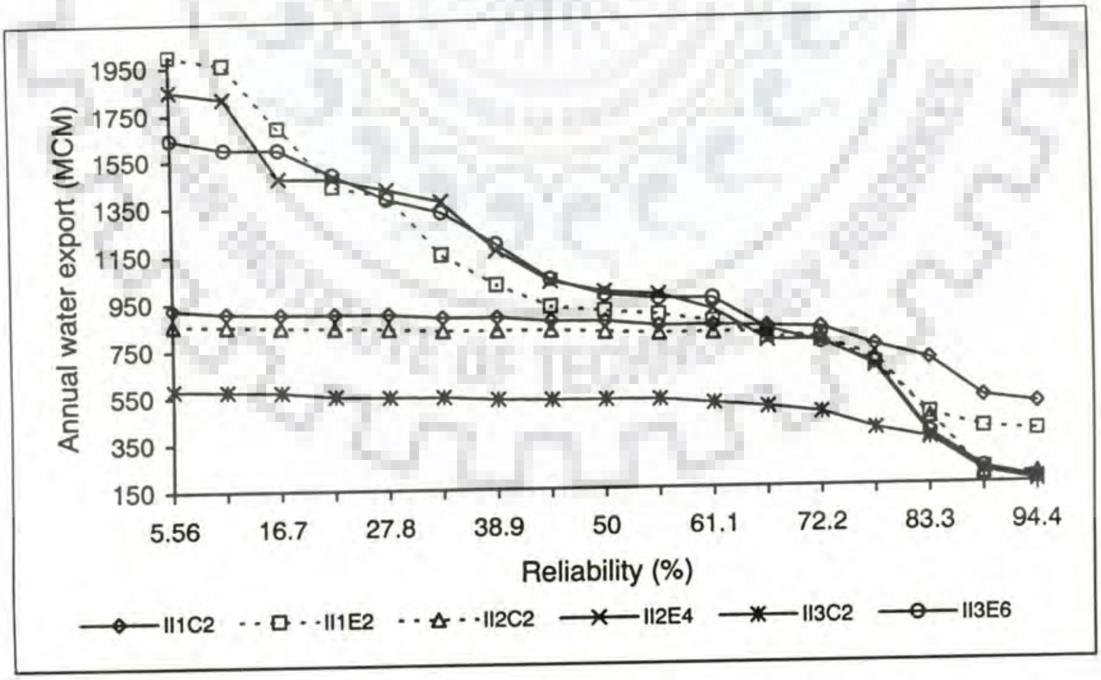

**Figure 9.1 (r)** Achieved annual water export from KUN reservoir for different reliabilities for Link Alternative II

**Table 9.2** Achieved annual system yield for irrigation obtained for different reliabilities through reservoir operation by CIM

| Reli. (%) | Achieved annual system yield for irrigation (MCM) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | CASES | | | | | | | |
| | I1A1 | I1B1 | I1C1 | I1D | I1E1 | I2A1 | I2B1 | I2C1 | I2D | I2E3 | I3A1 | I3B1 | I3C1 | I3D | I3E5 |
| 6 | 3855.95 | 3855.68 | 3862.31 | 3855.68 | 3855.95 | 3855.39 | 3855.25 | 3867.27 | 3855.25 | 3855.39 | 3856.18 | 3856.18 | 3884.59 | 3856.18 | 3856.18 |
| 11 | 3854.07 | 3854.09 | 3862.19 | 3854.09 | 3854.53 | 3854.37 | 3854.37 | 3866.62 | 3854.37 | 3854.37 | 3855.97 | 3855.97 | 3883.22 | 3855.97 | 3855.97 |
| 17 | 3853.89 | 3854.03 | 3861.92 | 3853.91 | 3853.89 | 3853.11 | 3853.08 | 3866.35 | 3853.08 | 3853.08 | 3855.94 | 3855.94 | 3883.06 | 3855.94 | 3855.94 |
| 22 | 3853.87 | 3853.91 | 3861.74 | 3853.89 | 3853.43 | 3853.08 | 3852.93 | 3866.12 | 3852.93 | 3852.92 | 3855.71 | 3855.71 | 3882.33 | 3855.71 | 3855.65 |
| 28 | 3853.23 | 3853.91 | 3861.27 | 3853.87 | 3853.24 | 3852.93 | 3852.57 | 3865.38 | 3852.57 | 3852.57 | 3853.64 | 3851.70 | 3881.88 | 3851.70 | 3853.64 |
| 33 | 3852.91 | 3853.23 | 3861.26 | 3853.23 | 3853.23 | 3852.57 | 3851.62 | 3865.05 | 3851.62 | 3851.62 | 3851.70 | 3849.92 | 3881.05 | 3849.92 | 3851.70 |
| 39 | 3852.77 | 3853.22 | 3860.56 | 3853.22 | 3852.52 | 3851.62 | 3851.22 | 3864.79 | 3851.22 | 3851.46 | 3849.08 | 3848.12 | 3878.18 | 3848.12 | 3851.14 |
| 44 | 3852.62 | 3853.21 | 3860.39 | 3853.21 | 3849.88 | 3851.22 | 3851.20 | 3864.72 | 3851.17 | 3851.22 | 3848.12 | 3848.04 | 3877.81 | 3848.04 | 3849.92 |
| 50 | 3852.29 | 3852.62 | 3860.37 | 3852.62 | 3847.62 | 3851.17 | 3851.17 | 3864.28 | 3850.45 | 3851.17 | 3848.05 | 3847.89 | 3877.32 | 3847.89 | 3849.50 |
| 56 | 3849.92 | 3852.29 | 3856.69 | 3852.29 | 3847.19 | 3850.45 | 3850.45 | 3863.46 | 3850.43 | 3850.45 | 3848.04 | 3847.60 | 3876.68 | 3847.60 | 3848.12 |
| 61 | 3848.38 | 3850.09 | 3856.31 | 3850.09 | 3845.75 | 3848.44 | 3850.43 | 3862.04 | 3849.88 | 3845.32 | 3847.89 | 3846.74 | 3875.62 | 3846.74 | 3848.04 |
| 67 | 3847.62 | 3848.94 | 3854.15 | 3848.94 | 3845.07 | 3845.79 | 3847.50 | 3861.77 | 3847.50 | 3844.81 | 3846.74 | 3846.31 | 3871.88 | 3846.67 | 3846.31 |
| 72 | 3846.78 | 3847.62 | 3854.14 | 3847.62 | 3844.82 | 3845.32 | 3847.20 | 3861.55 | 3847.20 | 3843.44 | 3846.31 | 3845.95 | 3870.96 | 3846.31 | 3845.95 |
| 78 | 3846.31 | 3846.65 | 3853.93 | 3846.65 | 3843.68 | 3843.93 | 3845.32 | 3859.71 | 3845.32 | 3842.98 | 3844.57 | 3844.57 | 3867.64 | 3845.95 | 3844.57 |
| 83 | 3840.09 | 3844.01 | 3852.76 | 3844.01 | 3840.09 | 3843.69 | 3845.32 | 3859.38 | 3845.32 | 3839.03 | 3840.54 | 3842.94 | 3865.75 | 3844.57 | 3841.79 |
| 89 | 3837.98 | 3840.09 | 3851.11 | 3840.09 | 3837.93 | 3843.45 | 3843.93 | 3859.03 | 3843.93 | 3825.56 | 3840.35 | 3836.23 | 3864.73 | 3842.94 | 3840.54 |
| 94 | 3824.98 | 3837.98 | 3835.44 | 3837.98 | 3824.98 | 3825.56 | 3840.64 | 3853.57 | 3840.64 | 3824.77 | 3833.07 | 3833.07 | 3829.50 | 3833.07 | 3833.07 |
| Reli. (%) | II1A2 | II1B2 | II1C2 | II1D | II1E2 | II2A2 | II2B2 | II2C2 | II2D | II2E4 | II3A2 | II3B2 | II3C2 | II3D | II3E6 |
| 6 | 3426.84 | 3424.86 | 3428.19 | 3424.86 | 3425.79 | 3426.39 | 3426.22 | 3442.53 | 3427.29 | 3426.22 | 3430.24 | 3430.24 | 3441.70 | 3430.24 | 3430.24 |
| 11 | 3423.56 | 3423.56 | 3426.08 | 3423.56 | 3423.56 | 3426.22 | 3424.97 | 3441.83 | 3426.26 | 3426.09 | 3427.10 | 3427.10 | 3440.53 | 3427.10 | 3427.10 |
| 17 | 3422.79 | 3423.07 | 3425.99 | 3423.07 | 3422.79 | 3424.68 | 3424.68 | 3439.36 | 3425.35 | 3424.68 | 3426.15 | 3426.15 | 3438.65 | 3426.15 | 3426.15 |
| 22 | 3422.47 | 3422.47 | 3425.76 | 3422.47 | 3422.47 | 3423.38 | 3423.38 | 3439.28 | 3424.20 | 3423.38 | 3423.15 | 3423.15 | 3437.83 | 3423.15 | 3423.47 |
| 28 | 3421.70 | 3421.70 | 3425.05 | 3421.70 | 3421.70 | 3423.22 | 3423.22 | 3438.62 | 3423.40 | 3423.22 | 3422.73 | 3422.73 | 3435.81 | 3422.73 | 3423.15 |
| 33 | 3421.12 | 3421.12 | 3424.65 | 3421.12 | 3421.27 | 3423.02 | 3423.02 | 3438.02 | 3423.24 | 3423.02 | 3422.51 | 3422.51 | 3433.27 | 3422.51 | 3422.51 |
| 39 | 3420.30 | 3420.30 | 3424.25 | 3420.30 | 3420.24 | 3420.92 | 3420.92 | 3437.99 | 3422.56 | 3420.92 | 3421.38 | 3421.38 | 3433.26 | 3421.38 | 3421.38 |
| 44 | 3420.14 | 3420.14 | 3424.00 | 3420.14 | 3420.14 | 3420.47 | 3420.47 | 3437.41 | 3420.78 | 3420.47 | 3421.18 | 3421.18 | 3432.82 | 3421.18 | 3421.18 |
| 50 | 3418.78 | 3418.97 | 3423.73 | 3418.97 | 3418.00 | 3419.97 | 3419.97 | 3436.83 | 3420.32 | 3419.97 | 3420.78 | 3420.78 | 3432.81 | 3420.78 | 3420.78 |
| 56 | 3418.67 | 3418.78 | 3423.19 | 3418.78 | 3418.00 | 3418.94 | 3418.94 | 3436.60 | 3420.26 | 3418.94 | 3417.55 | 3417.55 | 3432.47 | 3417.55 | 3417.55 |
| 61 | 3418.32 | 3418.32 | 3421.95 | 3418.32 | 3415.80 | 3416.51 | 3416.51 | 3433.89 | 3416.10 | 3416.23 | 3417.49 | 3417.49 | 3432.40 | 3417.49 | 3417.49 |
| 67 | 3418.00 | 3418.00 | 3421.13 | 3418.00 | 3414.69 | 3414.65 | 3414.65 | 3431.17 | 3416.07 | 3414.65 | 3415.57 | 3415.57 | 3429.95 | 3415.57 | 3415.57 |
| 72 | 3412.74 | 3411.67 | 3416.08 | 3411.67 | 3412.74 | 3414.19 | 3414.19 | 3431.03 | 3413.48 | 3414.19 | 3414.40 | 3414.40 | 3428.13 | 3414.40 | 3414.40 |
| 78 | 3409.92 | 3409.92 | 3415.54 | 3409.92 | 3409.92 | 3411.37 | 3411.37 | 3430.66 | 3411.44 | 3411.37 | 3412.79 | 3412.79 | 3425.50 | 3412.79 | 3412.79 |
| 83 | 3403.02 | 3406.82 | 3409.34 | 3406.82 | 3403.88 | 3408.09 | 3408.09 | 3422.29 | 3408.10 | 3408.09 | 3396.45 | 3396.45 | 3417.25 | 3396.45 | 3396.45 |
| 89 | 3395.89 | 3395.89 | 3395.96 | 3395.89 | 3398.33 | 3398.87 | 3398.87 | 3408.73 | 3395.97 | 3399.78 | 3396.21 | 3396.21 | 3412.52 | 3396.21 | 3396.21 |
| 94 | 3375.78 | 3375.78 | 3377.41 | 3375.78 | 3375.78 | 3376.48 | 3376.48 | 3386.99 | 3376.78 | 3376.48 | 3370.86 | 3370.86 | 3385.58 | 3370.86 | 3370.86 |

**Table 9.3** Achieved annual system yield for hydropower obtained for different reliabilities through reservoir operation by CIM

| Reli. (%) | Achieved annual system yield for hydropower (1000 MWhr) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CASES | | | | | | | | | | | | | | |
| | I1A1 | I1B1 | I1C1 | I1D | I1E1 | I2A1 | I2B1 | I2C1 | I2D | I2E3 | I3A1 | I3B1 | I3C1 | I3D | I3E5 |
| 6 | 309.67 | 309.67 | 304.07 | 309.76 | 309.42 | 309.58 | 309.59 | 304.99 | 309.59 | 309.58 | 309.08 | 309.08 | 262.29 | 309.08 | 309.08 |
| 11 | 309.28 | 309.25 | 300.64 | 309.71 | 309.28 | 308.95 | 308.95 | 304.55 | 308.95 | 308.95 | 308.75 | 308.21 | 262.00 | 308.21 | 308.75 |
| 17 | 308.53 | 308.32 | 300.27 | 308.46 | 309.15 | 308.45 | 308.07 | 302.65 | 308.07 | 308.45 | 308.21 | 307.85 | 261.93 | 307.67 | 308.46 |
| 22 | 308.05 | 308.07 | 299.40 | 308.18 | 308.05 | 307.85 | 307.92 | 302.61 | 307.92 | 307.92 | 307.18 | 307.18 | 261.72 | 307.18 | 308.21 |
| 28 | 307.98 | 307.98 | 298.93 | 307.50 | 307.98 | 307.62 | 307.62 | 302.48 | 307.62 | 307.62 | 306.58 | 306.31 | 261.53 | 306.31 | 307.18 |
| 33 | 306.66 | 306.66 | 298.93 | 307.16 | 306.66 | 307.16 | 307.34 | 302.37 | 307.34 | 307.16 | 306.31 | 305.95 | 261.39 | 305.95 | 306.37 |
| 39 | 306.40 | 306.13 | 297.81 | 307.05 | 306.13 | 306.72 | 307.16 | 302.32 | 307.16 | 306.54 | 306.21 | 305.75 | 261.38 | 305.75 | 306.31 |
| 44 | 306.13 | 305.74 | 297.52 | 306.01 | 305.56 | 305.99 | 306.72 | 302.14 | 306.72 | 305.56 | 304.45 | 305.65 | 261.20 | 305.65 | 304.25 |
| 50 | 306.06 | 305.16 | 297.38 | 305.81 | 305.52 | 305.66 | 306.65 | 300.08 | 306.65 | 305.14 | 304.32 | 304.59 | 260.92 | 304.59 | 304.09 |
| 56 | 305.41 | 304.94 | 296.70 | 305.23 | 305.01 | 305.13 | 306.61 | 299.93 | 306.61 | 305.01 | 304.14 | 304.03 | 259.68 | 304.03 | 304.03 |
| 61 | 304.74 | 304.71 | 296.55 | 304.72 | 304.74 | 304.57 | 306.13 | 299.80 | 306.13 | 304.57 | 304.03 | 303.85 | 258.87 | 303.97 | 303.85 |
| 67 | 304.44 | 304.51 | 296.15 | 304.40 | 304.37 | 303.60 | 304.57 | 299.66 | 304.57 | 304.53 | 303.85 | 303.49 | 258.86 | 303.85 | 303.66 |
| 72 | 303.77 | 304.36 | 295.05 | 304.38 | 303.99 | 302.96 | 303.66 | 299.18 | 303.66 | 303.26 | 300.19 | 303.48 | 257.88 | 303.49 | 303.12 |
| 78 | 302.67 | 303.97 | 294.39 | 304.37 | 302.86 | 301.97 | 303.37 | 298.71 | 303.56 | 302.70 | 298.51 | 302.57 | 257.40 | 302.57 | 302.68 |
| 83 | 301.81 | 303.39 | 294.16 | 304.36 | 302.67 | 301.83 | 303.10 | 297.86 | 303.10 | 302.66 | 297.89 | 302.06 | 257.02 | 302.06 | 297.89 |
| 89 | 300.43 | 303.11 | 287.61 | 303.52 | 300.73 | 298.87 | 302.85 | 297.82 | 302.85 | 301.83 | 295.49 | 297.89 | 255.00 | 297.89 | 297.72 |
| 94 | 298.00 | 301.13 | 285.06 | 302.41 | 299.67 | 297.95 | 299.91 | 294.07 | 299.91 | 298.72 | 294.05 | 295.49 | 254.00 | 295.49 | 295.47 |
| Reli. (%) | II1A2 | II1B2 | II1C2 | II1D | II1E2 | II2A2 | II2B2 | II2C2 | II2D | II2E4 | II3A2 | II3B2 | II3C2 | II3D | II3E6 |
| 6 | 273.32 | 273.33 | 272.45 | 273.33 | 273.32 | 295.93 | 295.93 | 295.36 | 296.04 | 295.93 | 296.09 | 296.09 | 274.36 | 296.09 | 296.09 |
| 11 | 272.80 | 272.98 | 272.42 | 272.98 | 272.80 | 295.80 | 295.74 | 295.33 | 295.74 | 295.80 | 295.93 | 295.93 | 274.07 | 295.92 | 295.93 |
| 17 | 272.55 | 272.80 | 271.82 | 272.80 | 272.57 | 295.74 | 295.61 | 294.91 | 295.69 | 295.74 | 295.37 | 295.37 | 273.67 | 295.37 | 295.30 |
| 22 | 271.71 | 272.56 | 271.55 | 272.56 | 272.56 | 294.87 | 294.87 | 294.39 | 294.79 | 294.87 | 295.21 | 295.21 | 273.65 | 295.21 | 295.21 |
| 28 | 271.50 | 271.50 | 270.83 | 271.50 | 271.50 | 294.48 | 294.48 | 293.91 | 294.63 | 294.48 | 294.67 | 294.67 | 272.54 | 294.68 | 294.67 |
| 33 | 271.26 | 271.26 | 270.36 | 271.26 | 271.26 | 294.29 | 294.29 | 293.76 | 294.33 | 294.25 | 294.45 | 294.45 | 272.10 | 294.45 | 294.30 |
| 39 | 271.01 | 271.18 | 270.14 | 271.18 | 270.95 | 294.25 | 294.25 | 293.75 | 294.16 | 294.02 | 294.30 | 294.30 | 272.01 | 294.30 | 294.30 |
| 44 | 270.95 | 270.97 | 270.06 | 270.97 | 270.95 | 294.02 | 294.02 | 293.14 | 293.98 | 294.00 | 294.30 | 294.30 | 271.79 | 294.30 | 294.17 |
| 50 | 270.95 | 270.95 | 269.64 | 270.95 | 270.91 | 293.55 | 293.55 | 292.06 | 293.07 | 293.55 | 293.20 | 293.20 | 270.72 | 293.20 | 293.20 |
| 56 | 270.79 | 270.95 | 269.44 | 270.95 | 270.49 | 292.37 | 292.37 | 291.94 | 292.35 | 292.37 | 292.29 | 292.29 | 270.12 | 292.29 | 292.09 |
| 61 | 270.53 | 270.51 | 269.26 | 270.51 | 270.42 | 291.78 | 291.78 | 291.52 | 291.91 | 291.78 | 291.69 | 291.69 | 270.03 | 291.69 | 291.69 |
| 67 | 270.50 | 269.70 | 269.03 | 269.70 | 270.28 | 291.07 | 291.07 | 290.82 | 291.24 | 291.07 | 291.68 | 291.68 | 269.80 | 291.68 | 291.68 |
| 72 | 269.58 | 269.56 | 268.93 | 269.56 | 269.68 | 289.76 | 289.76 | 290.47 | 289.61 | 289.76 | 291.38 | 291.38 | 269.24 | 291.38 | 291.38 |
| 78 | 269.35 | 269.29 | 268.49 | 269.29 | 269.56 | 287.44 | 287.44 | 289.63 | 287.44 | 287.44 | 288.48 | 288.48 | 268.62 | 288.48 | 288.48 |
| 83 | 269.08 | 269.08 | 268.35 | 269.08 | 269.08 | 286.79 | 286.79 | 287.01 | 287.05 | 286.79 | 287.02 | 287.02 | 266.14 | 287.02 | 287.02 |
| 89 | 268.83 | 268.84 | 267.80 | 268.84 | 268.62 | 269.05 | 281.54 | 285.33 | 280.30 | 260.50 | 272.55 | 282.30 | 261.94 | 282.30 | 262.37 |
| 94 | 264.91 | 265.60 | 264.13 | 265.60 | 265.08 | 253.48 | 253.48 | 266.25 | 254.91 | 252.59 | 251.67 | 251.67 | 250.94 | 251.67 | 251.67 |

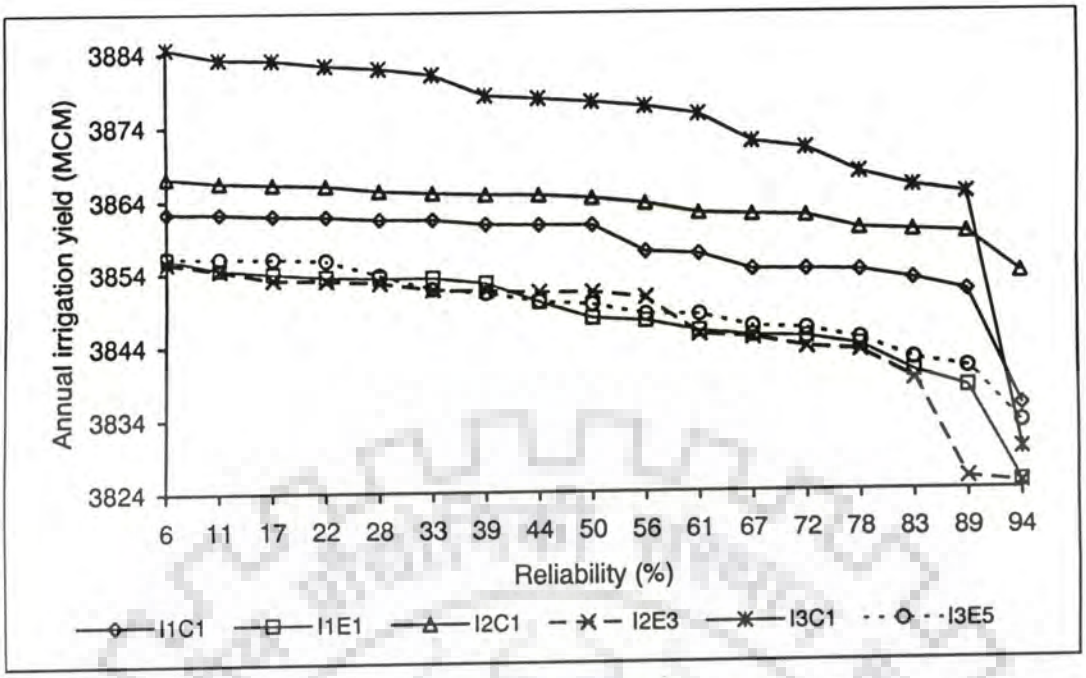

**Figure 9.2 (a)** Achieved annual system irrigation yield for different reliabilities for Link Alternative I

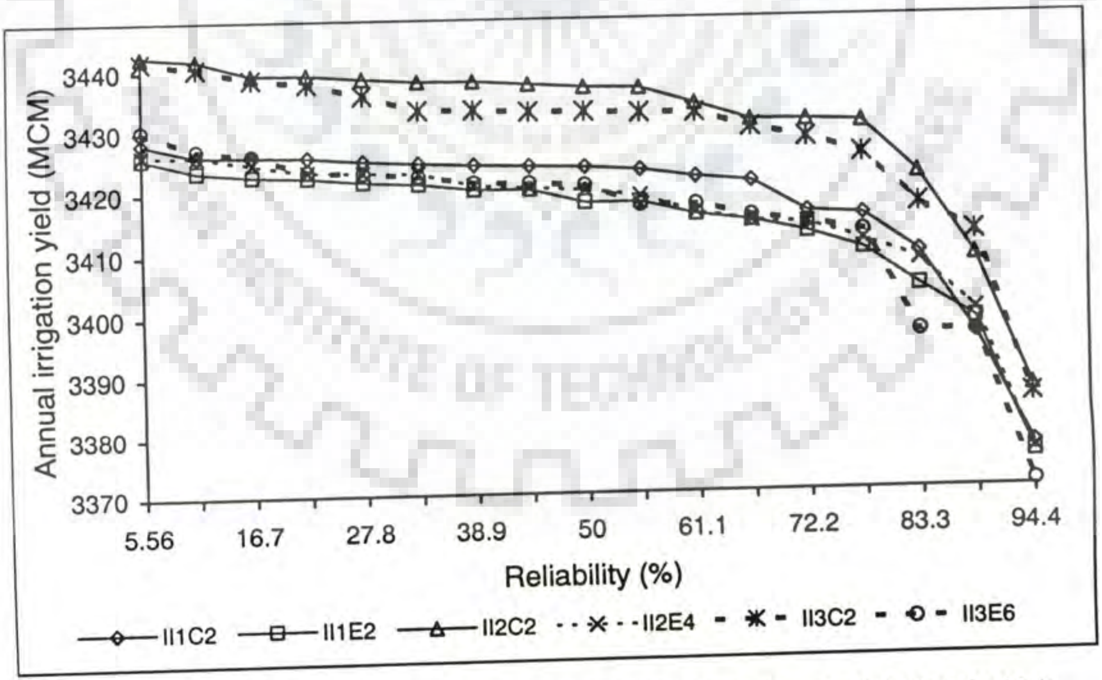

**Figure 9.2 (b)** Achieved annual system irrigation yield for different reliabilities for Link Alternative II

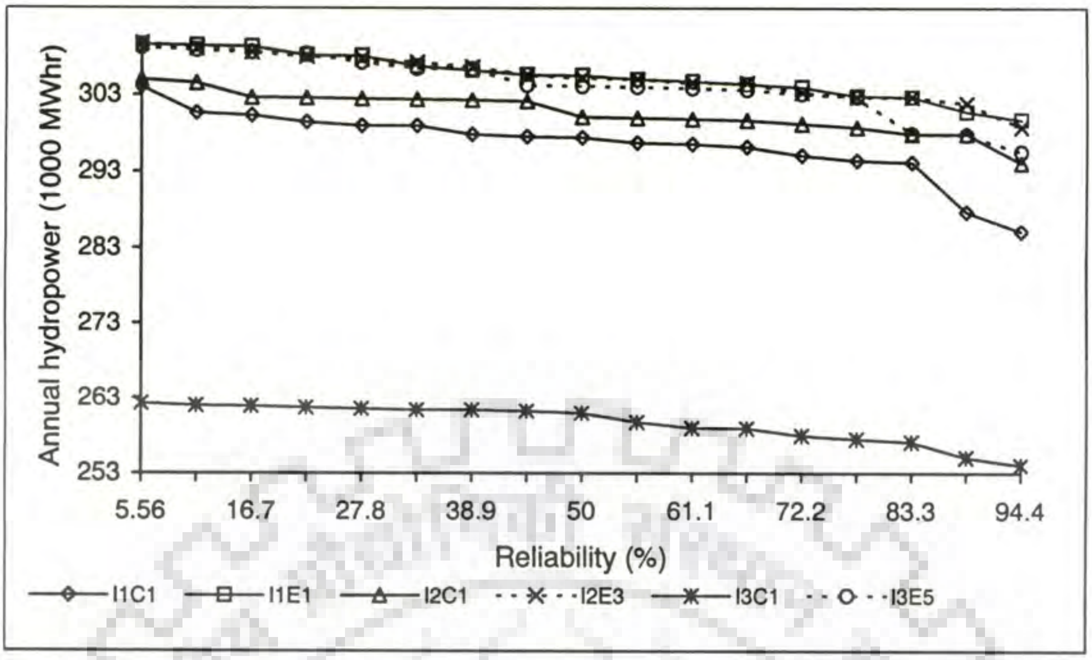

**Figure 9.3 (a)** Achieved annual system hydropower yield for different reliabilities for Link Alternative I

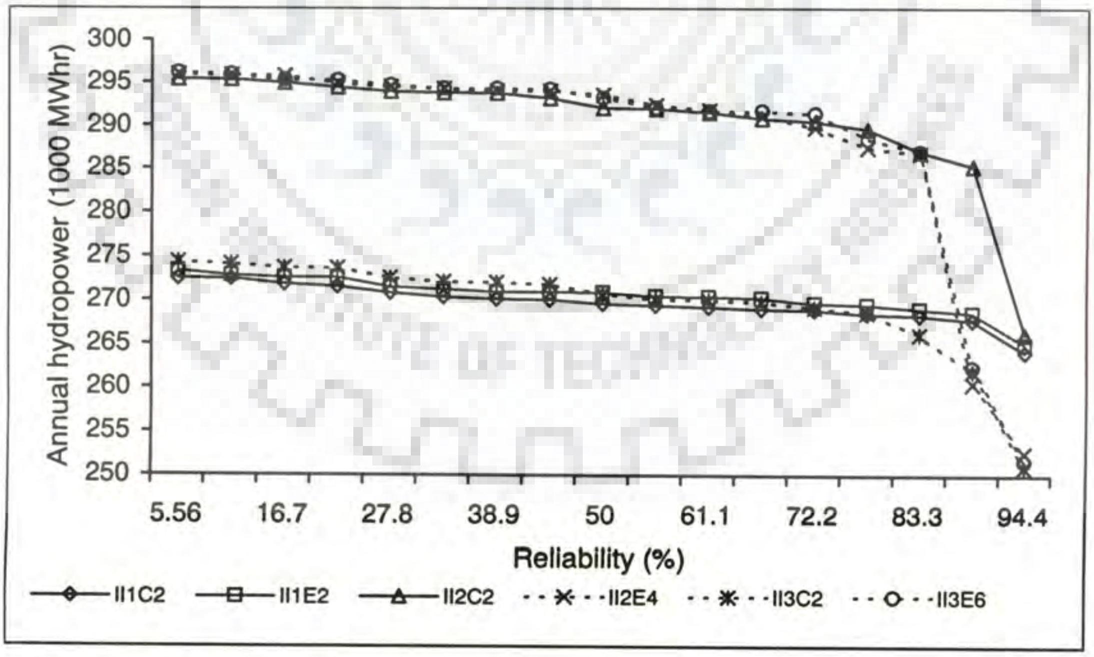

**Figure 9.3 (b)** Achieved annual system hydropower yield for different reliabilities for Link Alternative II

## 9.3 RESERVOIR OPERATION BY SIMULATION

The simulation model is applied for the cases I1E1, II1E2, I1C1, II1C2, I2E3, II2E4, I2C1, II2C2, I3E5, II3E6, I3C1 and II3C2, defined in Table 8.14. Reservoir capacity-area curves and capacity-elevation curves (Annexure-II) are used for reservoir surface area calculations and reservoir elevation calculations, respectively. The monthly design water demands obtained in reservoir planning by the application of CIM in Chapter 8 are taken as the target demands for domestic water supply, irrigation and energy for PAT, MOH, KUN and RPS reservoirs. The monthly fractions of the design water export demands are kept same as obtained in the planning stage, and the annual target water export demands for all the water exporting reservoirs are fixed by trial and error method. The maximum target water export demands, for which the achieved reliabilities for domestic water supply and irrigation do not fall below their corresponding target annual reliabilities, are adopted. The water transfer loss from an upper reservoir u to a reservoir i, $TL_{i,t}^{iu,u}$, is assumed equal to zero. Productive storage head of a hydropower-producing reservoir is calculated by subtracting the tail water level from reservoir elevation. The reservoir elevation is taken with respect to the initial storage at any stage. Due to curse of dimensionality in CIM application, the storage increment adopted for GS reservoir was 60 MCM. Compared to the storage capacity of GS reservoir, a storage increment of 60 MCM seems to be acceptable. But compared to the water demands at some stages (months), this storage increment is very high. Therefore irrigation yield obtained from the IGPYM results are taken as target irrigation demands for GS reservoir in simulation. The monthly fractions of annual energy are taken from CIM results.

In Link Alternative II, there is no water import to GS reservoir, i.e., the reservoir is not affected by any outside influences, and hence the irrigation and energy yields from the reservoir are same for all the cases for all the years. The achieved annual yields for different water uses are obtained from simulation results for different reliabilities and are presented in

Table 9.4 (a) to Table 9.4 (i). The achieved annual system yields for irrigation and hydropower obtained for different reliabilities for different cases are shown in Table 9.5 (a) and Table 9.5 (b), respectively. It is observed that the irrigation yields from GS reservoir for all the cases under Link Alternative I are almost same. To calculate the annual irrigation yields corresponding to different reliabilities, the irrigation yields from proposed reservoirs are added year-wise and then arranged in descending order of magnitude. The achieved annual irrigation yields at different reliabilities from the proposed reservoirs are presented in Table 9.6. The achieved annual system irrigation yields obtained for different reliabilities for different cases are presented in Fig. 9.4 (a) and Fig. 9.4 (b) for Link Alternatives I and II, respectively. The achieved annual system hydropower yields obtained for different reliabilities for different cases are presented in Fig. 9.5 (a) and Fig. 9.5 (b) for Link Alternatives I and II, respectively.

Analysis of simulation results shows the following:

(i) The maximum annual irrigation deficits in percentage in reservoirs in the system are

(a) 11, 10 and 7 for GS, GS and PAT in cases I1C1, I2C1 and I3C1, respectively;

(b) 9, 7 and 7 for GS, PAT and PAT in cases I1E1, I2E3 and I3E5, respectively;

(c) 10 for GS in cases II1C2, II2C2 and II3C2, respectively; and

(d) 7 for PAT in cases II1E2, II2E4 and II3E6, respectively.

(ii) It is observed that the irrigation yield from GS reservoir fails completely in some of the early monsoon and late non-monsoon months in some cases. The percentages of occurrence of complete irrigation failure months in GS reservoir are

(a) 2, 2, and 1 in cases I1C1, I2C1 and I3C1, respectively;

(b) 0.5 in Case-I1E1; and

(c) 2 in cases II1C2, II2C2 and II3C2.

(iii) A deficit of 98% in monthly design irrigation yield occurs in a single early monsoon month from PAT reservoir in cases of I1E1, I2E3, I3E5, II1E2, II2E4 and II3E6.

(iv) The number of spilling months from GS reservoir is three in cases I1E1, I2E3 and I3E5. For all other cases, the number of spilling month from GS reservoir is one.

(v) The number of spilling months is maximum from RPS reservoir out of all the reservoirs for all the cases.

(vi) Among the proposed reservoirs, the numbers of spilling months from PAT reservoir are minimum in canal capacity option C (C1 and C2, around 3%), and are maximum in canal capacity option E (E1, E2, E3, E4, E5 and E6; around 11%). The number of spilling months from MOH reservoir is around 5% in all the cases. For KUN reservoir, the numbers of spilling months are maximum in canal capacity option C (C1 and C2, around 14%), and are minimum in canal capacity option E (E1, E2, E3, E4, E5 and E6; around 3%).

(vii) All the spills from PAT, MOH, KUN and GS reservoirs occur during monsoon months, mainly confining in the late monsoon months. From RPS reservoir, major spills occur during monsoon months, some spills during early non-monsoon months and rarely in middle of non-monsoon period.

**Table 9.4 (a)** Achieved annual yields for irrigation (MCM) obtained from simulation from PAT reservoir

| Reli. (%) | Achieved annual yield for irrigation from PAT reservoir (MCM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cases | | | | | | | | | | | |
| | I1C1 | I1E1 | I2C1 | I2E3 | I3C1 | I3E5 | II1C2 | II1E2 | II2C2 | II2E4 | II3C2 | II3E6 |
| 6 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 11 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 17 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 22 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 28 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 33 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 39 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 44 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 50 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 56 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 61 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 67 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 72 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 78 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 83 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 | 136.98 | 133.69 | 136.98 | 133.69 | 136.97 | 133.69 |
| 89 | 128.54 | 129.65 | 136.74 | 133.69 | 136.97 | 133.69 | 128.54 | 127.28 | 136.74 | 133.69 | 136.97 | 133.69 |
| 94 | 127.49 | 124.26 | 127.60 | 124.20 | 127.47 | 124.24 | 127.49 | 124.29 | 127.60 | 124.23 | 127.47 | 124.30 |

**Table 9.4 (b)** Achieved annual yields for irrigation (MCM) obtained from simulation from MOH reservoir

| Reli. (%) | Achieved annual yield for irrigation from MOH reservoir (MCM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cases | | | | | | | | | | | |
| | I1C1 | I1E1 | I2C1 | I2E3 | I3C1 | I3E5 | II1C2 | II1E2 | II2C2 | II2E4 | II3C2 | II3E6 |
| 6 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 11 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 17 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 22 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 28 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 33 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 39 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 44 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 50 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 56 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 61 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 67 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 72 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 78 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 83 | 139.97 | 137.99 | 139.97 | 137.99 | 139.47 | 137.99 | 139.97 | 138.29 | 139.97 | 138.29 | 139.47 | 138.29 |
| 89 | 138.16 | 135.56 | 139.08 | 135.66 | 139.47 | 135.49 | 138.16 | 136.79 | 139.08 | 137.71 | 139.47 | 138.29 |
| 94 | 138.02 | 134.37 | 137.92 | 134.37 | 137.64 | 134.37 | 138.02 | 135.95 | 137.92 | 135.80 | 137.64 | 135.93 |

**Table 9.4 (c)** Achieved annual yields for irrigation (MCM) obtained from simulation from KUN reservoir

| Reli. (%) | Achieved annual yield for irrigation from KUN reservoir (MCM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cases | | | | | | | | | | | |
| | I1C1 | I1E1 | I2C1 | I2E3 | I3C1 | I3E5 | II1C2 | II1E2 | II2C2 | II2E4 | II3C2 | II3E6 |
| 6 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 11 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 17 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 22 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 28 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 33 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 39 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 44 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 50 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 56 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 61 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 67 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 72 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 78 | 313.00 | 301.98 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 303.12 | 313.00 | 304.57 | 313.00 | 307.62 |
| 83 | 313.00 | 296.19 | 313.00 | 302.15 | 313.00 | 308.19 | 313.00 | 297.94 | 313.00 | 304.57 | 313.00 | 307.62 |
| 89 | 307.64 | 286.94 | 307.44 | 296.22 | 310.04 | 303.02 | 307.64 | 294.73 | 307.44 | 300.01 | 310.04 | 305.45 |
| 94 | 303.51 | 283.32 | 307.14 | 283.49 | 307.41 | 289.53 | 303.51 | 287.81 | 307.14 | 299.70 | 307.41 | 301.94 |

**Table 9.4 (d)** Achieved annual yields for irrigation (MCM) obtained from simulation from GS reservoir

| Reli. | Achieved annual yield for irrigation from GS reservoir (MCM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cases | | | | | | | | | | | |
| (%) | I1C1 | I1E1 | I2C1 | I2E3 | I3C1 | I3E5 | II1C2 | II1E2 | II2C2 | II2E4 | II3C2 | II3E6 |
| 6 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 11 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 17 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 22 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 28 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 33 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 39 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 44 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 50 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 56 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 61 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 67 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 72 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 78 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 83 | 3363.00 | 3363.00 | 3334.71 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 | 3363.00 |
| 89 | 3301.21 | 3284.44 | 3149.43 | 3239.06 | 3337.95 | 3356.59 | 3297.52 | 3297.52 | 3297.52 | 3297.52 | 3297.52 | 3297.52 |
| 94 | 3006.40 | 3053.48 | 2954.76 | 3157.56 | 2951.39 | 3255.48 | 3029.21 | 3029.21 | 3029.21 | 3029.21 | 3029.21 | 3029.21 |

**Table 9.4 (e)** Achieved annual yields for water export (MCM) obtained from simulation from PAT reservoir

| Reli. | Achieved annual yield for water export from PAT reservoir (MCM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cases | | | | | | | | | | | |
| (%) | I1C1 | I1E1 | I2C1 | I2E3 | I3C1 | I3E5 | II1C2 | II1E2 | II2C2 | II2E4 | II3C2 | II3E6 |
| 6 | 1005.38 | 732.01 | 1003.34 | 707.58 | 999.88 | 668.95 | 1005.38 | 732.01 | 1003.34 | 707.58 | 999.88 | 669.04 |
| 11 | 988.08 | 709.45 | 977.77 | 692.06 | 973.91 | 665.34 | 988.08 | 711.87 | 977.77 | 692.13 | 973.91 | 665.34 |
| 17 | 904.57 | 596.89 | 901.98 | 566.03 | 895.85 | 527.26 | 904.57 | 596.94 | 901.98 | 569.36 | 895.85 | 531.92 |
| 22 | 869.59 | 588.46 | 867.22 | 563.48 | 867.52 | 526.77 | 869.59 | 590.88 | 867.22 | 563.54 | 867.52 | 526.91 |
| 28 | 836.29 | 570.47 | 847.69 | 555.18 | 861.51 | 517.43 | 836.29 | 570.55 | 847.69 | 555.30 | 861.51 | 517.57 |
| 33 | 772.38 | 560.80 | 762.42 | 545.64 | 773.28 | 505.73 | 772.38 | 560.88 | 762.42 | 545.75 | 773.28 | 505.82 |
| 39 | 755.32 | 522.84 | 760.90 | 511.49 | 741.34 | 491.68 | 755.32 | 525.23 | 760.90 | 514.80 | 741.34 | 496.27 |
| 44 | 749.46 | 484.35 | 747.04 | 480.09 | 741.31 | 470.75 | 749.46 | 484.43 | 747.04 | 480.21 | 741.31 | 470.89 |
| 50 | 640.20 | 438.85 | 647.17 | 422.78 | 657.81 | 399.73 | 640.20 | 438.85 | 647.17 | 422.84 | 657.81 | 399.82 |
| 56 | 616.49 | 436.10 | 623.79 | 416.35 | 628.10 | 377.74 | 616.49 | 436.15 | 623.79 | 416.35 | 628.10 | 377.74 |
| 61 | 602.72 | 378.09 | 610.02 | 364.87 | 623.20 | 355.31 | 602.72 | 378.14 | 610.02 | 364.99 | 623.20 | 355.46 |
| 67 | 588.90 | 369.25 | 586.72 | 364.77 | 585.14 | 349.95 | 588.90 | 369.33 | 586.72 | 364.84 | 585.14 | 350.10 |
| 72 | 541.93 | 345.17 | 539.40 | 341.34 | 533.40 | 335.71 | 541.93 | 345.25 | 539.40 | 341.41 | 533.40 | 335.86 |
| 78 | 481.66 | 343.63 | 470.36 | 340.91 | 453.05 | 331.59 | 481.66 | 343.68 | 470.36 | 341.03 | 453.05 | 331.74 |
| 83 | 429.82 | 330.90 | 427.67 | 326.84 | 424.31 | 317.82 | 429.82 | 330.97 | 427.67 | 326.95 | 424.31 | 317.97 |
| 89 | 249.56 | 255.74 | 258.16 | 264.76 | 271.50 | 279.97 | 249.56 | 255.76 | 258.16 | 264.80 | 271.50 | 280.00 |
| 94 | 229.66 | 231.76 | 227.64 | 229.71 | 226.15 | 226.13 | 229.66 | 231.81 | 227.64 | 229.78 | 226.15 | 226.23 |

**Table 9.4 (f)** Achieved annual yields for water export (MCM) obtained from simulation from MOH reservoir

| Reli. | Achieved annual yield for water export from MOH reservoir (MCM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cases | | | | | | | | | | | |
| (%) | I1C1 | I1E1 | I2C1 | I2E3 | I3C1 | I3E5 | II1C2 | II1E2 | II2C2 | II2E4 | II3C2 | II3E6 |
| 6 | 1701.34 | 1458.62 | 1699.42 | 1426.63 | 1718.28 | 1405.95 | 1701.34 | 1460.90 | 1699.42 | 1426.62 | 1718.28 | 1405.99 |
| 11 | 1586.12 | 1332.45 | 1581.54 | 1300.00 | 1580.45 | 1273.66 | 1586.12 | 1332.37 | 1581.54 | 1299.97 | 1580.45 | 1273.76 |
| 17 | 1522.68 | 1329.51 | 1518.21 | 1281.58 | 1516.99 | 1243.82 | 1522.68 | 1329.46 | 1518.21 | 1281.57 | 1516.99 | 1243.86 |
| 22 | 1419.24 | 1228.42 | 1424.23 | 1186.77 | 1439.53 | 1162.98 | 1419.24 | 1228.36 | 1424.23 | 1186.81 | 1439.53 | 1163.06 |
| 28 | 1295.53 | 1101.82 | 1321.67 | 1078.03 | 1340.50 | 1060.47 | 1295.53 | 1111.96 | 1321.67 | 1092.29 | 1340.50 | 1076.72 |
| 33 | 1052.15 | 892.83 | 1047.47 | 868.01 | 1044.30 | 834.96 | 1052.15 | 895.11 | 1047.47 | 871.27 | 1044.30 | 835.39 |
| 39 | 970.21 | 855.00 | 961.83 | 848.41 | 983.52 | 829.65 | 970.21 | 855.27 | 961.83 | 844.80 | 983.52 | 834.24 |
| 44 | 948.64 | 796.90 | 945.76 | 754.45 | 940.65 | 726.07 | 948.64 | 794.40 | 945.76 | 748.03 | 940.65 | 725.93 |
| 50 | 839.87 | 761.04 | 840.64 | 751.54 | 862.92 | 701.21 | 839.87 | 758.82 | 840.64 | 744.37 | 862.92 | 701.31 |
| 56 | 827.40 | 730.70 | 816.58 | 715.52 | 838.86 | 696.26 | 827.40 | 730.61 | 816.58 | 715.45 | 838.86 | 692.24 |
| 61 | 802.92 | 644.59 | 816.41 | 638.33 | 814.67 | 630.81 | 802.92 | 644.53 | 816.41 | 637.17 | 814.67 | 631.01 |
| 67 | 782.69 | 637.90 | 778.01 | 631.25 | 795.49 | 622.52 | 782.69 | 637.85 | 778.01 | 631.22 | 795.49 | 622.62 |
| 72 | 741.60 | 590.51 | 755.26 | 574.61 | 777.54 | 551.90 | 741.60 | 590.43 | 755.26 | 574.54 | 777.54 | 551.94 |
| 78 | 694.26 | 510.79 | 689.25 | 494.68 | 687.86 | 487.60 | 694.26 | 510.73 | 689.25 | 494.66 | 687.86 | 487.69 |
| 83 | 520.03 | 435.40 | 515.58 | 430.74 | 514.68 | 422.89 | 520.03 | 435.31 | 515.58 | 430.73 | 514.68 | 423.17 |
| 89 | 283.56 | 294.11 | 301.90 | 312.50 | 304.32 | 326.18 | 283.56 | 293.90 | 301.90 | 312.64 | 304.32 | 325.98 |
| 94 | 260.02 | 263.55 | 255.88 | 259.31 | 255.48 | 256.02 | 260.02 | 263.47 | 255.88 | 259.23 | 255.48 | 256.06 |

**Table 9.4 (g)** Achieved annual yields for water export (MCM) obtained from simulation from KUN reservoir

| Reli. | Achieved annual yield for water export from KUN reservoir (MCM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cases | | | | | | | | | | | |
| (%) | I1C1 | I1E1 | I2C1 | I2E3 | I3C1 | I3E5 | II1C2 | II1E2 | II2C2 | II2E4 | II3C2 | II3E6 |
| 6 | 739.69 | 1828.73 | 596.96 | 1773.71 | 532.64 | 1778.25 | 739.69 | 1909.60 | 596.96 | 1848.94 | 532.64 | 1778.80 |
| 11 | 687.62 | 1811.15 | 568.57 | 1660.81 | 461.86 | 1680.05 | 687.62 | 1730.24 | 568.57 | 1813.60 | 461.86 | 1663.86 |
| 17 | 687.62 | 1286.65 | 565.41 | 1310.16 | 461.86 | 1587.27 | 687.62 | 1238.65 | 565.41 | 1378.52 | 461.86 | 1604.81 |
| 22 | 687.62 | 1177.69 | 562.95 | 1300.47 | 457.98 | 1480.37 | 687.62 | 1226.57 | 562.95 | 1328.00 | 457.98 | 1480.93 |
| 28 | 687.62 | 1052.10 | 536.16 | 1223.62 | 439.84 | 1476.67 | 687.62 | 1050.57 | 536.16 | 1222.67 | 439.84 | 1477.26 |
| 33 | 687.62 | 1040.95 | 514.78 | 1095.65 | 403.82 | 1111.21 | 687.62 | 1047.10 | 514.78 | 1157.10 | 403.82 | 1116.30 |
| 39 | 687.37 | 990.83 | 514.18 | 1064.70 | 374.01 | 1106.74 | 687.37 | 978.27 | 514.18 | 1082.63 | 374.01 | 1107.31 |
| 44 | 687.14 | 911.13 | 514.18 | 1040.74 | 365.03 | 854.03 | 687.14 | 909.55 | 514.18 | 1043.80 | 365.03 | 856.07 |
| 50 | 686.67 | 704.60 | 514.18 | 906.62 | 365.03 | 839.47 | 686.67 | 717.60 | 514.18 | 925.64 | 365.03 | 840.08 |
| 56 | 685.54 | 694.45 | 514.18 | 743.61 | 365.03 | 804.65 | 685.54 | 706.21 | 514.18 | 733.66 | 365.03 | 803.92 |
| 61 | 633.31 | 614.00 | 514.18 | 699.01 | 365.03 | 717.79 | 633.31 | 566.00 | 514.18 | 698.85 | 365.03 | 713.78 |
| 67 | 581.00 | 614.00 | 514.18 | 531.82 | 365.03 | 698.16 | 581.00 | 566.00 | 514.18 | 571.40 | 365.03 | 698.76 |
| 72 | 581.00 | 614.00 | 452.21 | 445.56 | 358.88 | 605.02 | 581.00 | 566.00 | 452.21 | 440.58 | 358.88 | 605.57 |
| 78 | 581.00 | 614.00 | 399.88 | 428.00 | 321.84 | 476.22 | 581.00 | 566.00 | 399.88 | 404.00 | 321.84 | 475.64 |
| 83 | 580.57 | 614.00 | 349.00 | 428.00 | 305.92 | 241.42 | 580.57 | 566.00 | 349.00 | 404.00 | 305.92 | 241.03 |
| 89 | 542.08 | 513.35 | 349.00 | 428.00 | 194.70 | 238.65 | 542.08 | 556.41 | 349.00 | 404.00 | 194.70 | 240.29 |
| 94 | 539.39 | 465.85 | 348.74 | 428.00 | 175.54 | 187.00 | 539.39 | 538.59 | 348.74 | 404.00 | 175.54 | 189.00 |

**Table 9.4 (h)** Achieved annual yields for energy (1000 MWhr) obtained from simulation from GS reservoir

| Reli. | Achieved annual yield for energy from GS reservoir (1000 MWhr) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cases | | | | | | | | | | | |
| (%) | I1C1 | I1E1 | I2C1 | I2E3 | I3C1 | I3E5 | II1C2 | II1E2 | II2C2 | II2E4 | II3C2 | II3E6 |
| 6 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 11 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 17 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 22 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 28 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 33 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 39 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 44 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 50 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 56 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 61 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 67 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 72 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 78 | 261.29 | 267.26 | 260.90 | 267.26 | 236.36 | 267.02 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 83 | 261.29 | 265.89 | 250.89 | 265.89 | 236.36 | 265.64 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 | 196.87 |
| 89 | 246.02 | 256.07 | 218.23 | 253.25 | 233.11 | 256.04 | 189.11 | 189.11 | 189.11 | 189.11 | 189.11 | 189.11 |
| 94 | 222.50 | 228.85 | 197.19 | 240.75 | 193.76 | 248.10 | 159.51 | 159.51 | 159.51 | 159.51 | 159.51 | 159.51 |

**Table 9.4 (i)** Achieved annual yields for energy (1000 MWhr) obtained from simulation from RPS reservoir

| Reli. | Achieved annual yield for energy from RPS reservoir (1000 MWhr) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cases | | | | | | | | | | | |
| (%) | I1C1 | I1E1 | I2C1 | I2E3 | I3C1 | I3E5 | II1C2 | II1E2 | II2C2 | II2E4 | II3C2 | II3E6 |
| 6 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 138.55 | 139.30 | 117.47 | 139.42 |
| 11 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 138.55 | 139.30 | 117.47 | 139.42 |
| 17 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 138.55 | 139.30 | 117.47 | 139.42 |
| 22 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 138.55 | 139.30 | 117.47 | 139.42 |
| 28 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 138.55 | 139.30 | 117.47 | 139.42 |
| 33 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 138.55 | 139.30 | 117.47 | 139.42 |
| 39 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 138.55 | 139.30 | 117.47 | 139.42 |
| 44 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 138.55 | 139.30 | 117.47 | 139.42 |
| 50 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 138.55 | 139.30 | 117.47 | 139.42 |
| 56 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 138.55 | 139.30 | 117.47 | 139.42 |
| 61 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 138.55 | 139.30 | 117.47 | 139.42 |
| 67 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 130.38 | 139.30 | 117.47 | 139.42 |
| 72 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 128.02 | 131.25 | 109.49 | 139.29 |
| 78 | 103.30 | 105.28 | 104.98 | 105.28 | 94.26 | 104.99 | 115.34 | 116.42 | 122.81 | 130.29 | 107.84 | 131.26 |
| 83 | 103.30 | 105.28 | 104.98 | 105.28 | 93.40 | 104.99 | 115.34 | 116.42 | 104.49 | 129.51 | 95.42 | 128.70 |
| 89 | 103.30 | 105.28 | 104.98 | 105.28 | 91.40 | 104.99 | 115.34 | 116.42 | 96.45 | 95.05 | 82.61 | 97.01 |
| 94 | 101.94 | 104.52 | 103.62 | 104.51 | 85.29 | 104.21 | 102.18 | 103.26 | 85.22 | 91.64 | 71.50 | 95.43 |

**Table 9.5 (a)** Achieved annual system irrigation yield (MCM) obtained from simulation

| Reli. | Achieved annual system irrigation yield (MCM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cases | | | | | | | | | | | |
| (%) | I1C1 | I1E1 | I2C1 | I2E3 | I3C1 | I3E5 | II1C2 | II1E2 | II2C2 | II2E4 | II3C2 | II3E6 |
| 6 | 3952.95 | 3936.66 | 3952.95 | 3936.83 | 3952.44 | 3942.87 | 3952.95 | 3938.10 | 3952.95 | 3939.55 | 3952.44 | 3942.60 |
| 11 | 3952.95 | 3936.66 | 3952.95 | 3936.83 | 3952.44 | 3942.87 | 3952.95 | 3938.10 | 3952.95 | 3939.55 | 3952.44 | 3942.60 |
| 17 | 3952.95 | 3936.66 | 3952.95 | 3936.83 | 3952.44 | 3942.87 | 3952.95 | 3938.10 | 3952.95 | 3939.55 | 3952.44 | 3942.60 |
| 22 | 3952.95 | 3936.66 | 3952.95 | 3936.83 | 3952.44 | 3942.87 | 3952.95 | 3938.10 | 3952.95 | 3939.55 | 3952.44 | 3942.60 |
| 28 | 3952.95 | 3936.66 | 3952.95 | 3936.83 | 3952.44 | 3942.87 | 3952.95 | 3938.10 | 3952.95 | 3939.55 | 3952.44 | 3942.60 |
| 33 | 3952.95 | 3936.66 | 3952.95 | 3936.83 | 3952.44 | 3942.87 | 3952.95 | 3938.10 | 3952.95 | 3939.55 | 3952.44 | 3942.60 |
| 39 | 3952.95 | 3936.66 | 3952.95 | 3936.83 | 3952.44 | 3942.87 | 3952.95 | 3938.10 | 3952.95 | 3939.55 | 3952.44 | 3942.60 |
| 44 | 3952.95 | 3936.66 | 3952.95 | 3936.83 | 3952.44 | 3942.87 | 3952.95 | 3938.10 | 3952.95 | 3939.55 | 3952.44 | 3942.60 |
| 50 | 3952.95 | 3934.23 | 3952.71 | 3936.83 | 3952.44 | 3942.87 | 3952.95 | 3936.60 | 3952.95 | 3939.55 | 3952.44 | 3942.60 |
| 56 | 3951.14 | 3933.04 | 3952.06 | 3936.83 | 3952.44 | 3942.87 | 3951.14 | 3935.76 | 3952.71 | 3939.55 | 3952.44 | 3942.60 |
| 61 | 3951.00 | 3932.62 | 3950.90 | 3934.50 | 3952.44 | 3940.37 | 3951.00 | 3932.92 | 3952.06 | 3938.97 | 3952.44 | 3942.60 |
| 67 | 3947.59 | 3930.87 | 3947.39 | 3933.21 | 3950.61 | 3939.25 | 3947.59 | 3931.69 | 3950.90 | 3937.06 | 3950.61 | 3940.43 |
| 72 | 3944.51 | 3927.23 | 3947.09 | 3930.90 | 3949.48 | 3937.70 | 3944.51 | 3929.71 | 3947.39 | 3934.99 | 3949.48 | 3940.24 |
| 78 | 3943.46 | 3921.62 | 3943.57 | 3927.34 | 3946.85 | 3936.46 | 3943.46 | 3928.70 | 3947.09 | 3934.68 | 3946.85 | 3936.92 |
| 83 | 3943.46 | 3918.00 | 3924.66 | 3918.17 | 3942.94 | 3933.42 | 3943.46 | 3922.79 | 3943.57 | 3930.09 | 3942.94 | 3933.21 |
| 89 | 3891.16 | 3858.10 | 3739.38 | 3812.89 | 3927.39 | 3924.21 | 3887.47 | 3872.62 | 3887.47 | 3874.07 | 3886.96 | 3877.12 |
| 94 | 3596.35 | 3627.14 | 3544.71 | 3731.39 | 3540.83 | 3835.35 | 3619.16 | 3604.31 | 3619.16 | 3605.76 | 3618.65 | 3608.81 |

**Table 9.5 (b)** Achieved annual system energy (1000 MWhr) yield obtained from simulation

| Reli. | Achieved annual system energy yield (1000 MWhr) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cases | | | | | | | | | | | |
| (%) | I1C1 | I1E1 | I2C1 | I2E3 | I3C1 | I3E5 | II1C2 | II1E2 | II2C2 | II2E4 | II3C2 | II3E6 |
| 6 | 364.58 | 372.54 | 365.88 | 372.54 | 330.62 | 372.01 | 312.21 | 313.29 | 335.42 | 336.17 | 314.34 | 336.29 |
| 11 | 364.58 | 372.54 | 365.88 | 372.54 | 330.62 | 372.01 | 312.21 | 313.29 | 335.42 | 336.17 | 314.34 | 336.29 |
| 17 | 364.58 | 372.54 | 365.88 | 372.54 | 330.62 | 372.01 | 312.21 | 313.29 | 335.42 | 336.17 | 314.34 | 336.29 |
| 22 | 364.58 | 372.54 | 365.88 | 372.54 | 330.62 | 372.01 | 312.21 | 313.29 | 335.42 | 336.17 | 314.34 | 336.29 |
| 28 | 364.58 | 372.54 | 365.88 | 372.54 | 330.62 | 372.01 | 312.21 | 313.29 | 335.42 | 336.17 | 314.34 | 336.29 |
| 33 | 364.58 | 372.54 | 365.88 | 372.54 | 330.62 | 372.01 | 312.21 | 313.29 | 335.42 | 336.17 | 314.34 | 336.29 |
| 39 | 364.58 | 372.54 | 365.88 | 372.54 | 330.62 | 372.01 | 312.21 | 313.29 | 335.42 | 336.17 | 314.34 | 336.29 |
| 44 | 364.58 | 372.54 | 365.88 | 372.54 | 330.62 | 372.01 | 312.21 | 313.29 | 335.42 | 336.17 | 314.34 | 336.29 |
| 50 | 364.58 | 372.54 | 365.88 | 372.54 | 330.62 | 372.01 | 312.21 | 313.29 | 335.42 | 336.17 | 314.34 | 336.29 |
| 56 | 364.58 | 372.54 | 365.88 | 372.54 | 330.62 | 372.01 | 312.21 | 313.29 | 327.65 | 336.17 | 314.34 | 336.29 |
| 61 | 364.58 | 372.54 | 365.88 | 372.54 | 330.62 | 372.01 | 312.21 | 313.29 | 327.25 | 328.41 | 306.57 | 336.16 |
| 67 | 364.58 | 372.54 | 365.88 | 372.54 | 330.62 | 372.01 | 312.21 | 313.29 | 324.89 | 328.12 | 306.36 | 328.53 |
| 72 | 364.58 | 372.54 | 365.88 | 372.54 | 329.77 | 372.01 | 312.21 | 313.29 | 319.68 | 327.16 | 304.71 | 328.13 |
| 78 | 364.58 | 372.54 | 364.52 | 372.54 | 327.77 | 372.01 | 312.21 | 313.29 | 301.36 | 326.38 | 292.29 | 325.57 |
| 83 | 363.23 | 370.41 | 355.87 | 370.40 | 327.36 | 369.85 | 304.45 | 305.52 | 298.06 | 298.81 | 279.48 | 298.94 |
| 89 | 349.31 | 361.35 | 339.27 | 358.53 | 321.65 | 361.03 | 299.05 | 300.13 | 293.32 | 291.92 | 276.98 | 293.88 |
| 94 | 325.80 | 334.13 | 325.81 | 346.03 | 288.02 | 353.08 | 274.86 | 275.93 | 282.09 | 288.51 | 268.37 | 292.30 |

**Table 9.6** Achieved annual irrigation yield (MCM) from proposed reservoirs obtained from simulation

| Reli. | Achieved annual irrigation yield from proposed reservoirs (MCM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cases | | | | | | | | | | | |
| (%) | I1C1 | I1E1 | I2C1 | I2E3 | I3C1 | I3E5 | II1C2 | II1E2 | II2C2 | II2E4 | II3C2 | II3E6 |
| 6 | 589.95 | 573.66 | 589.95 | 573.83 | 589.44 | 579.87 | 589.95 | 575.10 | 589.95 | 576.55 | 589.44 | 579.60 |
| 11 | 589.95 | 573.66 | 589.95 | 573.83 | 589.44 | 579.87 | 589.95 | 575.10 | 589.95 | 576.55 | 589.44 | 579.60 |
| 17 | 589.95 | 573.66 | 589.95 | 573.83 | 589.44 | 579.87 | 589.95 | 575.10 | 589.95 | 576.55 | 589.44 | 579.60 |
| 22 | 589.95 | 573.66 | 589.95 | 573.83 | 589.44 | 579.87 | 589.95 | 575.10 | 589.95 | 576.55 | 589.44 | 579.60 |
| 28 | 589.95 | 573.66 | 589.95 | 573.83 | 589.44 | 579.87 | 589.95 | 575.10 | 589.95 | 576.55 | 589.44 | 579.60 |
| 33 | 589.95 | 573.66 | 589.95 | 573.83 | 589.44 | 579.87 | 589.95 | 575.10 | 589.95 | 576.55 | 589.44 | 579.60 |
| 39 | 589.95 | 573.66 | 589.95 | 573.83 | 589.44 | 579.87 | 589.95 | 575.10 | 589.95 | 576.55 | 589.44 | 579.60 |
| 44 | 589.95 | 573.66 | 589.95 | 573.83 | 589.44 | 579.87 | 589.95 | 575.10 | 589.95 | 576.55 | 589.44 | 579.60 |
| 50 | 589.95 | 573.66 | 589.95 | 573.83 | 589.44 | 579.87 | 589.95 | 575.10 | 589.95 | 576.55 | 589.44 | 579.60 |
| 56 | 589.95 | 573.66 | 589.95 | 573.83 | 589.44 | 579.87 | 589.95 | 575.10 | 589.95 | 576.55 | 589.44 | 579.60 |
| 61 | 589.95 | 571.23 | 589.95 | 573.83 | 589.44 | 579.87 | 589.95 | 573.60 | 589.95 | 576.55 | 589.44 | 579.60 |
| 67 | 588.14 | 570.04 | 589.71 | 573.83 | 589.44 | 579.87 | 588.14 | 572.76 | 589.71 | 576.55 | 589.44 | 579.60 |
| 72 | 588.00 | 569.62 | 589.06 | 571.50 | 589.44 | 577.37 | 588.00 | 569.92 | 589.06 | 575.97 | 589.44 | 579.60 |
| 78 | 584.59 | 567.87 | 587.90 | 570.21 | 587.61 | 576.25 | 584.59 | 568.69 | 587.90 | 574.06 | 587.61 | 577.43 |
| 83 | 581.51 | 564.23 | 584.39 | 567.90 | 586.48 | 574.70 | 581.51 | 566.71 | 584.39 | 571.99 | 586.48 | 577.24 |
| 89 | 580.46 | 558.62 | 584.09 | 564.34 | 583.85 | 570.42 | 580.46 | 565.70 | 584.09 | 571.68 | 583.85 | 573.92 |
| 94 | 580.46 | 555.00 | 580.57 | 555.17 | 579.94 | 561.21 | 580.46 | 559.79 | 580.57 | 567.09 | 579.94 | 570.21 |

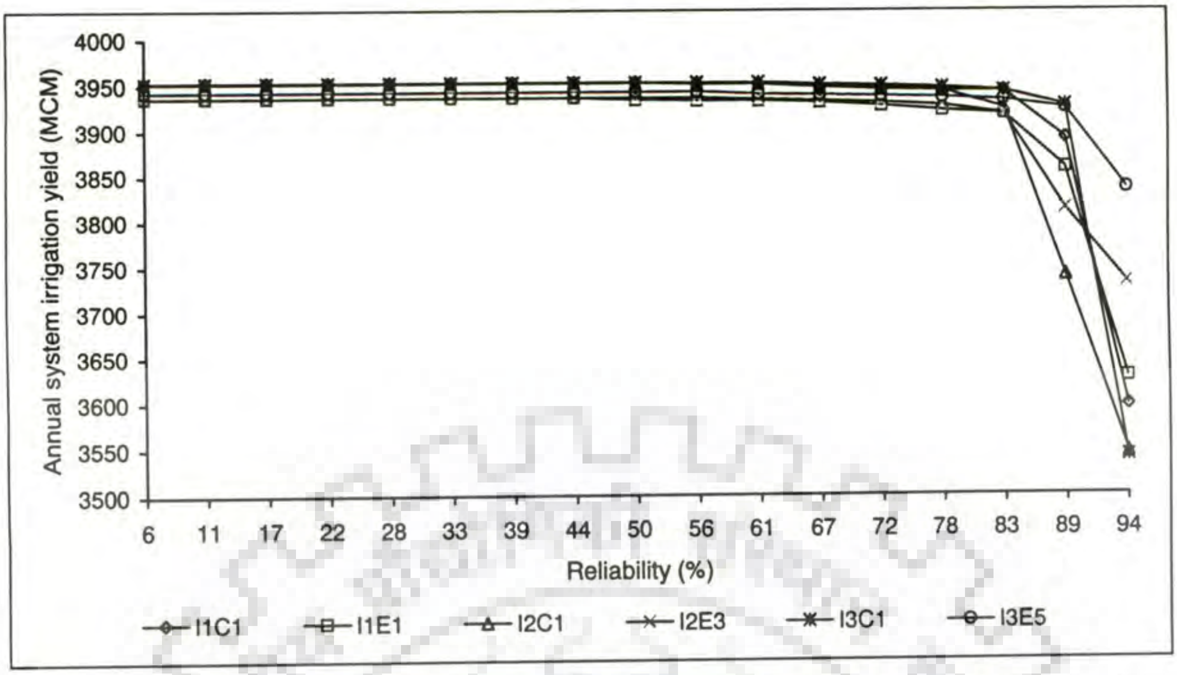

**Figure 9.4 (a)** Achieved annual system irrigation yield for different reliabilities for Link Alternative I obtained from simulation

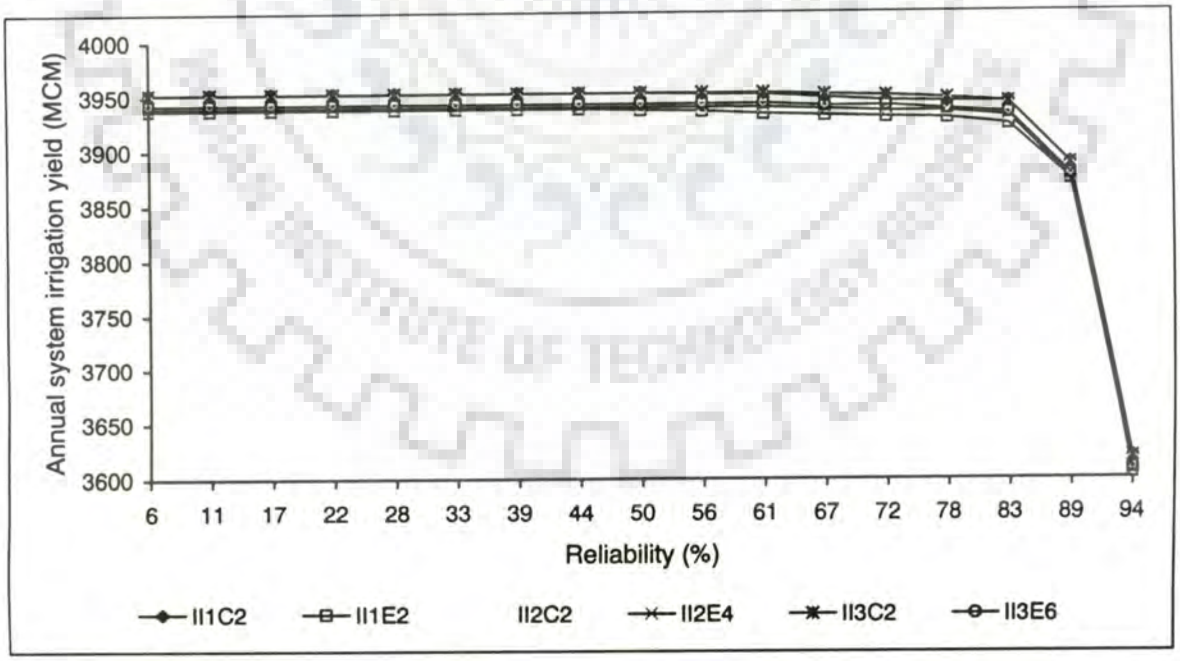

**Figure 9.4 (b)** Achieved annual system irrigation yield for different reliabilities for Link Alternative II obtained from simulation

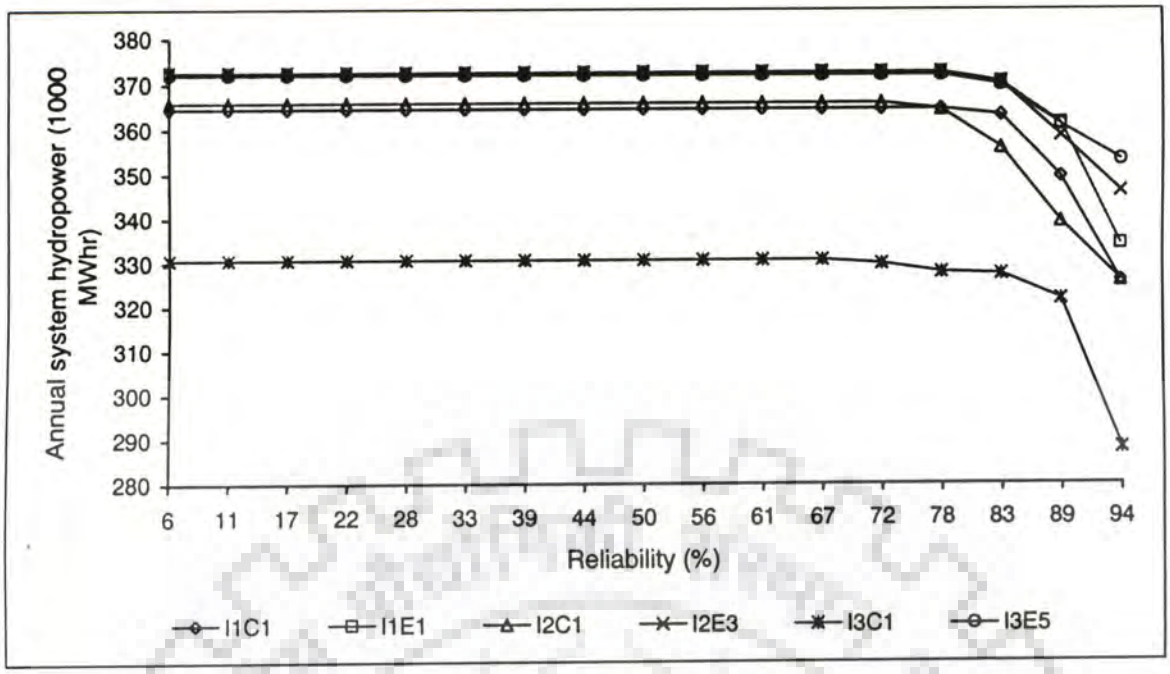

**Figure 9.5** (a) Achieved annual system hydropower yield for different reliabilities for Link Alternative I obtained from simulation

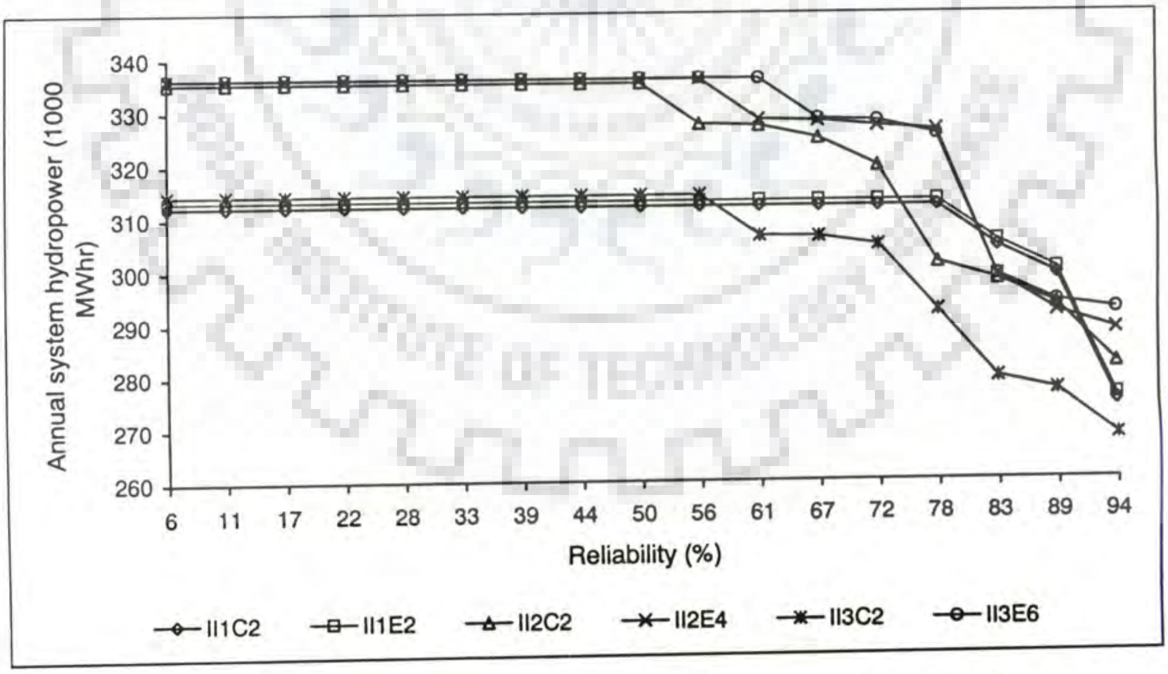

**Figure 9.5** (b) Achieved annual system hydropower yield for different reliabilities for Link Alternative II obtained from simulation

## 9.4 DISCUSSION

### 9.4.1 Comparison of CIM and Simulation Results

#### 9.4.1.1 Comparison with respect to reliability aspect

Results show that in case of simulation, the yields obtained from any reservoir for higher reliabilities are less and for lower reliabilities are more compared to the yields obtained through the CIM. This is represented graphically in Fig. 9.6 (a) and Fig. 9.6 (b) for the achieved annual yields for irrigation and hydropower, for different cases from PAT reservoir obtained from simulation and CIM, respectively. In the figure, legends prefix by 'S' and 'D' represent results obtained from simulation model and CIM (dynamic programming), respectively. This difference between simulation and CIM results is due to the fact that CIM is an optimization model and tries to allocate the yields optimally recursively in all the periods, whereas simulation considers each time period individually. In simulation if sufficient water is available at any time period, all the water needs are met without giving

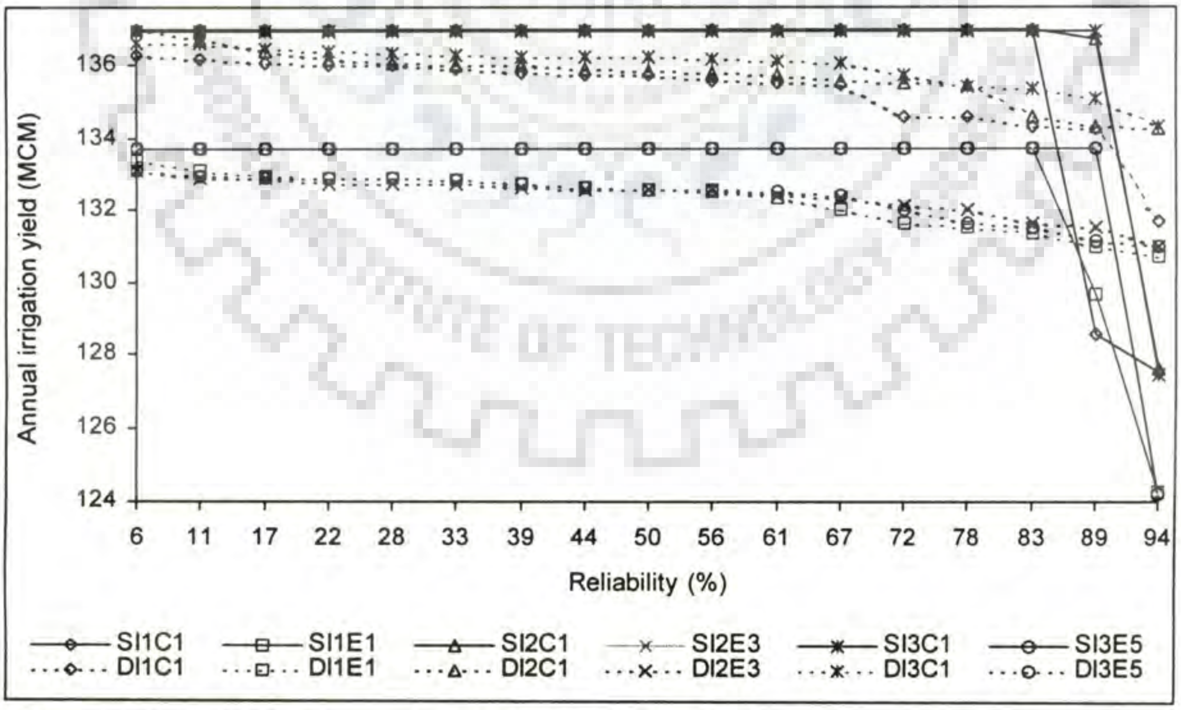

**Figure 9.6 (a)** Achieved annual irrigation yield from PAT reservoir obtained through CIM and simulation for different reliabilities for Link Alternative I

attention to future water needs. Development of rule curves for each individual reservoir operations may increase the reservoir yields for higher reliabilities, in case of simulation.

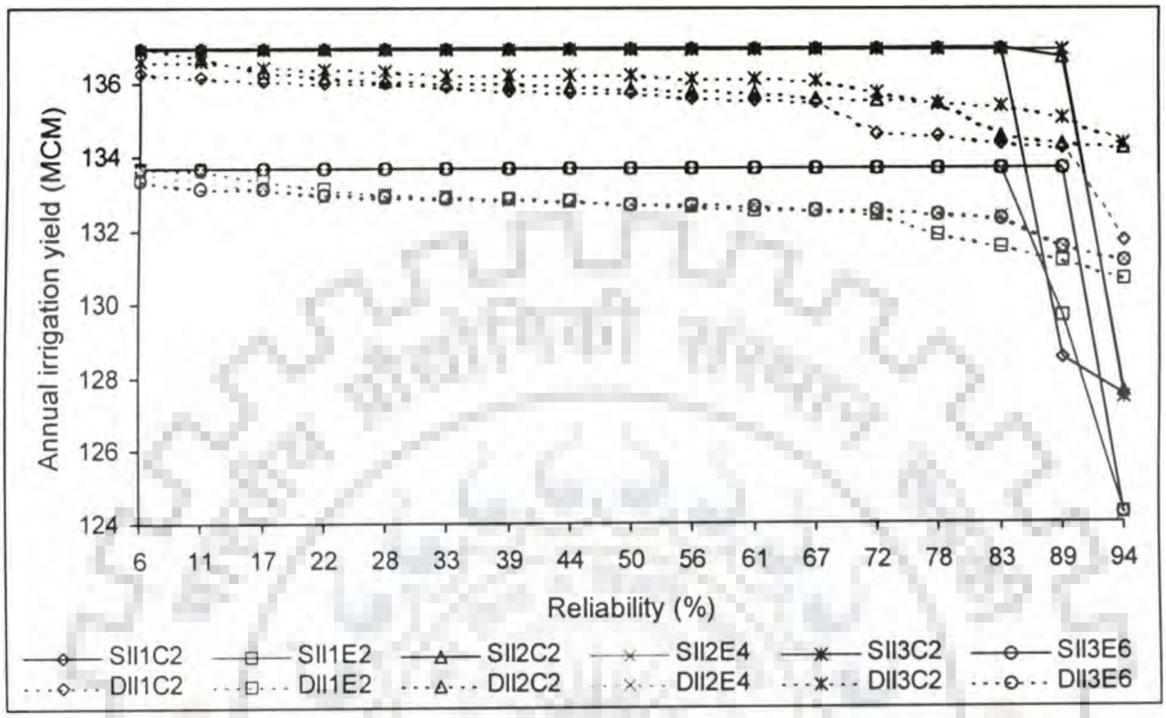

**Figure 9.6 (b)** Achieved annual irrigation yield from PAT reservoir obtained through CIM and simulation for different reliabilities for Link Alternative II

### 9.4.1.2 Comparison for monthly yields

The CIM application for GS reservoir suffers from curse of dimensionality. So there is a difference of annual yields from GS reservoir obtained by CIM and simulation. Simulation gives higher annual yields from GS reservoir both for irrigation and hydropower. But, comparison of the reservoir operation results for monthly yields by CIM and simulation shows that the monthly yields from each reservoir corresponding to different water uses are very close to each other. The monthly yields obtained by CIM and simulation for Case-I1C1 for irrigation and water export from PAT reservoir (smallest in the system), and irrigation and hydropower from GS reservoir (largest in the system) are shown in Fig. 9.7 (a) to Fig. 9.7 (d).

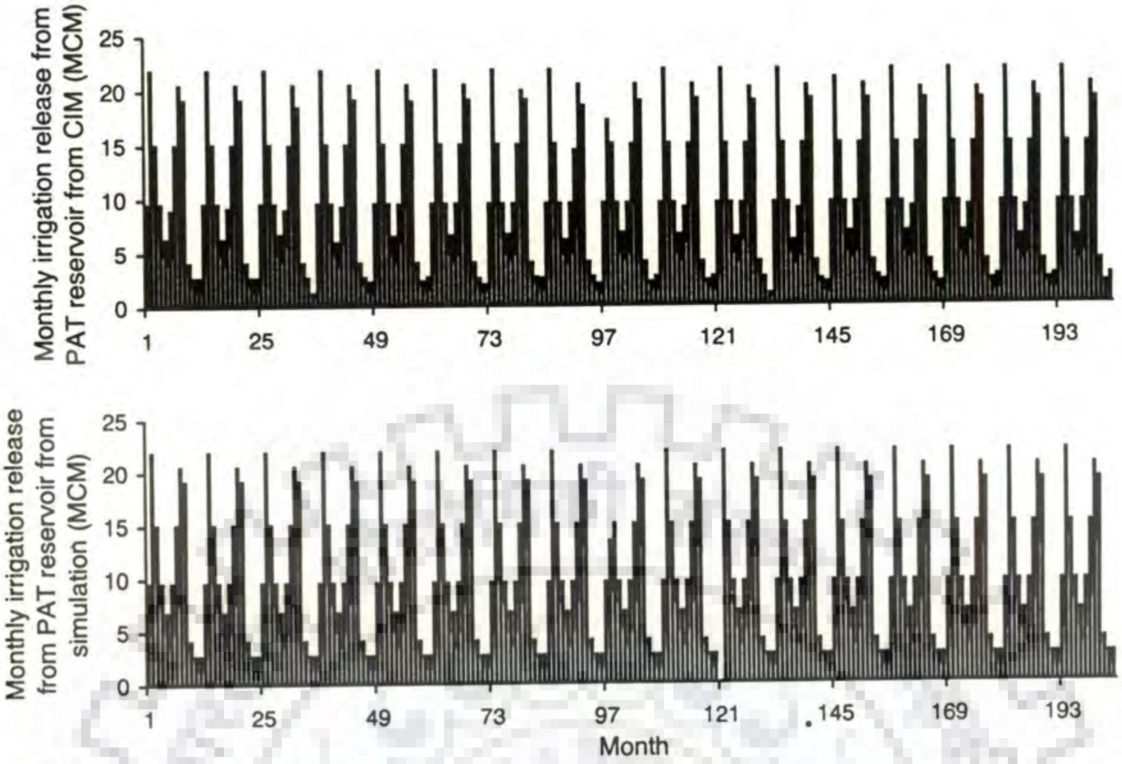

**Figure 9.7 (a)** Comparison of CIM and simulation results for monthly irrigation yield from PAT reservoir (Caes-I1C1)

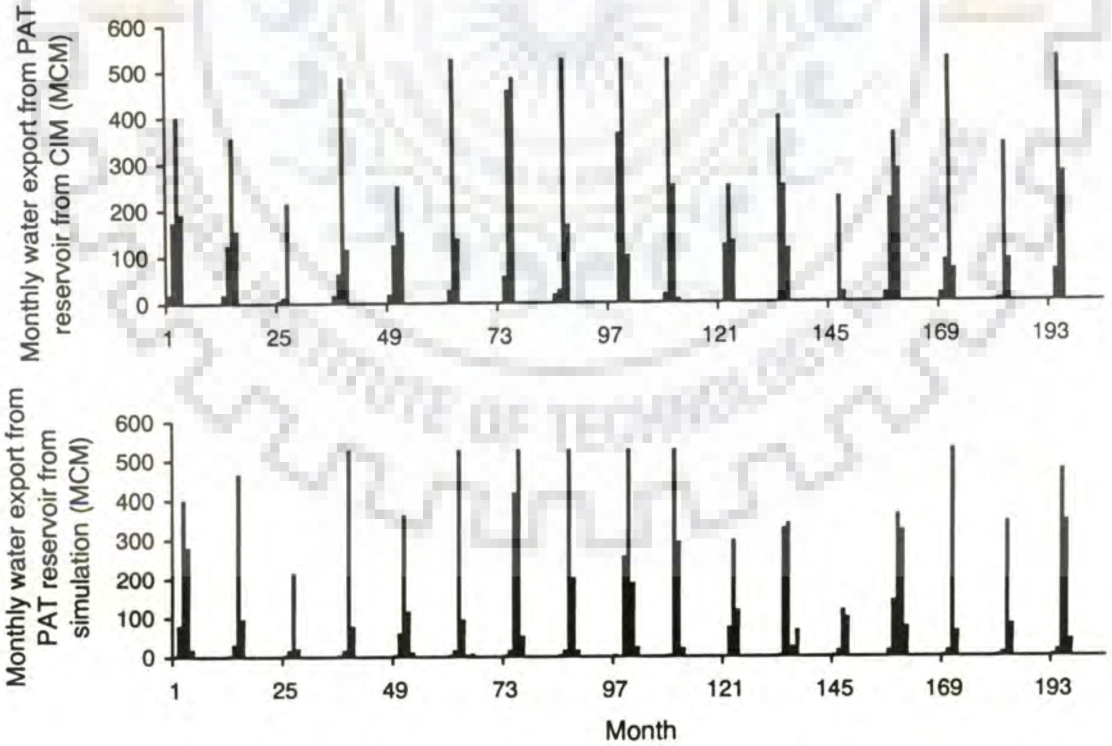

**Figure 9.7 (b)** Comparison of CIM and simulation results for monthly water export from PAT reservoir (Caes-I1C1)

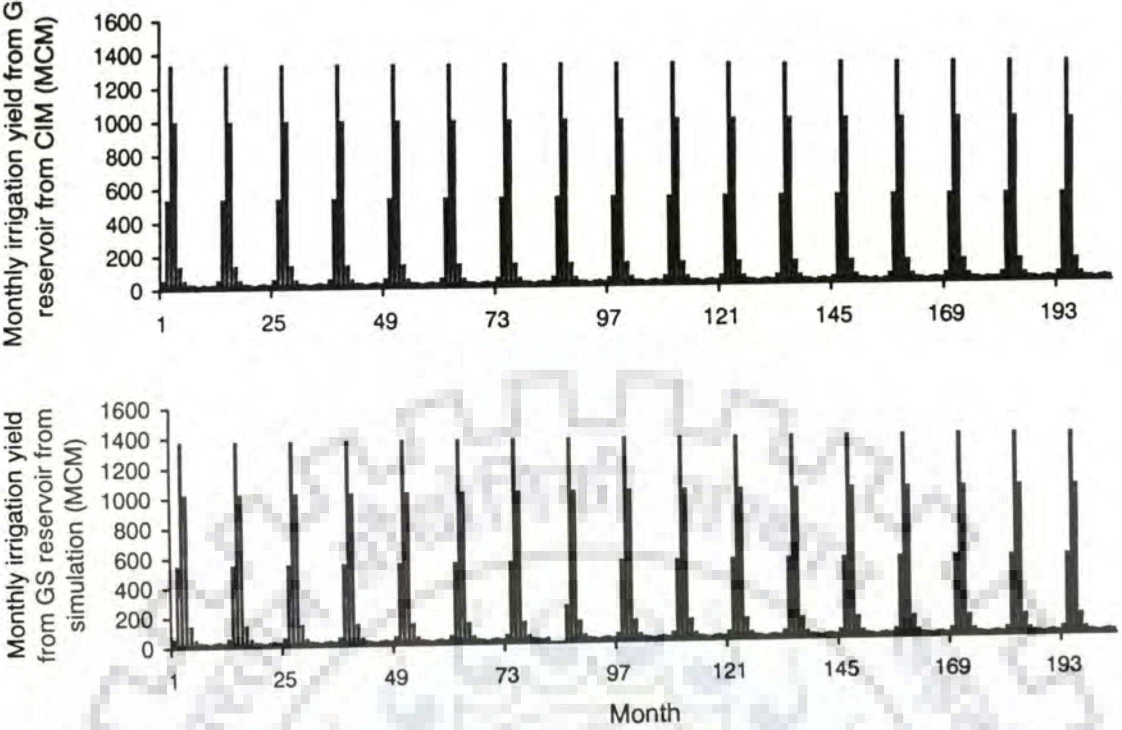

**Figure 9.7 (c)** Comparison of CIM and simulation results for monthly irrigation yield from GS reservoir (Caes-I1C1)

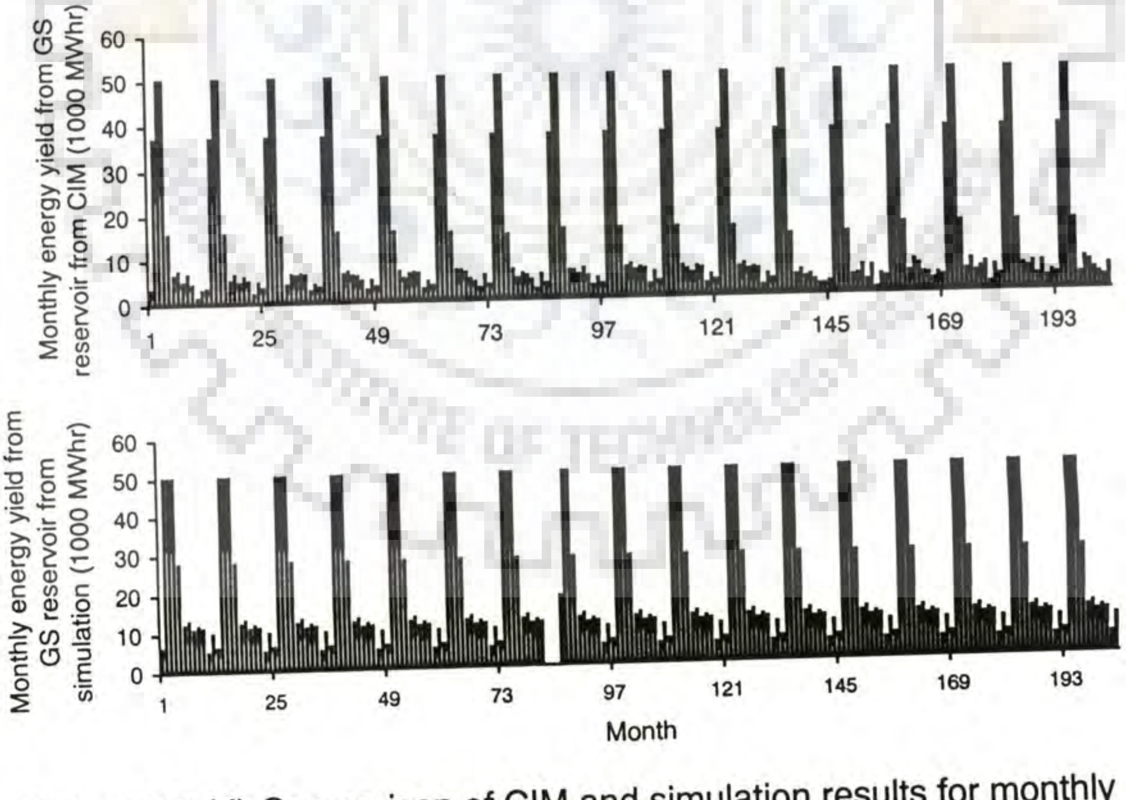

**Figure 9.7 (d)** Comparison of CIM and simulation results for monthly energy yield from GS reservoir (Caes-I1C1)

#### 9.4.1.2.1 Percentage difference of monthly yields

To compare the monthly yields obtained by simulation and CIM, let us define PD (percentage difference) as the ratio of the difference between simulation and CIM results for a yield for a given purpose from a reservoir in a month to the yield for that purpose obtained by simulation from the reservoir in that month in percentage. The percentage of months for which the PD for irrigation is below some assumed values for different irrigation reservoirs for the cases I1C1, I3C1, I3E5 and I2C1 under Link Alternative I are shown in Table 9.7. Out of these cases, Case-I1C1 is suggested by the NWDA and the rest are promising cases under Link Alternative I discussed in Section 9.4.4. Under Link Alternative II, Case-II1C2 is suggested by the NWDA and the Case-II2C2 seems to be the most promising (discussed in Section 9.4.4). In all the months, the PD values for PAT, MOH and KUN reservoirs for the cases II1C2 and II2C2 are exactly same with that of cases I1C1 and I2C1, respectively. The table shows that for most of the months the difference between the irrigation yields obtained by the two models are very less. The PD values are high when the yield given by simulation is very less.

#### 9.4.1.2.2 Nash-Sutcliffe efficiency of CIM with respect to simulation

Another way of comparing the two models is to use the Nash and Sutcliffe (1970) efficiency function. This function is generally used to estimate the efficiency of river flow forecasting models by comparing the computed values with that of observed values. In this function the observed values are replaced by the simulation results for a particular yield and corresponding computed values are replaced by the CIM results. Mathematically,

$$\text{Nash-Sutcliffe Efficiency} = \left[1 - \frac{\sum_{t=1}^{n}(Oy_t^{CIM} - Oy_t^{SIM})^2}{\sum_{t=1}^{n}(Oy_t^{SIM} - Oy_{mean}^{SIM})^2}\right] x100\% \qquad (9.1)$$

where t = time period considered in both the models (month), $Oy_t^{CIM}$ = yield obtained by the CIM in period t, $Oy_t^{SIM}$ = yield obtained by simulation in period t, $Oy_{mean}^{SIM}$ = mean yield obtained by simulation, and n = number of periods (204 months).

**Table 9.7** Comparison of CIM and simulation results for irrigation with respect to PD and Nash-Sutcliffe Efficiency for selected cases under Link Alternative I

| Case | Reser-voir | Percent of months for which | | | | | Nash-Sutcliffe Efficiency of CIM with respect to simulation (%) | Max difference between CIM and simulation results for irrigation in any month (MCM) |
|---|---|---|---|---|---|---|---|---|
| | | PD≤1 | PD≤3 | PD≤5 | PD≤7.5 | PD≤10 | | |
| I1C1 | PAT | 75 | 80 | 86 | 89 | 91 | 98.64 | 9.49 |
| | MOH | 42 | 58 | 72 | 77 | 85 | 99.10 | 5.75 |
| | KUN | 95 | 97 | 97 | 97 | 97 | 99.73 | 9.49 |
| | GS | 0 | 96 | 97 | 98 | 98 | 99.69 | 287.80 |
| I3C1 | PAT | 84 | 85 | 88 | 92 | 92 | 98.86 | 9.50 |
| | MOH | 83 | 88 | 93 | 95 | 95 | 99.89 | 1.83 |
| | KUN | 81 | 86 | 87 | 90 | 92 | 99.62 | 5.59 |
| | GS | 0 | 89 | 92 | 93 | 94 | 99.66 | 326.09 |
| I3E5 | PAT | 74 | 77 | 81 | 85 | 91 | 99.08 | 8.29 |
| | MOH | 72 | 77 | 85 | 88 | 91 | 99.80 | 2.50 |
| | KUN | 63 | 72 | 78 | 82 | 87 | 98.84 | 15.74 |
| | GS | 0 | 99.51 | 99.51 | 99.51 | 99.51 | 99.89 | 94.63 |
| I2C1 | PAT | 78 | 81 | 86 | 91 | 92 | 98.86 | 9.38 |
| | MOH | 76 | 86 | 93 | 93 | 95 | 99.51 | 5.76 |
| | KUN | 93 | 94 | 96 | 96 | 96 | 99.82 | 5.86 |
| | GS | 0 | 94 | 95 | 96 | 96 | 99.57 | 339.79 |

Note: PD = (Difference between Simulation and CIM results / Simulation result) X 100%

The Nash-Sutcliffe efficiencies calculated for all the reservoirs for all the yields are very high, which show the accuracy of the CIM. The Nash-Sutcliffe Efficiency obtained for the CIM with respect to irrigation yield in all the irrigation reservoirs for the cases I1C1, I3C1, I3E5 and I2C1 are shown in Table 9.7. The Nash-Sutcliffe Efficiency of CIM with respect to irrigation yield for the PAT, MOH and KUN reservoirs for the cases II1C2 and II2C2 are exactly same as that in cases I1C1 and I2C1, respectively, and for GS reservoir 96.75% in both the cases.

### 9.4.1.3 Comparison for monthly spills

Monthly spills obtained by CIM and simulation from PAT, MOH, KUN and RPS reservoirs are almost same. The monthly spills obtained from PAT reservoir for Case-I1C1 are shown in Fig. 9.8. It is noticed that, there is a considerable variation in the monthly spills obtained by the two models from GS reservoir. The monthly spills obtained from GS reservoir by the two models for Case-I1C1 are shown in Fig. 9.9. The possible reasons for the difference in spills in the two models may be-

(1) Due to curse of dimensionality in dynamic programming, the storage increment adopted for GS reservoir in CIM application is very high as compared to the water demands in some of the months. The storage levels (states) are discrete (e.g., 0, 60, 120, 180, 240 etc.) and the reservoir may need to spill some water even when storage space is available to absorb water, to attain the desired storage level. So there will be small spills (less than 60 MCM) at frequent intervals from GS reservoir in the CIM application. These spills will be reduced, if the storage increment adopted is very less. The spill from storage from big reservoirs due to curse of dimensionality is a limitation of CIM.

(2) There is a penalty associated with reservoir storage in CIM objective function. The CIM does not store water that is not necessary, whereas in case of simulation, spill occurs only when the reservoir is full and more water is available. Most of the spills in CIM occur in

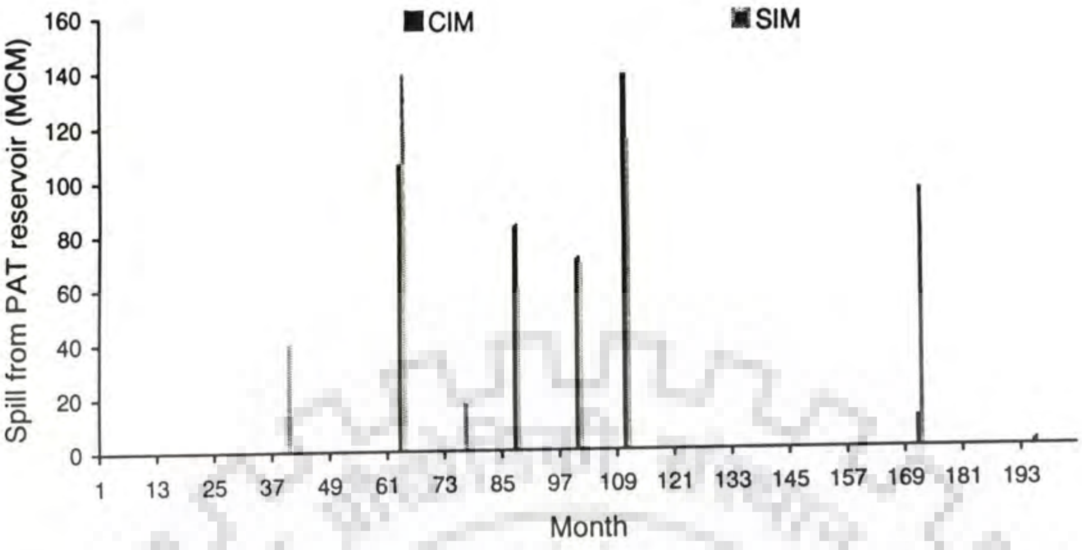

**Figure 9.8** Comparison of monthly spills from PAT reservoir from CIM and simulation (Caes-I1C1)

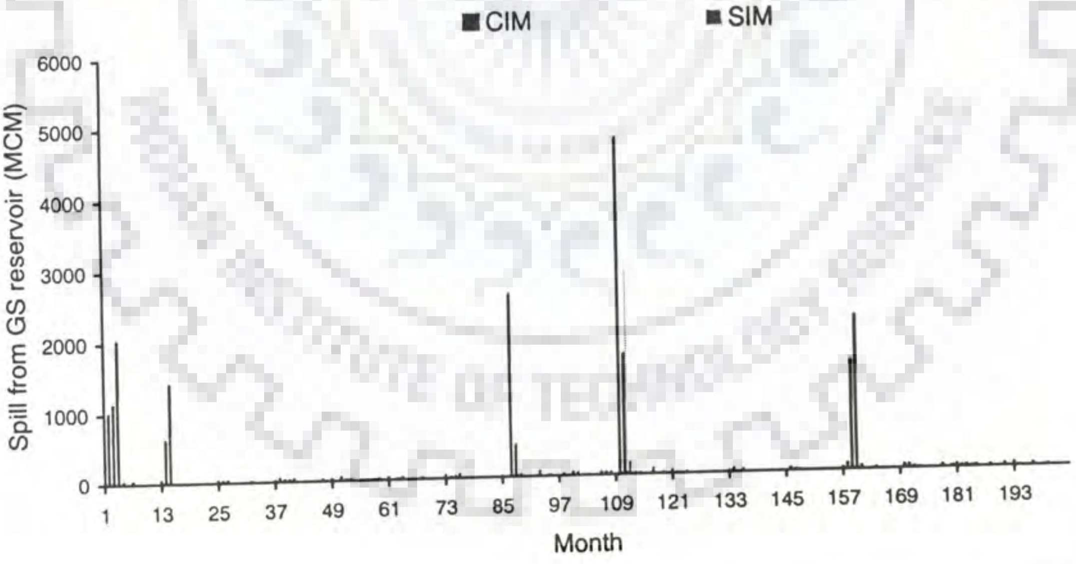

**Figure 9.9** Comparison of monthly spills from GS reservoir from CIM and simulation (Caes-I1C1)

month of July, when the penalty for spill ($CSP_r$) is minimum among all the months, and penalty for storage ($CSR_r$) is high.

Interestingly, the CIM results show that the GS reservoir was never full. The maximum gross storage reached during operation by CIM for GS reservoir is 4373 MCM against an existing gross reservoir capacity of 8449 MCM. It indicates that a smaller reservoir capacity would have been sufficient. Simulation also shows that out of 204 months, the reservoir spills only in one month. To justify the above statement simulation model is run for Case-I1C1 with reduced reservoir capacity and keeping all other parameters including demands, unchanged. The results show that irrigation and energy yields in each month are exactly the same for a gross storage capacity of 7200 MCM when compared with earlier results. The monthly spills from GS reservoir obtained through simulation with reduced reservoir capacity are shown in Fig. 9.10 (a). Simulation is also performed assuming the gross capacity of GS reservoir as 4373 MCM and taking the design water demands as given by CIM. In this case the reservoir spills are almost similar to that of CIM results for reservoir operation and are shown in Fig. 9.10 (b).

### 9.4.2 Reservoir Yields in Different Cases for Different Water Uses

#### *Domestic Water Supply*

The results show that the domestic water supply demands can be met with highest possible reliability from all the concerned reservoirs in all the cases. So with respect to domestic water supply demands all the cases are same.

#### *Irrigation*

For PAT, MOH and KUN reservoirs, it is observed that the cases related to the canal capacity option C (i.e., C1 and C2) give better annual irrigation yields compared to the cases related to canal capacity option E (E1 to E6) for both the Link Alternatives. For GS reservoir, the

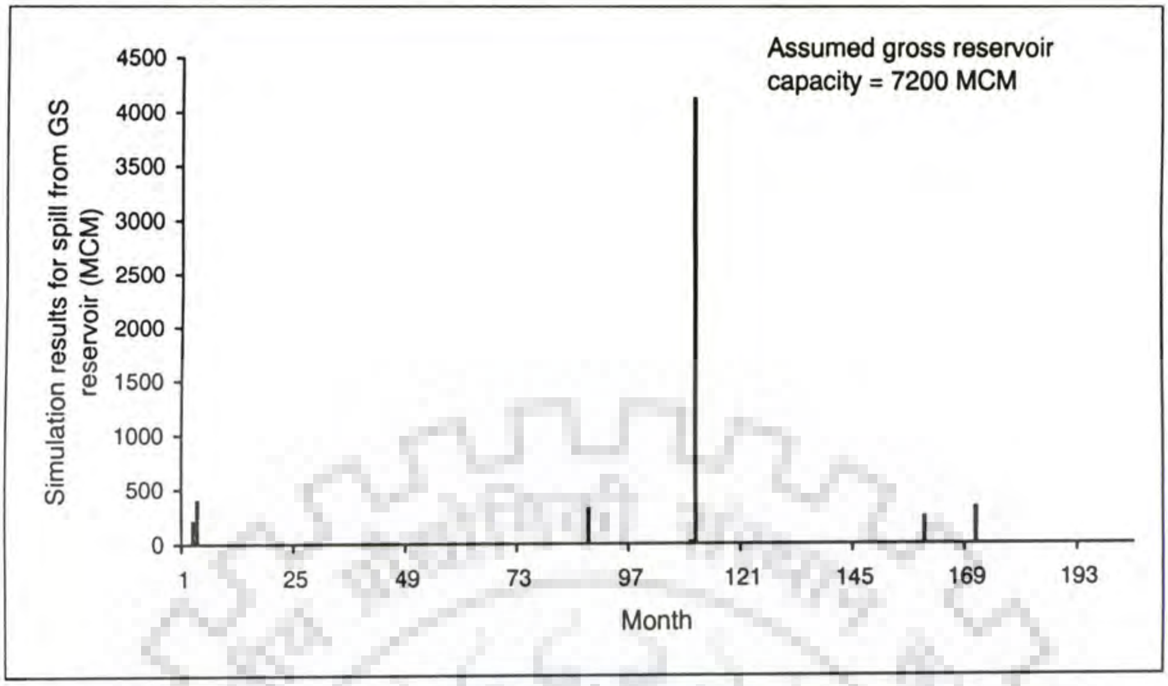

Figure 9.10 (a) Simulation results for monthly spills from GS reservoir with reduced capacity (Caes-I1C1)

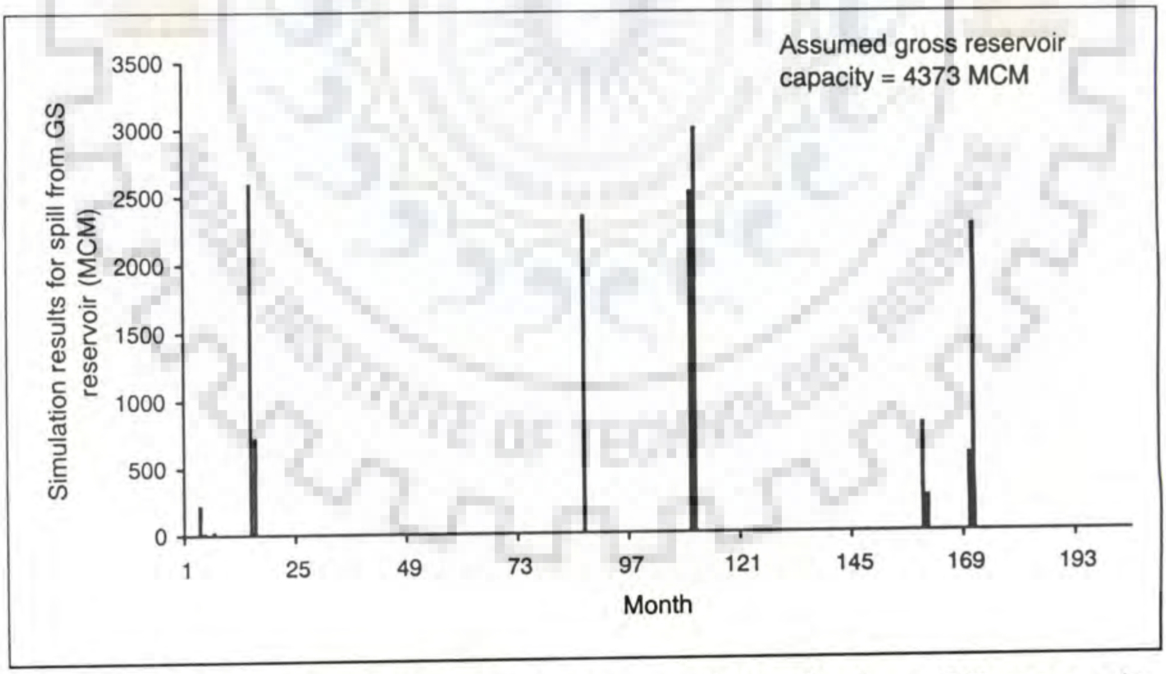

Figure 9.10 (b) Simulation results for monthly spills from GS reservoir with reduced capacity (Caes-I1C1)

annual irrigation yield is same for all the cases at or below 78% annual reliability. In Link Alternative I, at higher reliabilities, the cases related to canal capacity option E (E1, E3 and E5) give higher irrigation yields compared to canal capacity option C1. In Link Alternative II there is no water import to GS reservoir and hence the annual irrigation yield from GS reservoir is same for all the cases.

### *Water export*

In Link Alternative I, cases I1C1, I2C1 and I3C1 give better annual water export from PAT and MOH reservoirs; and cases I1E1, I2E3 and I3E5 give better annual water export from KUN reservoir.

In Link Alternative II, cases II1C2, II2C2 and II3C3 give better annual water export from PAT and MOH reservoirs. For KUN reservoir, Case-II1C2 gives best annual water export at higher reliabilities, Case-II1E2 gives better annual water export both at higher and lower reliabilities, and cases II2E4 and II3E6 give better annual water export at lower reliabilities.

### *Hydropower*

The hydropower generation at GS reservoir in Link Alternative II is same for all the cases, as there is no water import to GS reservoir. The hydropower generation from RPS reservoir is dependent on the water export from KUN reservoir, as well as on the spill and regenerated flows from the water uses of GS reservoir, apart from its own catchment inflows. It is noticed that the hydropower generation from GS and RPS reservoirs are better for cases related to the canal capacity option E (E1, E2, E3, E4, E5 and E6). It is due to the fact that in canal capacity option E, the water demands from GS and RPS reservoirs are taken into account for planning water transfer. But in case of canal capacity option C (C1 and C2), a uniform water export from KUN reservoir in all the months was tried. The results indicate that the sizes of the proposed reservoirs are not a governing factor for hydropower generation.

### 9.4.3 System Yields in Different Cases for Different Water Uses

Considering the system as a whole, the results show that both the links provide almost same annual irrigation yields. The total annual irrigation yield from the proposed reservoirs (all lying and in the state of Madhya Pradesh) may be used for comparing the cases. The annual irrigation yield obtained for different reliabilities through simulation from the proposed PAT, MOH and KUN reservoirs are presented in Fig. 9.11 (a) and Fig. 9.11 (b) for Link Alternatives I and II, respectively. For Link Alternative I, canal capacity option C1 and for Link Alternative II, canal capacity option C2 gives best system irrigation yields. For Link Alternative I, reservoir sizes corresponding to the index 3 give best system irrigation yields. For Link Alternative II, reservoir sizes corresponding to index 2 and 3 give better irrigation yields.

For hydropower generation, the results show that the power generation is more for Link Alternative I compared to Link Alternative II. For Link Alternative I, the dominant factor for power generation is the link canal capacities, rather than the capacity of proposed reservoirs. The power generation is almost same for the cases related to canal capacity options E1, E3 and E5, and are higher than the cases related to canal capacity option C1.

### 9.4.4 Selection of Most Promising Cases

It is observed that in Link Alternative I, the Case-I3C1 gives the maximum system annual irrigation yield and the minimum system annual hydropower yield. The Case-I3E5 gives the maximum system annual hydropower yield and it is the best option among the cases related to canal capacity option E for annual system irrigation yield. The Case-I2C1 is the second best option after Case-I3C1 for annual system irrigation yield, and it is the best option among

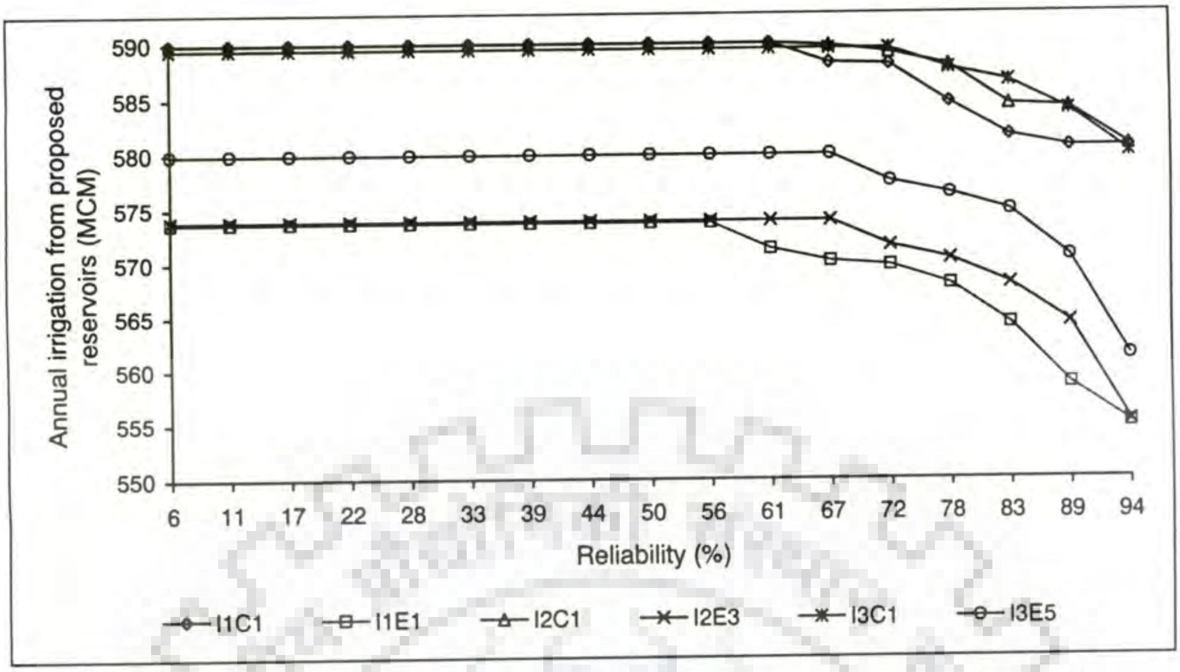

**Figure 9.11 (a)** Achieved annual irrigation yield from PAT, MOH and KUN reservoirs for different reliabilities for Link Alternative I obtained from simulation

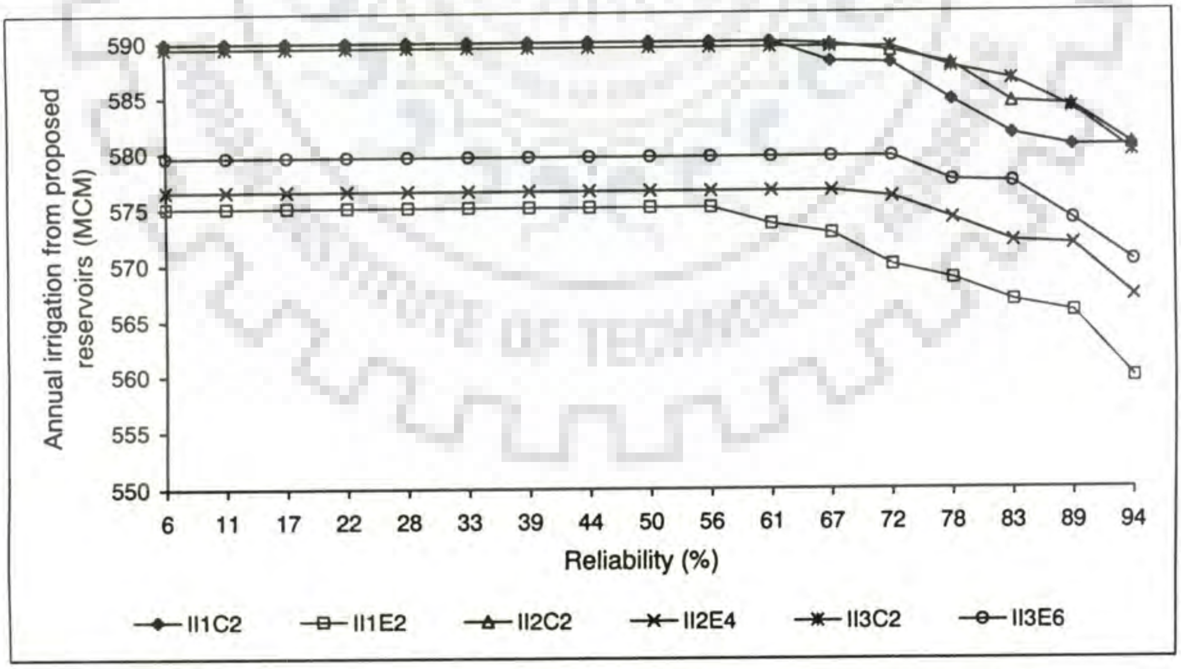

**Figure 9.11 (b)** Achieved annual irrigation yield from PAT, MOH and KUN reservoirs for different reliabilities for Link Alternative II obtained from simulation

the cases related to canal capacity option C1 for annual system hydropower generation. The system annual yield at selected reliabilities near target reliabilities for irrigation and hydropower generation for the selected cases I2C1, I3C1 and I3E5 are presented in Table 9.8 for comparison. The differences in values between CIM and simulation results are primarily due to the fact that the CIM application for GS reservoir suffers from curse of dimensionality. Also, the CIM results appear to be conservative when compared with simulation results. The pattern of results from both the models are same.

For Link Alternative II, cases II2C2 and II3C2 give higher annual irrigation yield. Case-II2C2 also provides high annual hydropower yield. So, for Link Alternative II, Case-II2C2 seems to be the best from overall system irrigation and hydropower yield consideration.

**Table 9.8** System annual yield at selected reliabilities near target reliabilities for irrigation and hydropower generation for selected cases under Link Alternative I

| Water use | Reliability (%) | Cases | | | | | |
|---|---|---|---|---|---|---|---|
| | | I2C1 (Good for both irrigation and hydropower) | | I3C1 (Best for irrigation) | | I3E5 (Best for hydropower) | |
| | | CIM result | Simulation result | CIM result | Simulation result | CIM result | Simulation result |
| Irrigation (MCM) | 66.67 | 3861.77 | 3947.39 | 3871.88 | 3950.61 | 3846.31 | 3939.25 |
| | 72.22 | 3861.55 | 3947.09 | 3870.96 | 3949.48 | 3845.95 | 3937.70 |
| | 77.78 | 3859.71 | 3943.57 | 3867.64 | 3946.85 | 3844.57 | 3936.46 |
| | 83.33 | 3859.38 | 3924.66 | 3865.75 | 3942.94 | 3841.78 | 3933.42 |
| Hydropower (1000 MWhr) | 77.78 | 298.71 | 364.52 | 257.40 | 327.77 | 302.68 | 372.01 |
| | 83.33 | 297.86 | 355.87 | 257.02 | 327.36 | 297.89 | 369.85 |
| | 88.89 | 297.82 | 323.20 | 255.00 | 321.65 | 297.72 | 361.03 |
| | 94.44 | 294.07 | 302.17 | 254.00 | 288.02 | 295.47 | 353.08 |

From the above discussions, it can be stated that the Link Alternative I is more promising than Link Alternative II, in terms of meeting the annual demands. If economic analysis permits, Link Alternative I should be adopted. Case-I3C1 is the best considering system annual irrigation yield. Case-I3E5 is the best for hydropower generation. Case-I2C1 is a compromise between irrigation and hydropower generation, where both irrigation and hydropower yields are high but not the best for individual irrigation and hydropower water uses. Case-II2C2 is the best from overall consideration of irrigation and hydropower, for Link Alternative II.

### 9.4.5 Consequences of the Adoption of Selected Cases

Adoption of the selected cases (cases I2C1, I3C1 and I3E5 in Link Alternative I; and Case-II2C2 in Link Alternative II) will increase or decrease the design capacity of proposed reservoirs and link canal capacities, and there will be consequent increase or decrease in reservoir yields with respect to the yield from the system with design values of reservoir capacities and canal capacities. Table 9.9 shows how the adoption of any of these selected cases will increase or decrease system parameters from that of design values, and the resulting increases or decreases in system yields.

**Table 9.9** Consequences of the adoption of selected cases

| Case | Increase/decrease in design | | Increase/decrease in annual yield | | | |
|---|---|---|---|---|---|---|
| | Reservoir capacity (MCM) | Canal capacity (MCM) | Irrigation (MCM) at 72.22 % annual reliability | | Hydropower (1000 MWhr) at 94.44% annual reliability | |
| | | | CIM result | Simulation result | CIM result | Simulation result |
| I3C1 | PAT=+30<br>MOH=+10<br>KUN=-677 | PAT to MOH=0<br>MOH to KUN=0<br>KUN to GS=0 | +16.82 | +4.97 | -31.06 | -37.78 |
| I3E5 | PAT=+30<br>MOH=+10<br>KUN=-677 | PAT to MOH=-304.36<br>MOH to KUN=-138.16<br>KUN to GS=+617.75 | -8.19 | -6.81 | +10.41 | +27.28 |
| I2C1 | PAT=+11<br>MOH=+12<br>KUN=-350 | PAT to MOH=0<br>MOH to KUN=0<br>KUN to GS=0 | +7.41 | +2.58 | +9.01 | +0.01 |
| II2C2 | PAT=+11<br>MOH=+12<br>KUN=-350 | PAT to MOH=0<br>MOH to KUN=0<br>KUN to GS=0 | +14.95 | +2.88 | +2.12 | +8.04 |

Note: '+' sign indicates increase and '–' sign indicates decrease from design values.

## NOTATION

$Oy_{mean}^{SIM}$ = mean yield obtained by simulation, and

$Oy_t^{SIM}$ = yield obtained by simulation in period t,

$Oy_t^{CIM}$ = yield obtained by the CIM in period t,

n = number of periods, and

t = time period considered in both the CIM and simulation model.

# SUMMARY, ANALYSIS AND CONCLUSIONS

## 10.1 INTRODUCTION

This study is carried out with an overall objective of proposing the use of a modeling approach for inter basin water transfers involving multipurpose multireservoir system. System analysis techniques, e.g., linear programming, dynamic programming and simulation are used. The models developed are demonstrated by applying them to the Chambal basin. The details of this study are chronologically presented in the previous chapters. The presentation in this chapter begins with an overview of this study and a summary of the accomplished work. The subsequent sections discuss the findings of this study and inferences drawn from the analysis of the results. Finally the conclusions of this study with reference to the modeling approach employed and its application to the Chambal basin are reported. Some suggestions are made at the end of this chapter to outline the scope for further related studies.

## 10.2 AN OVERVIEW OF THE STUDY

Water is the most precious gift of nature. It is most crucial for sustaining life and required in almost all activities of man, i.e., domestic and industrial use, irrigation to meet the growing food and fibre needs, power generation, navigation and recreation, etc. The development, conservation and use of water, therefore, form the main elements in development planning. The rainfall is confined to few monsoon months and is unevenly distributed both in space and time even during monsoon months. As a result, while large tracts are drought prone, floods affect some parts. The National Water Policy adopted by Govt. of India in 1987 emphasized the need for inter basin transfers of water. It states that water should be made available to water short areas by transfer from other areas including transfer from one river basin to another after taking into account requirements of the donor areas/basins.

Before taking any decision regarding inter basin water transfers, the status of the concerned basins with respect to their water resources, i.e., potential and projected future water needs and availability of water must be known. The assessments of surface water resources for the concerned basins are done as per the guideline framed by the NWDA. For overall water balance, the ground water potential in the basins is also considered. Since the main objective of this study is to offer a methodology for inter basin water transfers using the system analysis techniques, the guidelines framed by the NWDA are not under study. The water balance study reports by NWDA for the catchment areas of reservoirs were available and their results are taken as such.

When water resources availability and projected future demands are known, the search for possible project alternatives and methodologies that can solve the problems of drought and flood begins. For preliminary identification of efficient project designs and operating policies prior to a more detailed study, linear programming models are increasingly used. A preliminary screening reservoir yield model for multi yield multiple reservoir system available in literature is improved and extended for general-purpose use. The objective was to (a) allow water import to any reservoir and export from any reservoir in the system, (b) incorporate a reliability criterion for reservoir yields on an annual basis for different water needs, (c) identify the maximum possible fraction of an annual reservoir yield that can be provided during failure years without changing target reliabilities, and (d) find the trade-off between different reservoir yields. This improved general-purpose yield model (IGPYM) can be applied to a single or multiple reservoirs system consisting of single purpose and multipurpose reservoirs. The IGPYM offers better flexibility in application by including more than two numbers of water uses, both compatible and incompatible and in selecting release reliabilities of water uses and deciding their optimal yield failure fractions during failure years.

For detailed study of the system, two dynamic programming models are formulated. The objective was to find (a) import of water required by each water importing reservoir in the system, (b) annual and monthly design demands including water exports by each reservoir in the system, and (c) annual reservoir yields corresponding to different reliabilities. For any water transfer project, one has to know how much water have to be imported/exported by each water importing/exporting reservoir in a system; and also the best timing for import and export, depending on the availability of water, water demands and storage capacities of the donor and recipient reservoirs. The probable future inflows also influence the timing of the water transfers. The procurement problem model (PPM) is formulated to find the amount of import water requirements by each water importing reservoir and the best time for water transfers to meet the water needs completely. Though the PPM finds the amounts of import water requirements for the importing reservoir in a given time, it is not known whether this volume is available or not in the donor reservoir at that particular time. The controlled input model (CIM) is formulated to fix the annual design demands for all the water needs including the export demands that can be met with prescribed release reliabilities for all the reservoirs in a system. The CIM revises the input target demands so that they can be met. After fixing the annual design demands for a reservoir in planning stage, the CIM acts like simulation model in the operation stage, where the allocation of water for different water needs at different time periods are done optimally, depending on the relative penalty of not meeting a demand at a particular time. A simulation model is used to test the results of the DP model.

The models so developed are applied to a system of five reservoirs (three proposed and two existing) in the Chambal basin in India, to study two alternative proposals of water transfer from the proposed reservoirs to the existing reservoirs. The IGPYM is applied for different cases as demonstrated in Chapter 8. The water exports that can be made from each of the proposed reservoirs for known reservoir capacities are evaluated. The alternative set of reservoir capacities that can satisfy the above mentioned water demands at the prescribed reliability levels are found. The trade-off between reservoir yields for design reservoir capacities at each reservoir site are obtained. The PPM calculates amount of import water requirements at a reservoir to meet its water demands. The CIM estimates water demands that a reservoir can meet with specified reliabilities, and also amount of water it can export to other sites. Reservoir operation results through the application of CIM determine the annual yield achieved for each water need corresponding to different reliabilities at each reservoir in the system for all the cases considered. Comparison of the reservoir operation results by CIM and simulation shows close resemblances between the reservoirs releases made by the two models.

## 10.3 SUMMARY OF ACCOMPLISHED WORK

### 10.3.1 Water Balance Study

The Objective was to determine the status of future water balance (i.e., comparison of annual water availability and annual water requirements in a system) of the concerned basins and dam sites, in order to develop broad understanding of their being either water surplus or water deficit, and may act as donor and recipient basins/sites in the inter basin water transfer proposal, respectively. The water balance study was done for the year 2050 AD, with the expectation that the population will hopefully be stabilized by 2050 AD. The observed flows at all the gauge sites in the concerned basins were almost negligible during non-monsoon period. Naturally a water balance study on monthly basis would show water deficiency in the basins mainly during non-monsoon months. As reservoirs are involved in water transfer and they have the capability to conserve water for non-monsoon months, the water balance was done on yearly basis. The water balances were calculated at 75% and 50 % water year dependability. The water availability was calculated on the basis of surface water availability, existing and proposed water imports and exports, utilizable ground water potential after meeting projected needs, and regenerated flows from upstream water uses. The water demands were calculated for domestic water use (urban, rural and livestock population projected for the year 2050 AD), irrigation (existing, ongoing and future major, medium and minor projects), industrial use, hydropower and environment and ecology needs. The general guidelines framed by the NWDA were followed and the status of concerned basins as 'water surplus' or 'water deficit' were established.

### 10.3.2 Yield Model Development and Application

Yield model serves as an efficient screening model for reasonable reservoir design with release reliabilities near targets. This work extends and improves the yield model for multiple reservoir system as available in the present form. Two new terms, priority yield and second yield are introduced in the model, in place of firm yield and secondary yield previously used, to consider more number of water needs and to have better flexibility in selecting release reliabilities of different water uses and deciding optimal yield failure fractions (allowable deficits) during failure years for different water uses. The model is capable of considering different reliabilities for each purpose, allows deficit in annual yields during failure years, and redistribution of regenerated flows (contribution from upstream uses) in within the year period. The model can be applied to both compatible and incompatible purposes, and considers each purpose independently or in-group, depending on the total number of water needs to be considered in a reservoir. The focus is on dealing with different water needs and meeting them individually as much as possible, both for compatible and incompatible uses.

Though the model considered priority yield and second yield, it is also possible to calculate firm and secondary yields whenever required. When a reservoir has two yields, the previous yield models did not permit yield failures for both the yields, where yield was zero for secondary yield during failure years. The IGPYM permits complete or partial yield failures for both the yields (priority and second). The objective of this model development is to present a realistic and efficient linear model for screening purpose, related to multipurpose multireservoir system.

Suitability of IGPYM was accomplished by using stream flow data given in Loucks et al. (1981) and comparing the results of the model with the results of the models given in Loucks et al. (1981) and Dahe and Srivastava (2002). The comparison showed that IGPYM offers better flexibility in selecting reliabilities of water uses and deciding optimal yield failure fractions during failure years for different water uses. If the reliability criteria permits to have the reliabilities of both the yields less than the maximum possible reliabilities, with or without complete yield failure during failure years, the system represented by IGPYM is capable of supplying the same annual yields with desired reliabilities from reduced reservoir capacity, or supplying higher yields with the same desired reliabilities with the given reservoir capacity.

The IGPYM is applied to the five-reservoirs system in Chambal basin. For water transfer, two proposed alternative links are considered; Link Alternative I assumes that water will be exported from PAT to MOH, MOH to KUN and KUN to GS, and Link Alternative II assumes that the water transfer will be done from PAT to MOH, MOH to KUN, and KUN to RPS. One additional constraint, using the results of the water balance study is also included, i.e., the annual water export from a reservoir should be less than or equal to the surplus surface water balance at 75% water year dependability available in the catchment of the reservoir plus the total annual import coming to the reservoir. It is assumed that domestic water supply and firm energy demands will be met with the maximum possible reliability; and a minimum reliability of 72% will be maintained for irrigation, water export and secondary energy generation.

To select an appropriate set of $\beta_{i,t}$ (ratio of the inflow in period t of the critical year in record to the total inflow in that year) values, the following $\beta_{i,t}$ values are tried for PAT reservoir for application of IGPYM: (i) $\beta_{i,t}$'s based on average monthly flows, (ii) $\beta_{i,t}$'s based on the flow of driest year of record, and (iii) *mean* of the above two $\beta_{i,t}$'s. Simulation and IGPYM with the above $\beta_{i,t}$ values are applied to PAT reservoir and results are compared. The results show that IGPYM for *mean* of the $\beta_{i,t}$ values from driest and average year's inflows gives results closer to simulation results. So, it was decided to apply IGPYM to all the reservoirs in the system using *mean* $\beta_{i,t}$ values.

For PAT, MOH and KUN reservoirs, the domestic and irrigation demand are clubbed together and is termed as priority yield. The water export is considered as second yield. For GS reservoir, the irrigation use is considered as priority demand. The annual firm yield is used for annual firm power generation, and the annual secondary yield is used for annual secondary energy generation. Like GS reservoir, for RPS reservoir also, the annual firm yield is used for annual firm power generation, and the annual secondary yield is used for annual secondary energy generation. Since RPS is a single purpose hydropower reservoir, it is also decided that entire annual priority yield will be used for annual firm power generation. To get the maximum possible annual water export from each of the proposed reservoirs, following options are tried for water export release fraction ($D^{S}_{i,t}$) values: (a) transfer release fraction as per the 75% water year dependable inflow, (b) transfer release fraction as per average inflow, and (c) transfer release fraction as per the spills available from the reservoir operation (working) table of 75% water year dependable flow. The volume of water export that can be achieved by using the above $D_{i,t}^{S}$ values are obtained through model run and compared. Slight adjustments of $D_{i,t}^{S}$ values are made to get better results by few trial runs of the model. The set of $D_{i,t}^{S}$ values for each proposed reservoir that give the maximum export is adopted.

Three cases are considered for the application of IGPYM. In Case-1 reservoir capacities, annual domestic water supply and irrigation demands are considered to be known (i.e., design values for reservoir capacities and annual target water demands). Annual water export and energy demands are unknown. Two sub-cases are considered under Case-1. In Case-1 (a) preference is given to increase the volume of irrigation supply over water export during failure years, and in Case-1 (b) preference is given to increase the volume of water export over irrigation supply during failure years. Though In India, irrigation is given priority over water export, Case-1 (b) is formulated just to show the flexibility offered by the IGPYM in enhancing desired yield during failure years, maintaining the same annual yields for all water uses with prespecified reliabilities.

In Case-2 reservoir capacities and annual domestic demands are considered to be known (i.e., design values for reservoir capacities and annual target domestic water supply demands). Both annual priority and second yields are unknown. Preference is given to increase the volume of irrigation supply over water export during failure years.

In Case-3 reservoir capacities are considered unknown, annual domestic water supply and irrigation demands are known. The failure fraction values are assumed minimum under the adopted policy of supplying at least 50% of the irrigation target during failure years. For alternative capacity of a proposed reservoir, it is assumed that the increase in its design capacity is either restricted to 10% (Case-3I) or it has no restriction (Case-3II). Under Case-3I and Case-3II, again two cases are classified, i.e., the total energy benefit is assumed equal to the value as obtained in Case-1 (a) and Case-1 (b); and are termed as Case-3I.1(a) and 3I.1(b), and Case-3II.1(a) and 3II.1(b), respectively.

The outcomes of the model results provided the following information:

(i) The maximum water that can be exported from a reservoir with its design reservoir capacity after meeting the annual domestic water supply and irrigation demands at the reservoir at desired annual reliabilities;

(ii) The maximum annual reliabilities that can be achieved from a reservoir for irrigation, water export and secondary energy generation;

(iii) The values of failure fractions for priority yields and second yields during failure years, i.e., to know the amount of water a reservoir is capable of supplying for each water need, even in a failure year;

(iv) The trade-off between annual reservoir yields for different water needs for design reservoir capacity;

(v) The maximum firm and secondary energy that can be generated at a reservoir, and

(vi) The alternative capacity of a reservoir to derive the same weighted total system energy as obtained from its design reservoir capacity.

### 10.3.3 Dynamic Programming Models (DPM) Development and Application

Two dynamic programming models, namely, procurement problem model (PPM) and controlled input model (CIM) were formulated. The PPM was formulated to calculate the import water requirements for a reservoir. When reservoir demands are known and in case of deficits option is open for water import from some other sources or reservoirs to meet deficits, it is important to know when and how much import of water is required, to meet the demands fully. In PPM, the decision variable is the import of water required to meet the demands completely. It is also necessary to know whether target water demands for different water uses can be satisfied or not at prespecified reliabilities by a reservoir. If the target demands cannot be met, they should be revised, so that design demands that can be met at prespecified reliabilities are obtained. For this CIM is formulated. The decision variable in CIM is the water required to be used from the current inflow apart from storage to meet the demands. The upper limit of the decision variable at any stage is the current reservoir inflow. Thus in deciding the amounts and timing of water transfers, the PPM looks after the water demands of the importing reservoirs; and the CIM looks after the demands and water availability of the exporting reservoirs.

The penalty values in different stages are important parameters in both the models. In CIM at every stage these penalties control decision variable (how much water is required to be used from current inflow), change in end storages, spill and design demands. In PPM they control decision variable (how much import is to be made), change in end storages and spill. These penalty values were assumed keeping in mind the weightage (preference) at any stage given to import, spill, and increase in end storage. The models were formulated to minimize the total penalties. Therefore if a particular function, say, import of water is not preferred at some stages, the import penalty is made larger at those stages as compared to others. As the analysis of penalty is not the main issue, the pattern (weightage) of different penalties is more important rather than their values.

Thirty cases are considered on the basis of two alternative links, three sets of reservoir sizes, and different link canal capacities. As per the practice followed in India, the highest priority is given to domestic water supply followed by irrigation and water export and power generation. These models provided information regarding the following: (i) The PPM results presented monthly amount of import water requirements for all the water importing reservoirs to meet their target demands completely. The import water requirement by an importing reservoir is then taken as the target water export demand from the corresponding exporting reservoir in a given stage. (ii) The CIM found the annual design demands for all the water needs that can be met with prescribed reliabilities at all the reservoirs in the system. (iii) The CIM also performed reservoir operation, where monthly design water demands were given as input demands to the model for their respective water needs, and the monthly reservoir releases for the corresponding water uses are obtained. (iv) Annual yields for all the water uses were obtained at different reliabilities. (v) The results of the reservoir operation by CIM were tested by simulation, and the most promising cases were identified.

## 10.4 ANALYSIS OF WORK DONE

The analysis of the accomplished work is reported in this section. The findings of the study and inferences drawn with references to the assessment of annual water resources potential of the basins, the mathematical modeling approach for inter basin water transfers and the model results are discussed.

### 10.4.1 Assessment of the Water Resources

Annual water balance study for Upper Chambal, Lower Chambal, Kalisindh and Parbati basins were done following the guideline framed by the NWDA. The earlier studies carried out on water balance did not include the contribution from ground water. Hence to get a clearer picture of the water potential available in comparison to water demands in the basins, ground water was also included in water balance studies. The water balance study results showed that Lower Chambal, Kalisindh and Parbati basins; and Patanpur, Mohanpura and Kundaliya reservoirs are surplus by 4544 MCM, 4081 MCM, 3617 MCM, 1194 MCM, 1341 MCM and 1535 MCM, respectively, in their overall (surface water plus ground water) water resources at 75% water year dependability. Whereas Upper Chambal basin is deficit in its surface (4394 MCM) as well as in its overall water (2276 MCM) resources at 75% water year dependability; and deficit is also found in surface water (1929 MCM) at 50% water year dependability. It indicates that a severe water deficit situation occurs in Upper Chambal basin. The NWDA has suggested that annual irrigation through existing, ongoing and identified future projects based on surface water availability should be at least 30% of the culturable area in any basin. The annual irrigation through existing, ongoing and identified future projects based on surface water availability in Lower Chambal, Kalisindh and Parbati basins are 547346 ha, 569452 ha and 461417 ha, respectively. These values are 53%, 34% and 47%, of their respective basin culturable areas, respectively. Whereas annual irrigation through existing, ongoing and identified future projects based on surface water availability in Upper Chambal basin is 100948 ha (5.97% of the culturable area of the basin) which is less than 30% of the culturable area of the basin. For the enhancement of level of irrigation up to the extent of 30% (507078 ha), a provision of 2677 MCM of surface water has been made in this study. If this additional water requirement is not considered, then the basin is found marginally surplus (275.65 MCM) in overall water balance but deficit in surface water balance (1842.51 MCM) at 75% water year dependability. It shows that Upper Chambal basin needs serious considerations for water import from other basins through inter basin water transfers. As per the project report of Gandhi Sagar reservoir prepared by Madhya Pradesh state in respect of sharing of the Chambal waters, 3947 MCM of water is committed from Gandhi Sagar reservoir to meet the requirements of hydropower generation at Gandhi Sagar, Ranapratap Sagar and Jawahar Sagar reservoirs; and for downstream irrigation use. The water requirement for hydropower at Gandhi Sagar is assessed to be 584 MCM by the NWDA. The balance downstream committed use (3947-584 = 3363 MCM) is considered as the export from Upper Chambal basin to Lower Chambal basin. It indicates that in the absence of import water received from Upper Chambal, Lower Chambal basin would have been deficit in its surface water balance at 75% water year dependability.

There is no existing export from Kalisindh and Parbati basins, and it is observed that these two basins have the potential of exporting water annually to Upper Chambal or to

Lower Chambal basins by an amount of 1823 MCM and 2058 MCM, respectively. If the export can be made from Kalisindh and/or Parbati basins to Lower Chambal basin, then the export from Upper Chambal to Lower Chambal basin can be reduced.

### 10.4.2 The Mathematical Modeling Approach for Inter Basin Water Transfers

The modeling and analysis of multireservoir systems on the basis of river basin as a unit has been an important aspect of water resources planning and management, and the same was adopted in the current study for inter basin water transfers in Chambal basin. Identification and screening of the feasible solutions to provide potential candidates for detailed evaluation is a crucial stage during the search for optimal solution to real life problems. The overall effort in handling real life systems can be significantly reduced with screening models capable of better representing the system and providing fewer and more accurate candidate solutions for detailed evaluation, as the effort in a detailed evaluation is proportional to the number of candidate solutions to be evaluated and their proximity to the optimal solution. System engineering techniques were applied for studying and analyzing various aspects of the system and its response to various parameters by using optimization (LP and DP) and simulation models. Often these aspects are very complex with different objectives, scopes, scales and timing considerations. In such cases there is usually no unique model for the solution of the problems. A set of linked models (IGPYM using LP, PPM and CIM using DP, and simulation) were nested in such a fashion that outputs of one model were inputs to another or two models run in tandem. Use of nested models was found quite useful and is discussed in the following paragraphs.

#### 10.4.2.1 The improved general-purpose yield model (IGPYM)

This study demonstrates the feasibility and merits of the modeling approach employing the IGPYM with an application to the multireservoir system in the Chambal river basin. The

IGPYM is based on linear programming and is found to be a promising tool for handling multireservoir systems offering features like: flexible modeling structure with a straightforward translation of the concept of annual yield reliability and allowable deficit (failure fractions) in failure years while maintaining the identities of the individual water uses; superior estimates of the design and operating policy variables as compared to the earlier yield models; tractability of solutions and computational efficiency for large systems; and individual consideration of more number of compatible and incompatible water uses. The failure fractions applied to annual reservoir yields can be employed as a direct measure for the vulnerability of a reservoirs system. The output of the model can significantly improve the efficiency and accuracy of the subsequent detailed evaluations.

*Computational Aspect*

The numbers of continuity and reservoir capacity constraints in a complete linear model become very large when a large number of years and within year periods are considered. This is especially true if a number of reservoir sites are being considered. However, examination of solutions from reservoir storage models shows that it is only a relatively short sequence of flows within the total record of flows that generally determines the required active storage capacity in a reservoir. Since reservoir storage requirements are determined from critical periods of record, it is not necessary to include every period of every year in a reservoir storage yield model. Therefore the IGPYM reduced the numbers of storage continuity constraints and storage capacity constraints to a great extent. In a complete linear model, for a single reservoir for a hydrologic record of n (17) years, each having T (12) periods, the number of storage continuity and storage capacity constraints would have been 2nT (2 x 17 x 12 = 408). But in case of IGPYM, the numbers of constraints were reduced to 2(n+T) [2 x (17+12) = 58]. Correspondingly the numbers of variables were also reduced. Thus computationally the model became simpler.

*Reliability of Reservoir Yields*

The maximum flow that could be made available at a specific site by the regulation of the historic stream flows from a reservoir of a given size was referred here as the "firm yield" or "safe yield", i.e., this yield would always be available from the reservoir in future (i.e., 100% reliable). However firm yield has an annual reliability of 100% which could be only attained if in future years of reservoir operation no low flow periods will occur which are more severe than those occurred in the historic record. Cleary, this is not likely to be the case.

The annual reliability of a reservoir yield is governed by the length n (years) of the historic flow record and is estimated from a flow-duration analysis. For example, in this study the maximum possible annual reliability that the firm yield could attain in an analysis having 17 years of data was only 94.44% [17/(17+1) x 100%] and not 100%. Again annual target reliability, say 75% or 90%, could not be obtained directly by the above formula, only neighbouring reliabilities (72.22% and 77.78% or 88.89% and 94.44%) were obtained. This is a theoretical restriction. Of course, the yield corresponding to the desired reliability can be computed by interpolation from the model results.

The earlier multi yield models considered only annual firm and secondary yields. The models were applicable to a single purpose reservoir, say irrigation, where yields would be firm irrigation and secondary irrigation. In a multipurpose reservoir having two *compatible* yields, like irrigation and hydropower, where irrigation water could be used for power generation, these yields were firm irrigation, firm power, secondary irrigation and secondary power. Here, the secondary yield fails completely (zero yield) during failure years, otherwise it will add to the firm yield of the reservoir. If earlier yield models were applied to a multipurpose reservoir, having two *incompatible* water needs, lower priority water need (secondary yield) will fail completely during failure years, which is not desirable; and the higher priority water need (firm yield) will have the maximum possible reliability, which may not be required. So it was evident that the yield model as available in the previous form could not be applied with ease to all types of multipurpose reservoirs, especially serving incompatible water needs.

The IGPYM could resolve the above problem. Here the two annual yields, termed as priority and second, allowed the planner to select any desired number of failure years for a yield, i.e., the reliability of a yield could be less than the maximum possible reliability given by n/(n+1), unlike in previous yield models, where reliability of the firm yield had to be the maximum possible. The IGPYM also allows partial or total yield failures for both the priority and second yields during failure years. This modification allowed the planner to determine and analyze yield corresponding to a water need for any desired reliability, by changing the number of failure years. It added flexibility in selecting a proper annual reliability for a water need and derive a suitable design yield.

Further determinations of annual firm and secondary yields were also made possible. The annual firm yield is the failure fraction of priority yield times the annual priority yield plus the failure fraction of second yield times the annual second yield. The annual secondary yield is the annual total yield (priority yield plus second yield) minus the annual firm yield. With respect to the reliability aspect, IGPYM will behave similar to that given in Dahe and Srivastava (2002), if failure fraction of priority yield is made one for all the years and the failure fraction of second yield is made zero for failure years and one for successful years.

It is also observed that at a given reservoir, the desired reliabilities of both the priority and second yields are less than the maximum possible reliability given by n/(n+1), with or without complete yield failure for any yield (priority or second) during failure years. In such cases the system represented by the IGPYM is capable of supplying with desired reliabilities the given annual yields from reduced reservoir capacity, or higher annual yields with the given reservoir capacity. This was confirmed by simulation.

*Vulnerability of the System*

The flexibility in specifying separate values of failure fractions for both the priority yield and second yield at a reservoir in the system allowed the planner to monitor the extent of failure for a water use at the reservoir to get the desired annual yield. When water allocation priorities for different water needs are known, the failure fraction values can represent the vulnerability of the reservoir systems. In India, irrigation use has higher priority over water export. Let us consider the MOH reservoir in Case-1 (a) in Chapter 5 [Table 8.8 (a)]. Here the adopted failure fraction values for priority and second yields during failure years were 1 and 0.85, respectively. These failure fraction values were obtained by few trial runs of the IGPYM. For these trials, initially the failure fraction values were kept minimum (Table 8.7). Then the model was run with the objective function of maximizing the total annual reservoir yields. As the values of failure fractions were minimum, the model gave the maximum possible priority and second yields. Then the value of the failure fraction for priority yield was increased by trial to see the variation in the value of reservoir yields. The value of the failure fraction for priority yield was increased till the value of the reservoir yields did not decrease. This was done in order to know the maximum possible failure fraction value for priority yield, i.e., the maximum amount of priority yield that could be supplied even during a failure year, without decreasing the annual priority and second yields. After this value of failure fraction for priority yield was arrived, trials were made by varying the value of the failure fraction for second yield. Thus the value of the failure fraction for second yield was increased till the values of the annual priority and second yields did not decrease. For MOH reservoir these trials resulted in failure fraction values of 1.00 and 0.85 for annual priority (domestic water supply and irrigation) and second (water export) yields, respectively. The values of these yields were 144.00 MCM (Table 8.3) and 201.31 MCM [Table 8.8 (a)], respectively. It means if the reservoir is planned to operate in such a way that 100% of the annual domestic water supply and irrigation, and 85% of the annual water export will be made available during failure years; the reservoir can supply annually 144 MCM for domestic water supply and irrigation, and 201.31 MCM for water export during successful years. Now if an attempt is made to export 90% of the annual water export during failure years ($\theta_{p2,j}$=0.9), the annual water export during successful years is reduced from 201.31 MCM to 194.84 MCM [Table 8.8 (a)]. That is, the adopted value of failure fraction [e.g., 0.85 for second yield for MOH reservoir in Case-1(a)] for a yield (water need/needs) indicates the maximum amount of water that can be supplied for that/those water need/needs during failure years, without decreasing the annual reservoir yields during successful years. In other words, it can be said that the total annual reservoir yield would fail or the system is vulnerable if the yields corresponding to the failure years exceed the amount specified by the failure fractions for any yield. Thus the vulnerability of the system can be addressed.

### *Trade-off Between Water Uses*

Incorporation of the priority yield and second yield relation constraint (Eq. 5.61) helped in finding the trade-off between different water uses. When reservoir capacity is known, the model can be run to find the demands it can meet with desired reliabilities. In each run of the model, if a separate $\alpha_i$ value were used, the model would give a list of second yields corresponding to a list of priority yields. This would allow plotting of relationship between priority yield and second yield, thus the trade-off (e.g., Fig. 8.4).

### *Distribution of Regenerated Flows from Upstream Water Uses*

The modifications made in the within year equation 5.51 of a reservoir allows redistribution of the flows regenerated from upstream water uses and water imports, which is more logical. This provision was absent in the earlier versions of the yield models. To allow redistribution of regenerated flows and water imports, the basic assumption in the yield model that *the total* *inflow in the critical year is equal to the total yearly yield including evaporation in that year* is followed. The within the year continuity equation is so arranged, considering within year regenerated flows and imports, that the initial storage at the beginning of the year equals the storage at the end of the year in the critical year. Correspondingly the annual regenerated flows and imports are also added to reservoir inflows in the over year storage continuity equation 5.50. By these modifications, the basic assumption regarding critical years inflow in Loucks et al. (1981) is not violated and at the same time the model also allows redistribution of regenerated flows and water imports in the within year time periods.

*Modifications in the Power Equations*

In previous versions of the yield models, the firm reservoir yield was used for firm irrigation and firm hydropower generation (equations 5.40 and 5.42). Similarly the secondary reservoir yield was used for secondary irrigation and secondary hydropower generation (equations 5.40 and 5.43). The annual irrigation yield is distributed as per within the year (say, month) irrigation requirements and the annual firm energy is distributed as per within the year firm energy requirements. This may sometimes pose a limitation on the model, as the same volume of water (firm reservoir yield) is used for two compatible water needs, the model may not be able to adjust the water requirements for both the water needs as per their respective within the year distributions in each time period and may cause infeasibility in model runs. Equation (5.40) may allow adjustments in the model by reducing the annual firm irrigation yield and increasing the annual secondary irrigation yield in secondary yield successful years. But there is no such scope for failure years when secondary yield is zero, and the model is bound to give infeasible results. Dahe (2001) distributed the system firm energy from all the hydropower producing reservoirs as per within the year requirements to allow wider scope of adjustments by the model, and got feasible results. The modifications in the power equations in IGPYM allowed distribution of firm energy at a reservoir as per it's within the year firm energy requirements.

#### 10.4.2.2 The dynamic programming (DP) models

To consider water transfer in a system of reservoirs (sites), it was felt important to look into two aspects: (a) excess water availability at a source (export) point and (b) annual water demands both at source (export) and destination (import) points. The PPM looked after the estimation of annual water demands at destination points, and the CIM looked after the estimation of availability of water and annual water demands at source points. Initially it was assumed that at each reservoir all the known annual target water demands were to be met completely and the PPM found the amount of import of water required for doing so at all the importing reservoirs. The objective at the importing reservoir was to minimize penalties assigned in a given time period to water import, increase in the resulting reservoir end storage and reservoir spill. Water import penalty values were so selected that they encouraged water transfer, when excess water is available at the source point (water exporting reservoir) and discouraged otherwise. The penalty for increase in the reservoir end storage and reservoir spill were so selected that an importing reservoir is ready to accommodate in its storage high flows during monsoon periods and conserve water for non-monsoon periods. The PPM assumed that unlimited water is available at the upper most exporting reservoir (starting point of the water transfer link) and hence all the annual water demands could be met. This assumption is not practical, but the model was successful in giving the annual target water export demands for all the water exporting reservoirs.

The CIM fixed the annual design demands for all the water needs that can be met with respective prescribed reliabilities. Like the PPM, the objective for all the water importing, exporting and reservoirs not participating in the transfer, was to minimize the penalties assigned in a given time period to increase in the resulting reservoir end storage, reservoir spill and for not meeting the target demands. The penalty for storage and spill were selected similar to the PPM. The penalty for not meeting the water demands were so selected that priority water demands are met first. When the annual target water demands could not be met, the model revised these target water demands and gave annual design water demands that could be met with prespecified reliabilities for each water need.

The curse of dimensionality (Yakowitz, 1982) limited the application of the above DP models. The accuracy of the DP models depends on the state (storage) increment adopted. Ideally the errors in the important parameters, like end storage, reservoir releases and spill at each stage are within the size of the state increment adopted. The minimum storage (state) increment that allowed running the DP model programme was adopted for each reservoir. For big reservoirs, like GS, it is not possible to adopt a small state increment due to the curse of dimensionality. The adopted storage increment was 60, i.e., number of states was 128 for GS reservoir.

The objective of the work was to present a realistic and efficient dynamic programming modeling approach for reservoir planning and operation, related to a multipurpose, multi site reservoir system. The combined application of PPM and CIM can be very useful for inter basin water transfer projects. The PPM can be applied for reservoir planning only, whereas CIM is useful for both reservoir planning and operation. The CIM has the potential of optimal simulation where releases from reservoir for different purposes are done optimally.

#### 10.4.2.3 The simulation model

As per general perception and practice, simulation was carried out wherever needed for refining and testing various model results. Domestic water supply, irrigation, water export and hydropower demands were considered in the multi yield multireservoir simulation model. The total inflow to a reservoir i includes: catchments inflow, local inflow to reservoir from surrounding area, precipitation directly upon reservoir, regenerated flow from upstream water uses, and import to the reservoir. Provision was kept to add the spill of the reservoir at any given time to the water export yield at that time up to the permissible link canal capacity. Thus annual reservoir spill would decrease and the annual water utilization from the reservoir would increase. This provision also helped in comparing the results of reservoir operation by CIM and simulation.

#### 10.4.2.4 The summary of model results

The IGPYM results show that the annual target domestic water supply and irrigation demands (Table 3.11) can be met at all the reservoirs for both the Link Alternatives, with release reliabilities equal or more than the desired annual target reliabilities (Table 8.9). The trade-off curves (Fig. 8.4) for reservoir yields obtained for the design reservoir capacities can be very useful during the planning stages in deriving the information about the possible relative variations in reservoir yields. It is observed from IGPYM results that by a marginal increase in capacities of PAT and MOH reservoirs by 11 MCM for PAT and 12 MCM for MOH the required capacity of KUN reservoir can be reduced substantially by 350 MCM in Case-3I.1(a), such that they can meet the same annual domestic water supply and irrigation demands at each individual reservoir and also produce the same weighted system energy as obtained with design capacities. Similarly in Case-3II.1(a), these values are 30 MCM, 10 MCM and 678 MCM for PAT, MOH and KUN, respectively.

The applications of the dynamic programming models in planning stage show that:

(i) The target domestic water supply demands at all the time periods can be met, but the target irrigation and export demands in some months cannot be met, i.e., the design demands in these months are less than the target demands.

(ii) The power generation in case of Alternative I is always higher than that obtained in Alternative II (with maximum by 21% in Case-I3E5 and minimum by 7% in Case-I3C1).

(iii) When PPM is allowed to run without any constraint on amount of export, i.e., except in canal capacity option C1 and C2, where export release from KUN reservoir are prefixed, the water exports are mainly confined during monsoon periods (July, August and September), when excess water is generally available at a donor reservoir; and

(iv) The CIM results show that amount of import water required by an importing reservoir to meet its target demands are usually high in some months as compared to the amount of water that the exporting reservoirs can export. It is observed that the maximum target water export demand from all the water exporting reservoirs in all the cases occur in the month of September. The maximum deviations of monthly design water export from respective monthly target water export in PAT, MOH and KUN reservoirs are 83%, 76% and 100%, respectively. In PAT and MOH reservoirs, the maximum percentages of deviations occur in the month of September. In canal capacity option C (C1 and C2), the maximum percentage of deviation from KUN reservoir occurs in some of the non-monsoon months, where design water export is zero. In the month of September the maximum percentage of deviation from Kun reservoir is 62.

Reservoir operation indicated that in case of simulation, annual yields obtained from a reservoir for higher annual reliabilities are less and for lower annual reliabilities they are more as compared to the yields obtained from CIM [Fig. 9.6 (a) and Fig. 9.6 (b)]. This difference between simulation and CIM results is due to the fact that the CIM is an optimization model and optimally allocates yields recursively in all the periods, whereas simulation considers each time period individually. In simulation if sufficient water is available at any time period, it allocates water for various water needs as per priority, without considering the future scenario. In simulation, development of rule curves for operation at a reservoir may increase annual reservoir yields and improve their reliabilities.

Comparison of the model results for annual irrigation and hydropower yields at annual target reliabilities for Link Alternative I, for design reservoir and canal capacities are shown in Fig. 10.1 (a) and Fig. 10.1 (b). Simulation results for reservoir releases are taken as the basis for comparison. It is observed that irrigation releases from reservoirs obtained from IGPYM, CIM and simulation are very close to each other. Hydropower release from the system obtained by the IGPYM is quite high and it may be due to the inherent limitation of the linear programming models to deal with the non-linear energy functions. Dynamic programming models are known to be conservative and hence reservoir releases are less in CIM as compared to simulation.

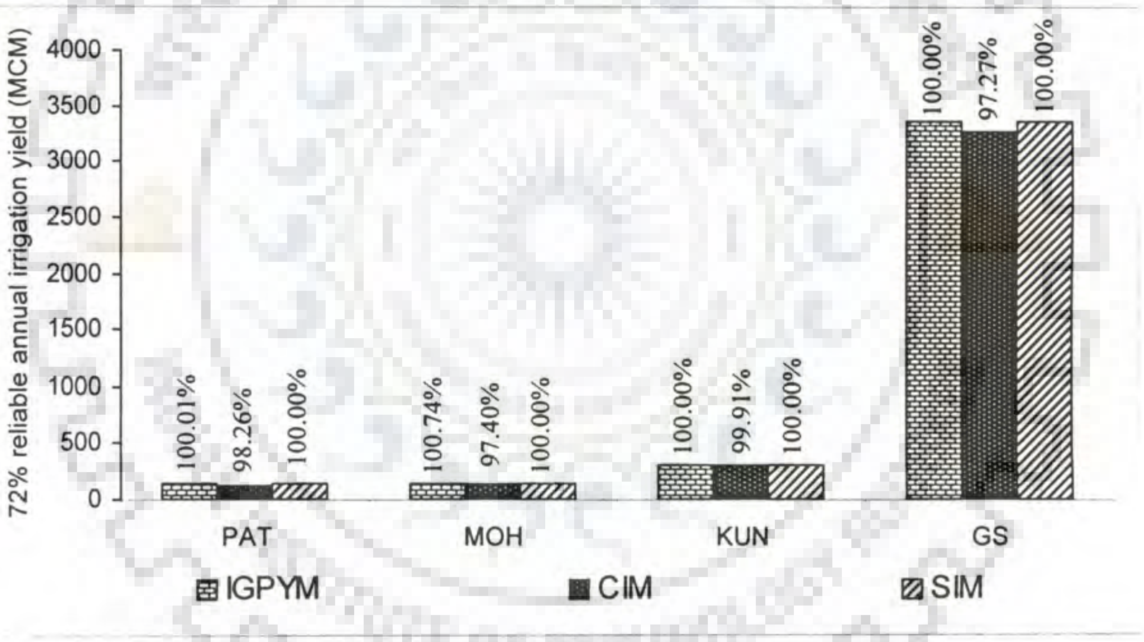

**Figure 10.1 (a)** Comparison of various model results for annual irrigation for design reservoir and canal capacities for Link Alternative I

Results show that annual yields for different water needs at different reliabilities obtained by CIM closely follow the results obtained by simulation for PAT, MOH, KUN and RPS reservoirs. CIM application for GS reservoir suffers from curse of dimensionality. Compared to the storage capacity of GS reservoir, a storage increment of 60 MCM seems to be acceptable. But compared to the water demands at some periods, this storage increment is very high. There are small spills at frequent intervals from GS reservoir due to discrete nature of the problem. Comparison of reservoir operation results for monthly yields by CIM and simulation shows that the monthly yields from each reservoir corresponding to different water needs are very close to each other. Percentage difference (the ratio of the difference between simulation and CIM results for a yield from a reservoir in a month to the yield for that purpose obtained by simulation in percentage) calculated for each water need from each reservoir in the system shows that for most of the months the difference between the irrigation yields obtained by the two models are very less (Table 9.7). The Nash-Sutcliffe Efficiencies calculated for all the reservoirs for all the yields are also very high (Table 9.7), which shows the efficiency of CIM.

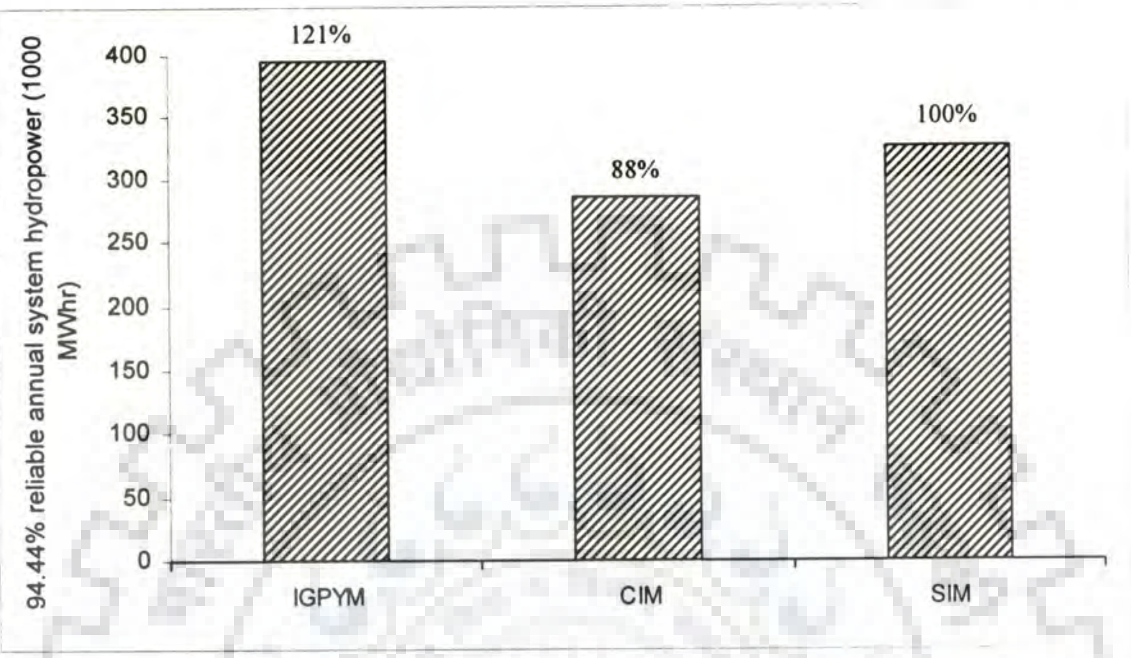

**Figure 10.1 (b)** Comparison of various model results for system annual hydropower for design reservoir and canal capacities for Link Alternative I

## 10.5 CONCLUSIONS

The objective of the present study was to develop a methodology for planning inter basin water transfer projects using system analysis techniques. Linear programming and dynamic programming were used as optimization techniques and simulation for testing the results. The developed methodology is demonstrated by applying it to the Chambal basin, involving three proposed reservoirs and two existing reservoirs.

The following conclusions may be drawn from the above study:

### 10.5.1 General

**Water Balance Study**

(1) Upper Chambal basin is severely suffering from water deficits. The basin is deficit by 1929 MCM in its surface water resources at 50% water year dependability but is marginally surplus by 189 MCM at 50% water year dependability, considering both surface and ground water (overall) resources. At 75% water year dependability the water balances are –4394 MCM and –2276 MCM for surface and overall water resources, respectively.

(2) Lower Chambal basin is marginally surplus by 1796 MCM in its surface water resources at 75% water year dependability due to the import of water (3363 MCM) it is receiving from Upper Chambal basin. Considering the overall water resources, the basin is surplus by 4544 MCM.

(3) Parbati and Kalisindh basins are surplus both in their surface and overall water resources. At 75% water year dependability, the surface water balances in Parbati and Kalisindh basins are 2058 MCM and 1823 MCM, respectively; and overall water balances are 3617 MCM and 4081 MCM, respectively.

(4) The above facts further support the proposal of NWDA for water transfers from Parbati and Kalisindh basins either to Upper Chambal or Lower Chambal basins.

(5) In Upper Chambal basin, the ratio of annual irrigation area under existing, ongoing and future irrigation projects to the culturable area is found 5.97. This value is far below 30% as recommended by NWDA for all basins. There is a need to enhance the level of irrigation in Upper Chambal basin.

### The Improved General Purpose Yield Model (IGPYM)

(1) The IGPYM incorporated the concept of two new yields, i.e., the priority and second. This made model capable of considering more than two numbers of water uses and different annual reliabilities for each water use in comparison to earlier yield models. These water uses are clubbed in two groups (yields), i.e. the priority and second, depending on total number of water needs to be considered in a reservoir.

(2) The model can be applied to both compatible and incompatible water uses.

(3) The model incorporates in the continuity equation of a reservoir the redistribution of the upstream regenerated flows. This provision was absent in the previous versions of the yield models.

(4) The model offers better flexibility in selecting annual reliabilities and deciding optimal yield failure fractions during failure years for different water uses.

(5) The model allows partial or total yield failure for both the priority and second yields during failure years.

(6) The model considers import of water to or export from a reservoir in the system.

(7) The vulnerability of the system can be examined by using separate values of failure fractions for both the priority and second yields at each reservoir in the system. This allows the planner to monitor the extent of failure during failure years for each water use to get desired annual yields.

(8) The incorporation of the priority yield and second yield relation constraint in the model helps in deriving the trade-offs among different water uses.

(9) The energy equations are improved to remove infeasibility conditions earlier experienced in the previous yield model applications, and at the same time the within the year demand distributions for irrigation and firm energy are also maintained.

(10) The IGPYM offers overall flexibility in its application, and possesses to be a better screening tool in planning. When compared with simulation the IGPYM provides optimistic results.

## Dynamic Programming (DP) Models

(1) The beauties of DP models were that they considered two major aspects (Chander, 2003; Sharma and Sarma, 2003) of water transfer, i.e., estimation of (i) surplus water availability at a source (exporting or donor reservoir) and (ii) annual design water demands for various water uses at the source and destination (importing or recipient reservoir).

(2) At the planning stage the PPM was able to determine import water requirements at a reservoir (needing export of water from a donor reservoir) to meet its annual target water demands completely, thereby determining the annual target water export demand at the donor reservoir.

(3) The CIM could determine at the planning stage the annual design water demands from the available annual target water demands for different water uses at a reservoir. The CIM also served as a tool for deriving reservoir operation policy.

(4) The CIM can be effectively used in sizing of reservoir capacity. It is has the potential of simulation where releases from reservoir for different purposes are done optimally.

(5) The combined use of PPM and CIM served the purpose of planning and operations for inter basin water transfer projects.

### 10.5.2 The Parbati-Kalisindh-Chambal Inter Basin Water Transfer Proposal

(1) Link Alternative I (PAT to MOH, MOH to KUN, and KUN to GS) is more promising than Link Alternative II (PAT to MOH, MOH to KUN, and KUN to RPS) with respect to meeting various annual water demands. Both the links provide almost the same annual irrigation yields, but annual hydropower yields are more in case of Link Alternative I, for a given set of reservoir and canal capacities.

(2) Among the various cases considered under Link Alternative I, Case-I3C1 gives best irrigation yield, Case-I3E5 gives best hydropower yield, and Case-I2C1 is a compromise between the two yields.

(3) Case-II2C2 is the best among all the cases considered under Link Alternative II.

(4) Adoption of the cases I3C1, I2C1, I3E5 and II2C2 will decrease the design capacity of KUN reservoir substantially at the cost of marginal increase in the design capacities at Patanpur and Mohanpura reservoirs.

## 10.6 RECOMMENDATION FOR FUTURE STUDY

- General practice of carrying water balance study of a river basin in India is on yearly basis. A monthly water balance study on an annual basis will depict a clearer picture of the temporal variation of water availability in the basin and will provide a better estimate of surplus and deficit.
- IGPYM can serve to estimate an initial trial policy for rule curve in reservoir operation. To illustrate how an operation rule can be developed, let us assume that a reservoir of given capacity and known annual design water demands is to serve three water purposes, i.e., domestic water supply (with maximum possible annual reliability), irrigation and either water export to other reservoirs or energy (with given annual reliabilities); in order of their priorities. Initially, the model is run with the objective function of minimizing the active storage at the end of the monsoon period

and considering only one water use, i.e., domestic water supply as the priority yield. The value of failure fraction for all the years is unity and the second yield is then essentially made zero. The model will give values of over year storage and within year storage requirements for all the time periods t. The sum of dead storage, over year storage and within year storage requirement in each period t defines the rule curve-I (water supply zone) for water supply, i.e., storage volume required in the reservoir to supply the domestic water need in each period t. The model can then be run with the same objective function and considering two water uses, i.e., domestic water supply and irrigation. Here, domestic water supply may be considered as the priority yield without allowing any failures (failure fraction values are unity for all the years) and irrigation may be considered as the second yield. The failure fraction values during failure years may be adopted as per any existing policy decision, like supplying at least 50% of irrigation yield during failure years, (i.e., $\theta_{p2,j} = 0.5$). From model results, the sum of dead storage, over year storage and within year storage for each time period will define the rule curve-II (irrigation supply zone) for irrigation. Lastly the model can be run considering all the three water uses. Two water uses may be clubbed and considered as priority yield. The sum of dead storage, over year storage and within year storage for each time period from model results will define rule curve-III (full supply zone) for meeting all the water needs. Any water stored above curve-III may be allowed to spill. Once developed, these rule curves may be refined by simulation. The application of hedging rule in reservoir operation (Awchi, 2004) then may be further explored.

- The DP models discussed were deterministic in nature. A stochastic analysis may give more realistic picture of water transfers.

- A multi-objective analysis of such problems is another field of investigation. This may include aspects such as socio-economic, environmental, legal, water demands, water availability, water rights, etc.

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*Annexure-I*

# ELEVATION-CAPACITY-AREA DATA OF RESERVOIRS

**Table I.1** Elevation-capacity-area data of Patanpur Reservoir

| Elevation (m) | Capacity (MCM) | Area (sq km) |
|---|---|---|
| 400.0 | 0.001 | 0.001 |
| 402.0 | 1.35 | 0.01 |
| 403.0 | 3.75 | 1.50 |
| 404.0 | 4.58 | 1.87 |
| 405.0 | 7.50 | 2.25 |
| 406.0 | 9.16 | 2.71 |
| 407.0 | 12.50 | 3.25 |
| 408.0 | 15.78 | 3.91 |
| 409.0 | 24.00 | 4.75 |
| 410.0 | 24.92 | 5.23 |
| 411.0 | 31.25 | 6.87 |
| 412.0 | 38.80 | 8.64 |
| 412.6 | 44.00 | 10.20 |
| 413.0 | 48.10 | 10.57 |
| 414.0 | 59.40 | 11.95 |
| 415.0 | 72.50 | 14.50 |
| 416.0 | 88.43 | 17.08 |
| 417.0 | 106.25 | 20.25 |
| 418.0 | 130.67 | 25.15 |
| 419.0 | 156.25 | 30.25 |
| 420.0 | 195.70 | 30.87 |

**Table I.2** Elevation-capacity-area data of Mohanpura Reservoir

| Elevation (m) | Capacity (MCM) | Area (sq km) |
|---|---|---|
| 378.50 | 0.00 | 0.00 |
| 379.00 | 0.00 | 0.02 |
| 380.00 | 0.05 | 0.08 |
| 382.00 | 0.46 | 0.33 |
| 384.00 | 1.49 | 0.71 |
| 386.00 | 3.72 | 1.52 |
| 388.00 | 7.54 | 2.30 |
| 389.00 | 10.60 | 3.09 |
| 390.00 | 13.71 | 3.87 |
| 392.00 | 23.94 | 6.36 |
| 393.00 | 32.40 | 8.40 |
| 394.00 | 40.75 | 10.46 |
| 395.00 | 52.50 | 12.45 |
| 396.00 | 65.68 | 14.47 |
| 398.00 | 97.79 | 17.65 |
| 400.00 | 140.64 | 25.20 |
| 402.00 | 198.30 | 32.46 |
| 404.00 | 270.48 | 39.73 |

**Table I.3** Elevation-capacity-area data of Kundaliya Reservoir

| Elevation (m) | Capacity (MCM) | Area (sq km) |
|---|---|---|
| 334.00 | 0.00 | 0.00 |
| 335.00 | 0.15 | 0.85 |
| 336.00 | 0.31 | 0.18 |
| 337.00 | 0.41 | 0.28 |
| 338.00 | 0.82 | 0.40 |
| 339.00 | 1.65 | 0.79 |
| 340.00 | 2.48 | 0.94 |
| 341.00 | 4.00 | 1.20 |
| 342.00 | 5.64 | 1.68 |
| 343.00 | 7.75 | 1.87 |
| 344.00 | 9.50 | 2.06 |
| 345.00 | 11.25 | 2.64 |
| 346.00 | 12.50 | 2.95 |
| 347.00 | 13.75 | 3.50 |
| 348.00 | 15.00 | 3.75 |
| 349.00 | 16.25 | 4.38 |
| 349.20 | 18.25 | 4.52 |
| 350.00 | 29.14 | 5.10 |
| 351.00 | 36.00 | 6.25 |
| 352.00 | 43.00 | 7.19 |
| 353.00 | 50.00 | 8.44 |
| 354.00 | 59.00 | 9.38 |
| 355.00 | 68.00 | 11.38 |
| 356.00 | 75.00 | 13.13 |
| 357.00 | 83.00 | 14.69 |
| 358.00 | 93.75 | 16.88 |
| 359.00 | 112.50 | 19.37 |
| 360.00 | 159.27 | 25.32 |
| 361.00 | 170.60 | 26.30 |
| 362.00 | 190.63 | 27.81 |
| 363.00 | 212.50 | 31.25 |
| 364.00 | 288.60 | 34.06 |
| 365.00 | 318.96 | 39.06 |
| 366.00 | 330.40 | 41.88 |
| 367.00 | 340.80 | 44.69 |
| 368.00 | 376.25 | 46.87 |
| 369.00 | 418.75 | 51.56 |
| 370.00 | 559.91 | 57.95 |
| 371.00 | 562.50 | 59.68 |
| 372.00 | 643.75 | 65.62 |
| 373.00 | 721.88 | 71.56 |
| 374.00 | 812.50 | 76.56 |
| 375.00 | 920.64 | 87.34 |
| 376.00 | 984.38 | 93.75 |
| 377.00 | 1062.50 | 101.25 |
| 378.00 | 1175.00 | 110.00 |
| 379.00 | 1284.38 | 121.25 |
| 380.00 | 1489.94 | 142.65 |

**Table I.4** Elevation-capacity-area data of Gandhi Sagar reservoir

| Elevation (m) | Capacity (MCM) | Area (sq km) |
|---|---|---|
| 374.90 | 312.07 | 41.80 |
| 375.21 | 326.87 | 45.65 |
| 375.51 | 340.44 | 49.33 |
| 375.82 | 357.71 | 53.01 |
| 376.12 | 374.98 | 56.66 |
| 376.43 | 392.25 | 60.46 |
| 376.73 | 411.98 | 65.15 |
| 377.04 | 431.72 | 69.77 |
| 377.34 | 453.92 | 75.27 |
| 377.65 | 478.59 | 80.94 |
| 377.95 | 503.26 | 86.60 |
| 378.26 | 530.40 | 90.24 |
| 378.56 | 558.77 | 93.89 |
| 378.87 | 587.14 | 99.55 |
| 379.17 | 619.21 | 101.37 |
| 379.48 | 650.05 | 105.22 |
| 379.78 | 684.58 | 109.87 |
| 380.09 | 717.89 | 114.53 |
| 380.39 | 754.89 | 118.98 |
| 380.70 | 791.90 | 123.83 |
| 381.00 | 832.60 | 145.69 |
| 381.30 | 888.11 | 150.95 |
| 381.61 | 931.28 | 155.80 |
| 381.91 | 962.12 | 160.66 |
| 382.22 | 1023.79 | 166.33 |
| 382.52 | 1066.96 | 171.59 |
| 382.83 | 1147.14 | 177.25 |
| 383.13 | 1184.14 | 182.11 |
| 383.44 | 1258.15 | 187.77 |
| 383.74 | 1307.49 | 193.44 |
| 384.05 | 1363.00 | 199.11 |
| 384.35 | 1424.67 | 204.77 |
| 384.66 | 1486.35 | 210.44 |
| 384.96 | 1549.25 | 216.91 |
| 385.27 | 1615.86 | 222.58 |
| 385.57 | 1683.70 | 229.05 |
| 385.88 | 1757.71 | 234.72 |
| 386.18 | 1831.72 | 241.60 |
| 386.49 | 1911.90 | 247.67 |
| 386.79 | 1985.91 | 254.55 |
| 387.10 | 2066.08 | 261.02 |
| 387.40 | 2152.43 | 267.50 |
| 387.71 | 2232.60 | 274.78 |
| 388.01 | 2318.95 | 281.66 |
| 388.32 | 2399.12 | 288.54 |
| 388.62 | 2485.47 | 295.42 |
| 388.92 | 2571.81 | 302.71 |
| 389.23 | 2664.32 | 309.58 |
| 389.53 | 2769.17 | 317.27 |
| 389.84 | 2861.68 | 324.96 |
| 390.14 | 2960.36 | 333.06 |
| 390.45 | 3059.04 | 341.15 |
| 390.75 | 3163.88 | 348.84 |
| 391.06 | 3274.90 | 357.74 |
| 391.36 | 3385.91 | 365.84 |
| 391.67 | 3496.92 | 374.33 |
| 391.97 | 3607.94 | 383.24 |
| 392.28 | 3725.12 | 392.55 |
| 392.58 | 3842.30 | 400.64 |
| 392.89 | 3984.15 | 410.35 |
| 393.19 | 4119.83 | 420.06 |
| 393.50 | 4255.52 | 429.78 |
| 393.80 | 4385.03 | 439.49 |
| 394.11 | 4514.55 | 449.61 |
| 394.41 | 4662.57 | 459.72 |
| 394.72 | 4804.42 | 469.44 |
| 395.02 | 4940.10 | 479.55 |
| 395.33 | 5106.62 | 489.67 |
| 395.63 | 5248.47 | 500.19 |
| 395.94 | 5402.66 | 510.71 |
| 396.24 | 5556.84 | 521.24 |
| 396.54 | 5729.53 | 532.16 |
| 396.85 | 5896.05 | 542.68 |
| 397.15 | 6056.40 | 554.42 |
| 397.46 | 6222.92 | 565.75 |
| 397.76 | 6389.44 | 576.68 |
| 398.07 | 6592.97 | 588.41 |
| 398.37 | 6759.49 | 600.15 |
| 398.68 | 6969.18 | 611.89 |
| 398.98 | 7154.20 | 623.62 |
| 399.29 | 7357.73 | 635.36 |
| 399.90 | 8449.34 | 688.68 |

**Table I.5** Elevation-capacity-area data of Ranapratap Sagar reservoir

| Elevation (m) | Capacity (MCM) | Area (sq km) |
|---|---|---|
| 317.75 | 0.00 | 0.00 |
| 319.28 | 7.03 | 2.61 |
| 320.80 | 14.19 | 5.22 |
| 322.33 | 22.70 | 7.81 |
| 323.85 | 31.21 | 10.44 |
| 325.37 | 73.76 | 19.47 |
| 326.90 | 119.28 | 28.57 |
| 328.42 | 167.51 | 37.43 |
| 328.73 | 178.86 | 39.25 |
| 329.03 | 189.96 | 41.04 |
| 329.34 | 201.30 | 42.90 |
| 329.64 | 212.78 | 44.64 |
| 329.95 | 224.25 | 46.54 |
| 330.25 | 238.06 | 48.56 |
| 330.56 | 252.25 | 50.30 |
| 330.86 | 267.05 | 52.20 |
| 331.17 | 281.23 | 54.03 |
| 331.47 | 298.50 | 55.85 |
| 331.77 | 315.52 | 57.67 |
| 332.08 | 331.81 | 59.49 |
| 332.38 | 355.24 | 61.43 |
| 332.69 | 368.81 | 63.05 |
| 332.99 | 388.92 | 65.07 |
| 333.30 | 408.90 | 66.69 |
| 333.60 | 428.64 | 68.47 |
| 333.91 | 451.45 | 70.33 |
| 334.21 | 473.66 | 72.12 |
| 334.52 | 496.48 | 74.06 |
| 334.82 | 519.30 | 75.80 |
| 335.13 | 545.20 | 77.70 |
| 335.43 | 570.49 | 79.44 |
| 335.74 | 596.39 | 81.14 |
| 336.04 | 621.68 | 83.16 |
| 336.35 | 650.05 | 84.98 |
| 336.65 | 678.42 | 87.21 |
| 336.96 | 707.40 | 89.44 |
| 337.26 | 737.62 | 91.38 |
| 337.57 | 762.29 | 93.48 |
| 337.87 | 791.90 | 95.51 |
| 338.18 | 822.73 | 97.12 |
| 338.48 | 853.57 | 99.63 |
| 338.79 | 971.98 | 101.78 |
| 339.09 | 917.71 | 103.60 |
| 339.39 | 947.31 | 105.95 |
| 339.70 | 979.39 | 108.05 |
| 340.00 | 1011.46 | 110.07 |
| 340.31 | 1042.29 | 112.10 |
| 340.61 | 1075.60 | 114.12 |
| 340.92 | 1110.13 | 116.35 |
| 341.22 | 1142.21 | 118.45 |
| 341.53 | 1176.74 | 120.60 |
| 341.83 | 1230.40 | 122.62 |
| 342.14 | 1245.82 | 124.64 |
| 342.44 | 1276.65 | 126.87 |
| 342.75 | 1317.36 | 128.69 |
| 343.05 | 1353.13 | 130.92 |
| 343.36 | 1393.84 | 157.02 |
| 343.66 | 1430.84 | 135.17 |
| 343.97 | 1471.55 | 137.19 |
| 344.27 | 1511.02 | 139.21 |
| 344.58 | 1554.19 | 141.24 |
| 344.88 | 1594.89 | 143.26 |
| 345.19 | 1638.07 | 145.48 |
| 345.49 | 1677.54 | 147.31 |
| 345.80 | 1714.54 | 149.53 |
| 346.10 | 1768.81 | 151.55 |
| 346.41 | 1813.22 | 153.58 |
| 346.71 | 1860.09 | 155.80 |
| 347.01 | 1909.43 | 157.83 |
| 347.32 | 1955.07 | 159.85 |
| 347.62 | 2005.64 | 161.87 |
| 347.93 | 2037.71 | 164.30 |
| 348.23 | 2074.72 | 166.33 |
| 348.54 | 2124.06 | 168.35 |
| 348.84 | 2177.10 | 170.78 |
| 349.15 | 2227.67 | 172.80 |
| 349.45 | 2281.94 | 174.82 |
| 349.76 | 2331.28 | 177.05 |
| 350.06 | 2460.80 | 179.28 |
| 350.37 | 2442.30 | 181.10 |
| 350.67 | 2466.97 | 183.73 |
| 350.98 | 2547.14 | 185.35 |
| 351.28 | 2602.65 | 187.77 |
| 351.59 | 2658.16 | 188.99 |
| 351.89 | 2713.66 | 192.23 |
| 352.20 | 2769.17 | 194.25 |
| 352.50 | 2824.68 | 196.27 |
| 352.81 | 2898.68 | 199.11 |
| 353.11 | 2981.33 | 202.18 |
| 353.42 | 3043.00 | 242.08 |
| 353.72 | 3108.38 | 209.14 |
| 354.03 | 3173.75 | 212.62 |
| 354.33 | 3237.89 | 214.36 |

*Annexure-II*

# STORAGE-AREA AND STORAGE-ELEVATION CURVES AT RESERVOIR SITES

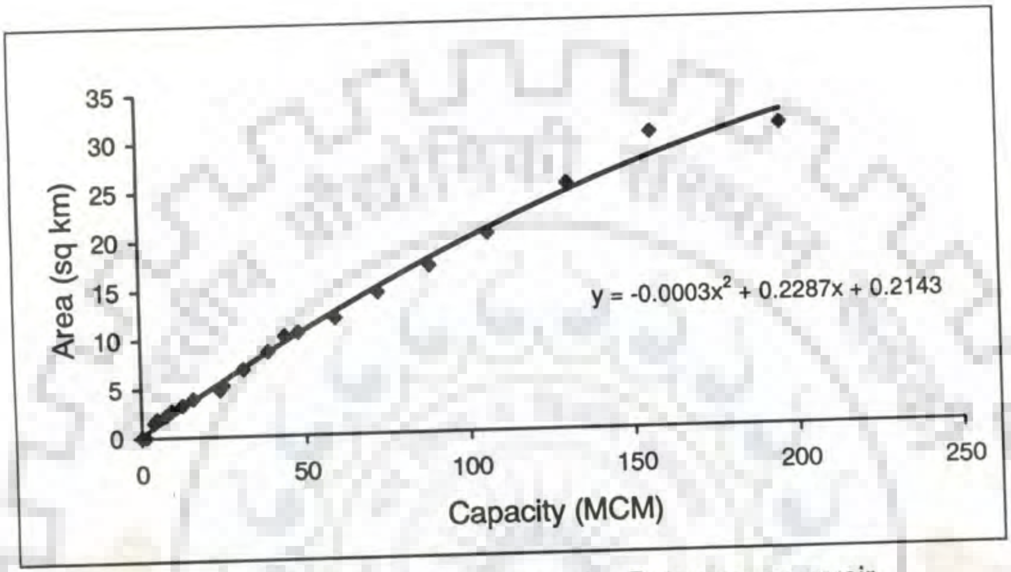

**Figure II.1** Storage-area curve for Patanpur reservoir

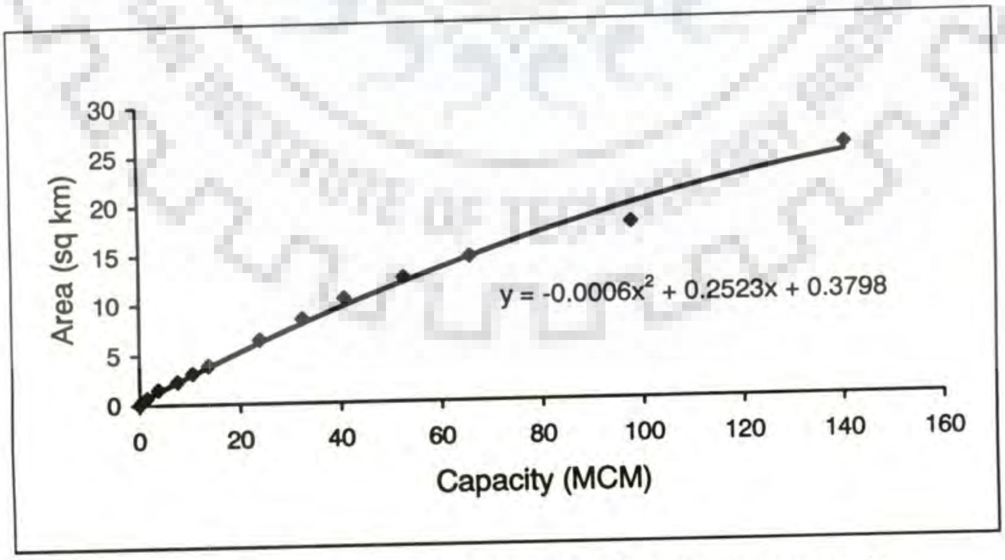

**Figure II.2** Storage-area curve for Mohanpura reservoir

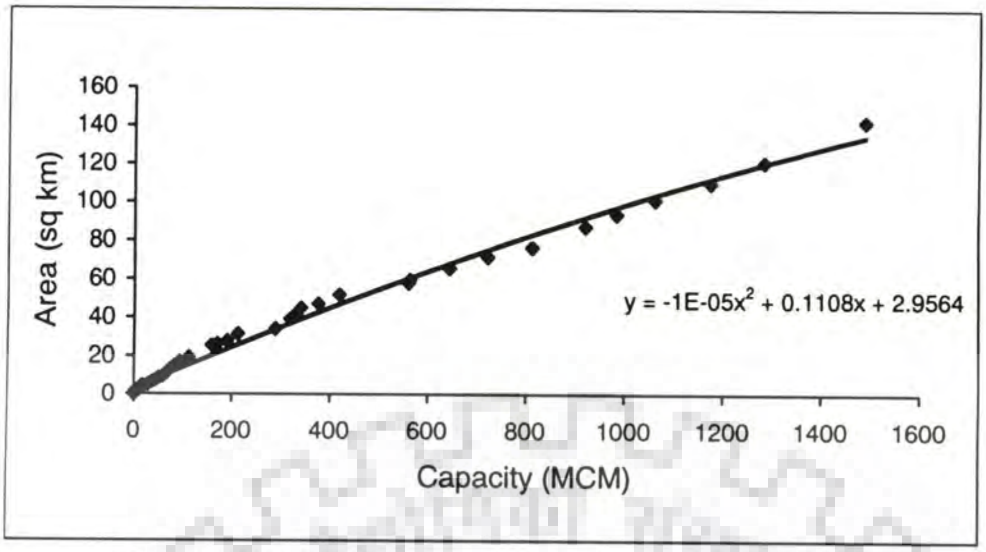

Figure II.3 Storage-area curve for Kundaliya reservoir

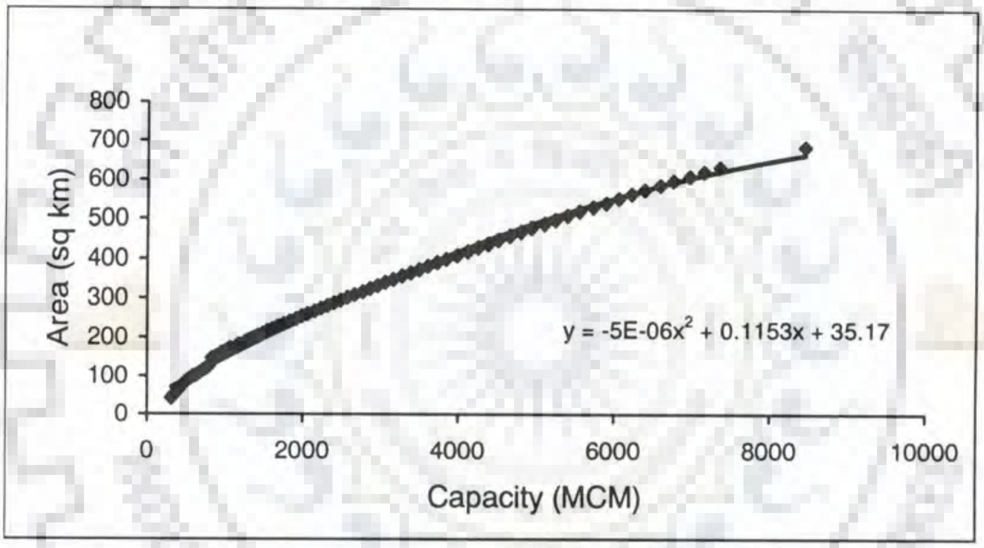

Figure II.4 Storage-area curve for Gandhi Sagar reservoir

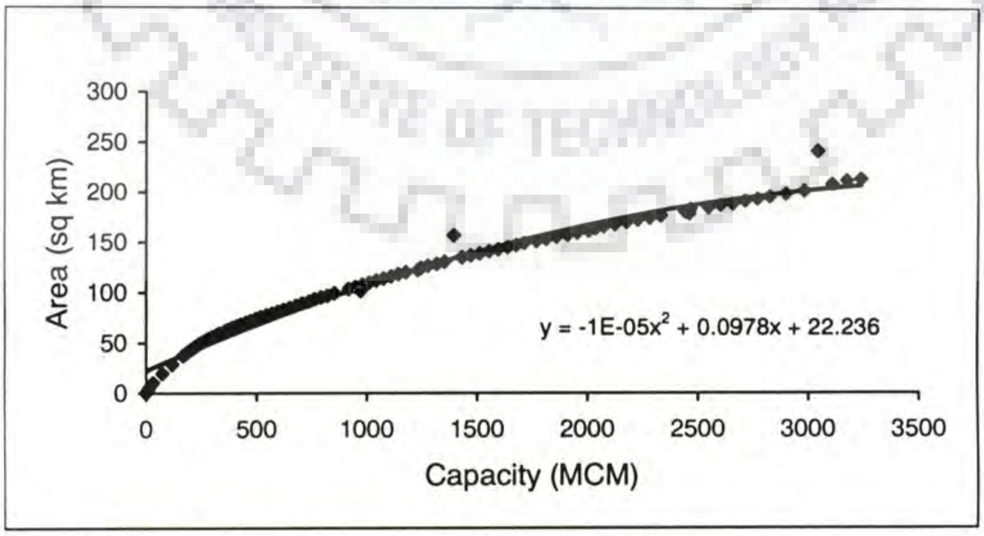

Figure II.5 Storage-area curve for Ranapratap Sagar reservoir

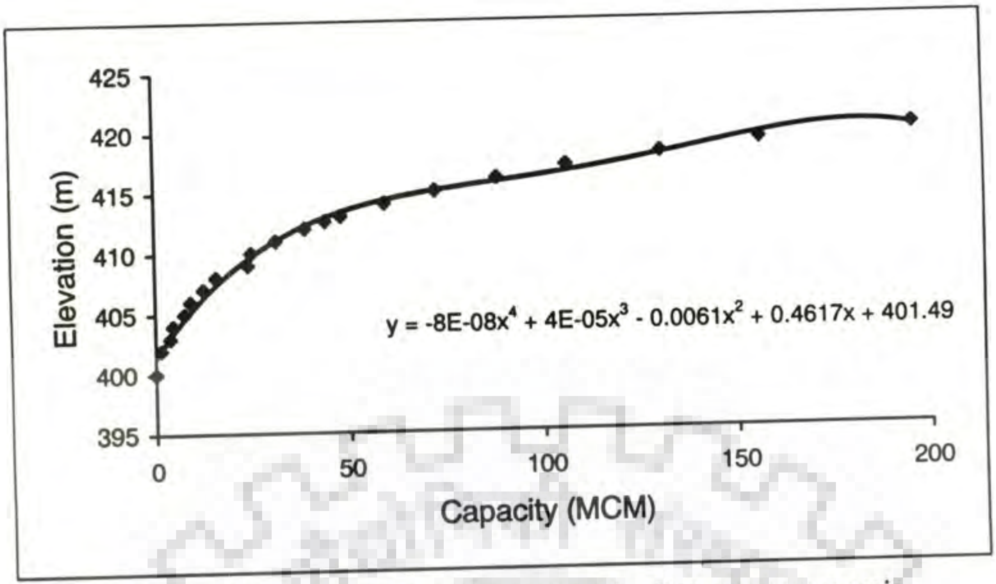

**Figure II.6** Storage-elevation curve for Patanpur reservoir

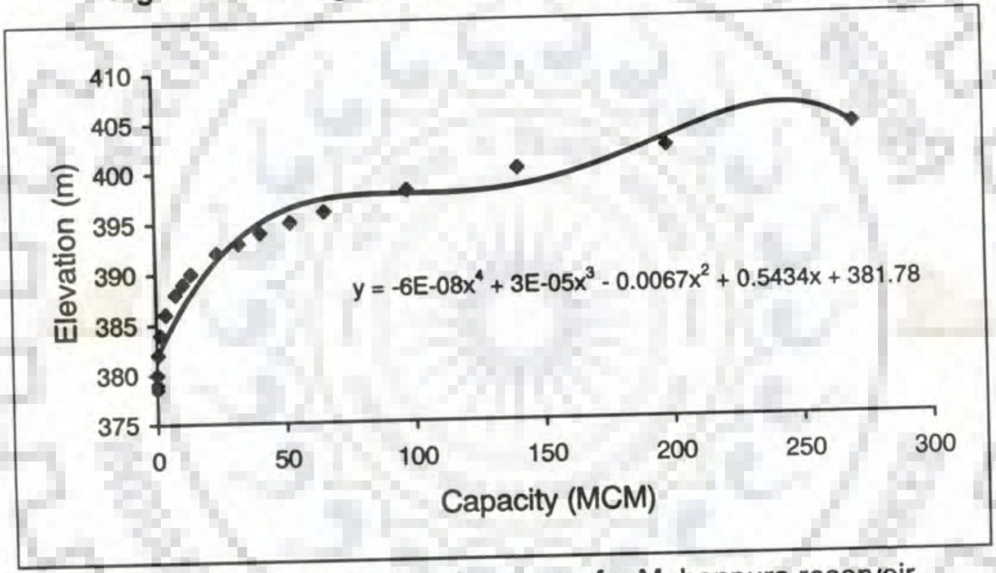

**Figure II.7** Storage-elevation curve for Mohanpura reservoir

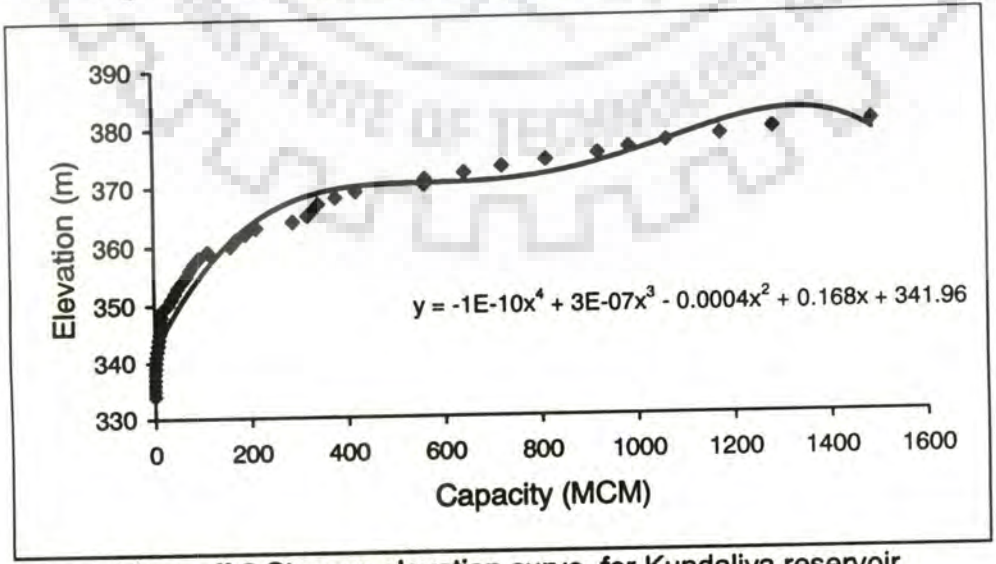

**Figure II.8** Storage-elevation curve for Kundaliya reservoir

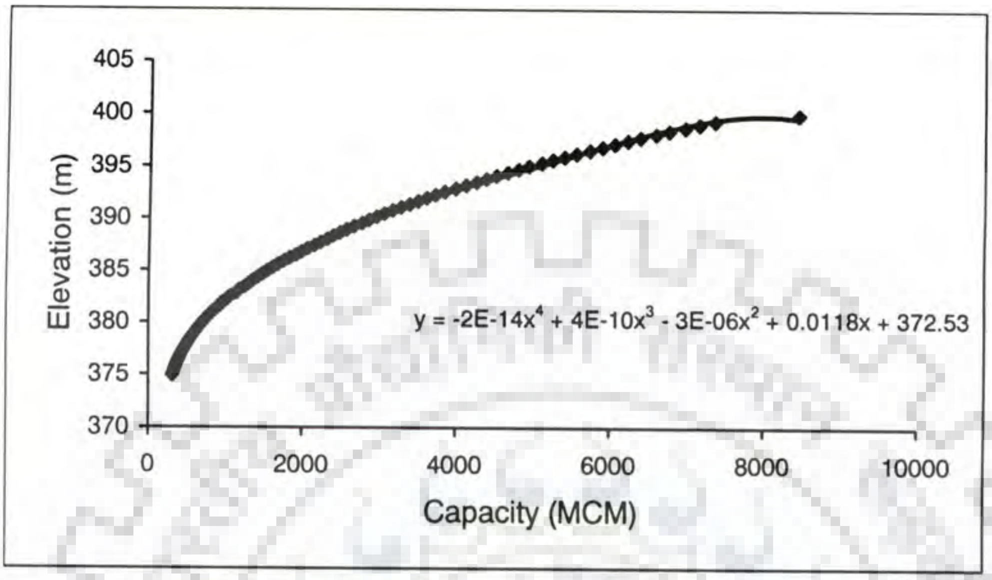

**Figure II.9** Storage-elevation curve for Gandhi Sagar reservoir

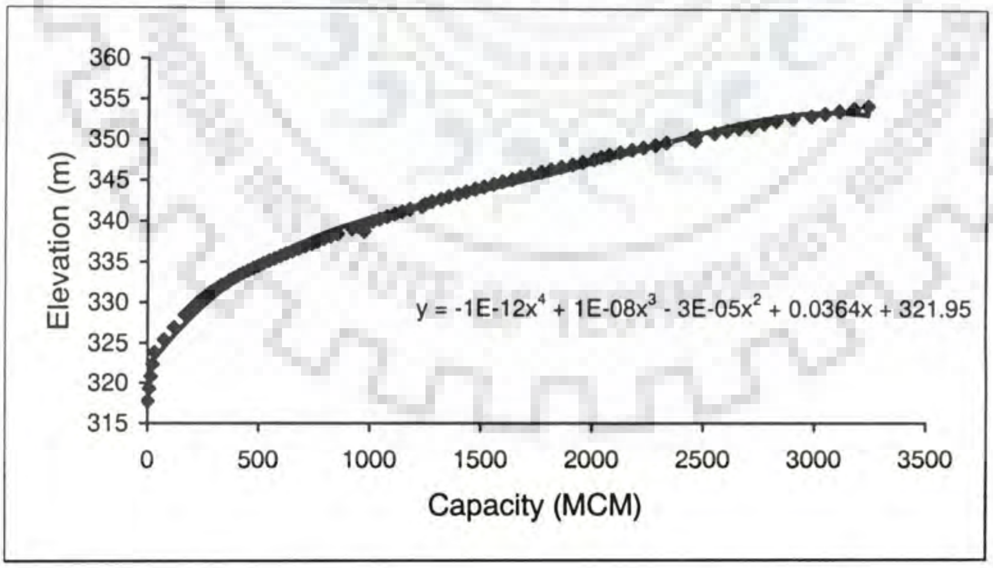

**Figure II.10** Storage-elevation curve for Ranapratap Sagar reservoir

*Annexure III (a)*

# Location of rain gauge stations in Upper Chambal, Lower Chambal, Kalisindh and Parbati basins

**Table III.1** Raingauge stations in Upper Chambal, Lower Chambal, Kalisindh and Parbati Basins

| Raingauge stations | Index used in the map | Raingauge stations | Index used in the map |
|---|---|---|---|
| Indore | a | Sheopur | C |
| Badnagar | b | Sabulgarh | D |
| Ujjain | c | Bijaipur | E |
| Dewas | d | Shahabad | F |
| Agar | e | Shivpuri | G |
| Khachrod | f | Guna | H |
| Salina | g | Sankatch | I |
| Jaora | h | Ashta | J |
| Sitamau | i | Shajapur | K |
| Neemuch | j | Shujalpur | L |
| Dhar | k | Sarangapur | M |
| Mhow | l | Biaora | N |
| Depalpur | m | Khilchipur | O |
| Taraha | n | Pirawah | P |
| Mahidpur | o | Pachpachar | Q |
| Mandsaur | p | Aklera | R |
| Manasa | q | Jhalawar | S |
| Garoth | r | Sangod | T |
| Begun | s | Angach | U |
| Hindoli | t | Itawah | V |
| Bindi | u | Ichhawar | W |
| Kota | v | Sehore | X |
| Naenwa | w | Narsingarh | Y |
| Indergarh | x | Chachaura | Z |
| Itawah | y | Aklera | a' |
| Antah | z | Chhipabarod | b' |
| Sawai Madhopur | A | Mangrol | c' |
| Khander | B | | |

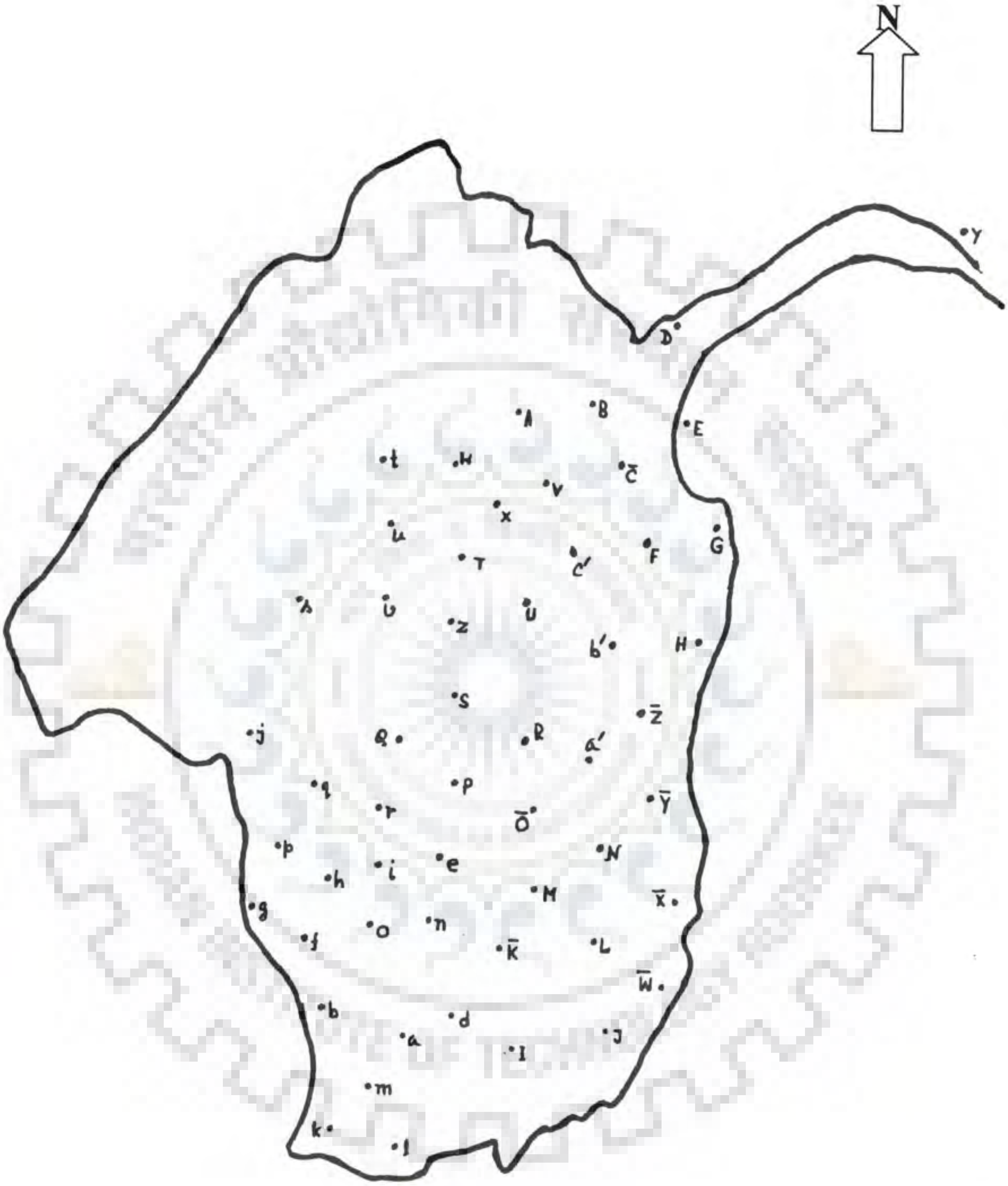

**Figure III.1** Location of raingauge stations in Upper Chambal, Lower Chambal, Kalisindh and Parbati basins.

# RAINFALL-RUNOFF RELATIONSHIP FOR VARIOUS BASINS

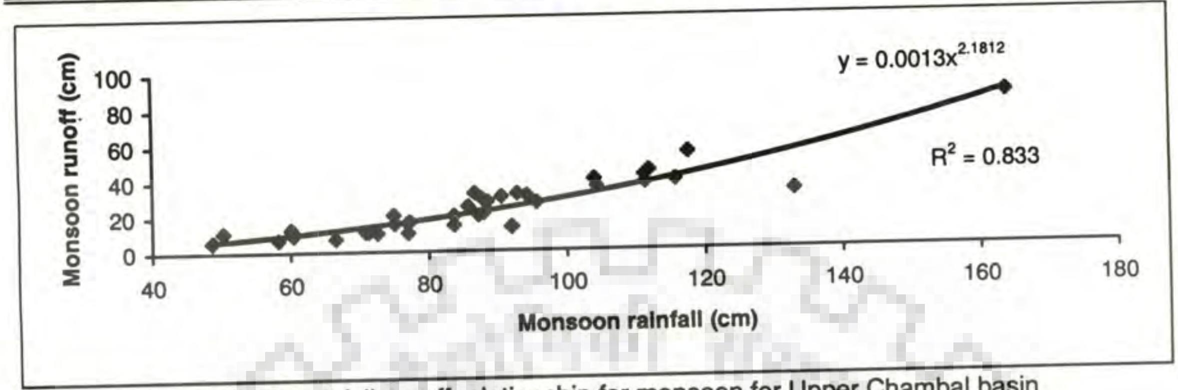

**Figure III.1** Rainfall-runoff relationship for monsoon for Upper Chambal basin

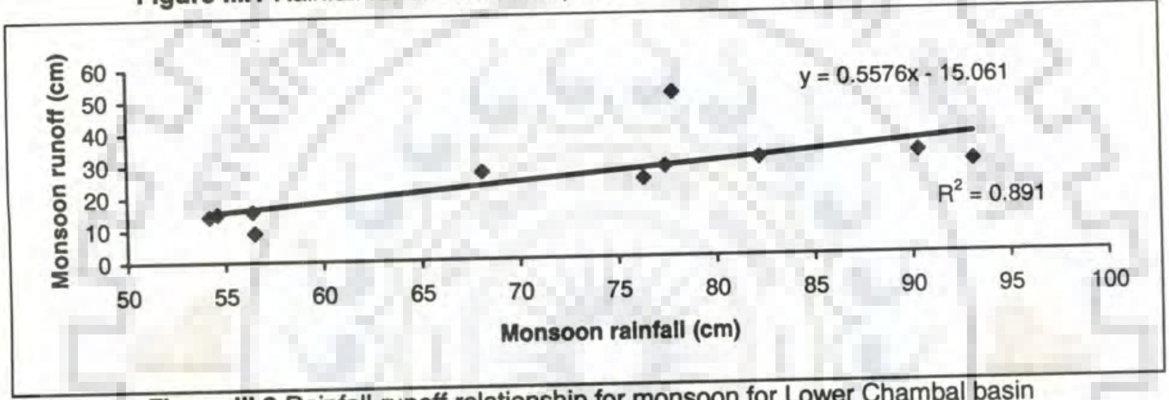

**Figure III.2** Rainfall-runoff relationship for monsoon for Lower Chambal basin

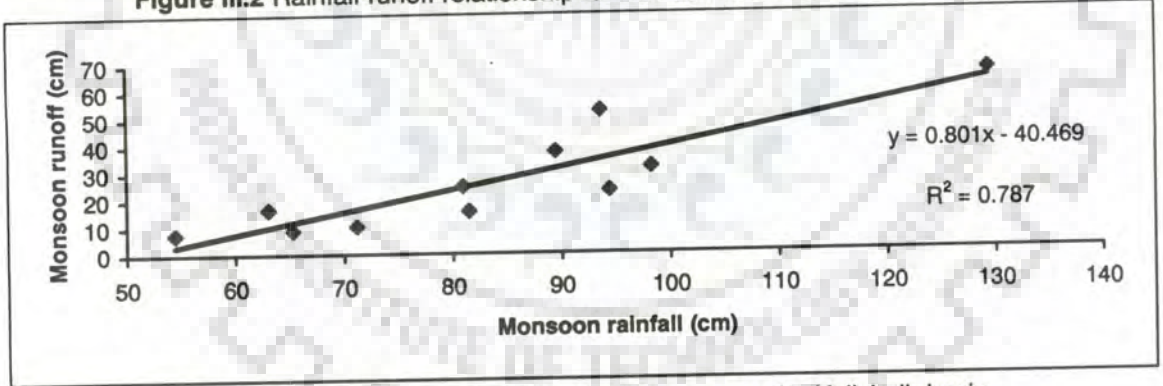

**Figure III.4** Rainfall-runoff relationship for monsoon for Kalisindh basin

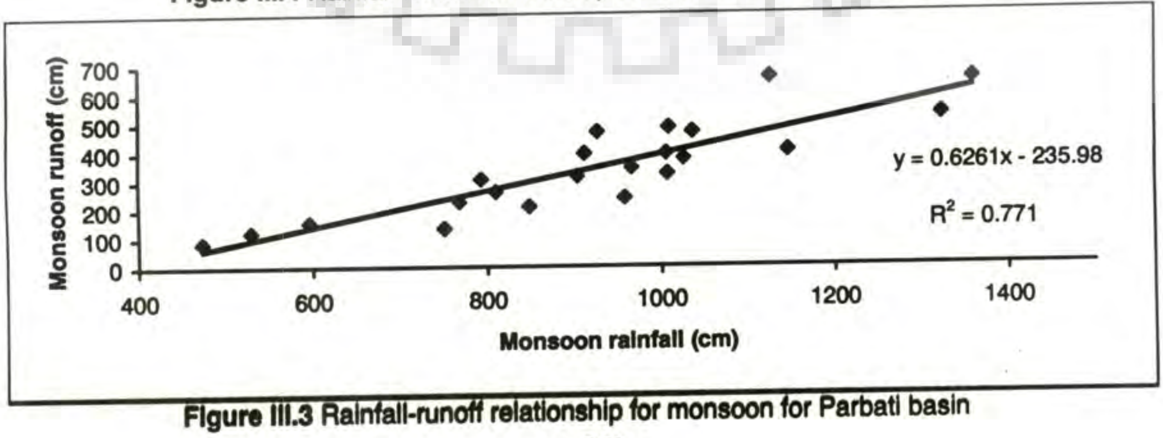

**Figure III.3 Rainfall-runoff relationship for monsoon for Parbati basin**

# GROUND WATER POTENTIAL AND EXISTING DRAFT

**Table IV.1** Ground water potential and existing draft from Upper Chambal basin

| District | Percentage of area lying in the basin | Total replenishable ground water resource from normal natural recharge (MCM/year) | Total replenishable ground water resource from canal irrigation system (MCM/year) | Total repleni-shable ground water resource (MCM/ year) | Provision for domestic, industrial & other uses (MCM/year) | Available ground water resource for irrigation in net terms (MCM/year) | Utilisable ground water resource for irrigation in net terms (MCM/ year) | Gross draft (MCM/ year) | Net draft (MCM/ year) | Balance ground water resource for future use (MCM/ year) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| **Madhya Pradesh** | | | | | | | | | | |
| Dewas | 14.26 | 121.91 | 2.99 | 124.90 | 18.74 | 106.16 | 95.54 | 51.41 | 35.99 | 70.17 |
| Dhar | 20.15 | 236.10 | 7.50 | 243.60 | 36.54 | 207.06 | 186.35 | 89.77 | 62.84 | 144.22 |
| Indore | 74.72 | 355.82 | 8.37 | 364.19 | 54.63 | 309.56 | 278.61 | 240.30 | 168.21 | 141.35 |
| Mandsaur | 67.75 | 687.53 | 17.62 | 705.15 | 105.77 | 599.38 | 539.44 | 323.17 | 226.22 | 373.16 |
| Ratlam | 60.34 | 312.86 | 12.55 | 325.41 | 48.81 | 276.60 | 248.94 | 178.06 | 124.64 | 151.96 |
| Shajapur | 10.40 | 41.39 | 4.11 | 45.50 | 6.83 | 38.67 | 34.80 | 25.13 | 17.59 | 21.08 |
| Ujjain | 93.82 | 498.93 | 115.40 | 614.33 | 92.15 | 522.18 | 469.96 | 272.36 | 190.65 | 331.53 |
| **Rajasthan** | | | | | | | | | | |
| Chittargarh | 8.74 | 51.75 | 2.67 | 54.42 | 8.16 | 46.26 | 41.63 | 38.05 | 26.63 | 19.63 |
| Jhalawar | 9.95 | 37.71 | 2.11 | 39.82 | 5.97 | 33.85 | 30.46 | 31.05 | 21.74 | 12.11 |
| Total | | 2344.00 | 173.32 | 2517.32 | 377.60 | 2139.72 | 1925.73 | 1249.30 | 874.51 | 1265.21 |

**Note:** Column (5)= Column (3) + Column (4); Column (6)= 15% of Column (5); Column (7)= Column (5) – Column (6); Column (8)= 90% of Column (7); Column (10)= 70% of Column (9); Column (11)= Column (7) – Column (10).

**Table IV.2** Ground water potential and existing draft from Lower Chambal basin

| District | Percentage of area lying in the basin | Total replenishable ground water resource from normal natural recharge (MCM/year) | Total replenishable ground water resource from canal irrigation system (MCM/year) | Total repleni-shable ground water resource (MCM/ year) | Provision for domestic, industrial & other uses (MCM/year) | Available ground water resource for irrigation in net terms (MCM/year) | Utilisable ground water resource for irrigation in net terms (MCM/ year) | Gross draft (MCM/ year) | Net draft (MCM/ year) | Balance ground water resource for future use (MCM/ year) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| **Madhya Pradesh** | | | | | | | | | | |
| Bhind | 6.27 | 36.12 | 18.61 | 54.73 | 8.21 | 46.52 | 41.87 | 13.33 | 9.33 | 37.19 |
| Guna | 5.45 | 47.72 | 3.61 | 51.33 | 7.70 | 43.63 | 39.27 | 9.07 | 6.35 | 37.28 |
| Mandsaur | 14.57 | 147.86 | 3.79 | 151.65 | 22.75 | 128.90 | 116.01 | 69.50 | 48.65 | 80.25 |
| Morena | 47.32 | 870.64 | 402.03 | 1272.67 | 190.90 | 1081.77 | 973.59 | 171.11 | 119.78 | 961.99 |
| Shivpuri | 19.37 | 153.88 | 8.74 | 162.62 | 24.39 | 138.23 | 124.40 | 45.85 | 32.09 | 106.14 |
| **Uttar Pradesh** | | | | | | | | | | |
| Agra | 8.51 | 48.86 | 38.38 | 87.24 | 13.09 | 74.15 | 66.74 | 58.70 | 41.09 | 33.06 |
| Etawah | 5.44 | 35.36 | 33.35 | 68.71 | 10.31 | 58.40 | 52.56 | 27.61 | 19.33 | 39.07 |
| **Rajasthan** | | | | | | | | | | |
| Bharatpur | 9.53 | 39.72 | 9.75 | 49.47 | 7.42 | 42.05 | 37.84 | 43.32 | 30.33 | 11.72 |
| Bhilwara | 12.03 | 61.44 | 15.71 | 77.15 | 11.57 | 65.58 | 59.02 | 42.33 | 29.63 | 35.95 |
| Bundi | 98.00 | 286.16 | 389.65 | 675.81 | 101.37 | 574.44 | 516.99 | 112.70 | 78.89 | 495.55 |
| Chittorgarh | 16.66 | 98.64 | 5.10 | 103.74 | 15.56 | 88.18 | 79.36 | 72.52 | 50.76 | 37.42 |
| Kota | 23.84 | 206.93 | 166.40 | 373.33 | 56.00 | 317.33 | 285.60 | 44.08 | 30.86 | 286.47 |
| Sawai Madhopura | 15.39 | 94.40 | 7.79 | 102.19 | 15.33 | 86.86 | 78.18 | 72.35 | 50.64 | 36.22 |
| Tonk | 6.01 | 24.65 | --- | 24.65 | 3.70 | 20.95 | 18.86 | 24.65 | 17.26 | 3.69 |
| Total | | 2152.38 | 1102.91 | 3255.29 | 488.30 | 2766.99 | 2490.29 | 807.12 | 564.99 | 2202.00 |

**Note:** Column (5)= Column (3) + Column (4); Column (6)= 15% of Column (5); Column (7)= Column (5) – Column (6); Column (8)= 90% of Column (7); Column (10)= 70% of Column (9); Column (11)= Column (7) – Column (10).

Table IV.3 Ground water potential and existing draft from Kalisindh basin

| District | Percentage of area lying in the basin | Total replenishable ground water resource from normal natural recharge (MCM/year) | Total replenishable ground water resource from canal irrigation system (MCM/year) | Total repleni-shable ground water resource (MCM/ year) | Provision for domestic, industrial & other uses (MCM/year) | Available ground water resource for irrigation in net terms (MCM/year) | Utilisable ground water resource for irrigation in net terms (MCM/ year) | Gross draft (MCM/ year) | Net draft (MCM/ year) | Balance ground water resource for future use (MCM/ year) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| **Madhya Pradesh** | | | | | | | | | | |
| Dewas | 30.44 | 260.23 | 6.39 | 266.62 | 39.99 | 226.63 | 203.96 | 109.74 | 76.82 | 149.81 |
| Guna | 1.73 | 15.15 | 1.15 | 16.30 | 2.45 | 13.86 | 12.47 | 2.88 | 2.02 | 11.84 |
| Mandsaur | 9.96 | 101.07 | 2.59 | 103.66 | 15.55 | 88.11 | 79.30 | 47.51 | 33.26 | 54.85 |
| Rajgarh | 87.29 | 917.85 | 64.33 | 982.18 | 147.33 | 834.85 | 751.37 | 289.63 | 202.74 | 632.11 |
| Sehore | 6.75 | 39.06 | 2.03 | 41.09 | 6.16 | 34.93 | 31.44 | 14.72 | 10.30 | 24.63 |
| Shajapur | 89.20 | 355.02 | 35.23 | 390.25 | 58.54 | 331.71 | 298.54 | 215.51 | 150.86 | 180.85 |
| Ujjain | 6.18 | 32.87 | 7.60 | 40.47 | 6.07 | 34.40 | 30.96 | 17.94 | 12.56 | 21.84 |
| **Rajasthan** | | | | | | | | | | |
| Chittorgarh | 1.51 | 8.94 | 0.46 | 9.40 | 1.41 | 7.99 | 7.19 | 6.57 | 4.60 | 3.39 |
| Jhalowar | 89.39 | 338.79 | 18.95 | 357.74 | 53.66 | 304.08 | 273.67 | 278.99 | 195.29 | 108.79 |
| Kota | 35.5 | 308.92 | 248.42 | 557.34 | 83.60 | 473.74 | 426.37 | 65.81 | 46.07 | 427.67 |
| Total | | 2344.66 | 383.86 | 2728.52 | 409.28 | 2319.25 | 2087.32 | 1029.12 | 720.39 | 1598.86 |

**Note:** Column (5)= Column (3) + Column (4); Column (6)= 15% of Column (5); Column (7)= Column (5) – Column (6); Column (8)= 90% of Column (7); Column (10)= 70% of Column (9); Column (11)= Column (7) – Column (10).

**Table IV.4** Ground water potential and existing draft from Parbati basin

| District | Percentage of area lying in the basin | Total replenishable ground water resource from normal natural recharge (MCM/year) | Total replenishable ground water resource from canal irrigation system (MCM/year) | Total replenishable ground water resource (MCM/year) | Provision for domestic, industrial & other uses (MCM/year) | Available ground water resource for irrigation in net terms (MCM/year) | Utilisable ground water resource for irrigation in net terms (MCM/year) | Gross draft (MCM/year) | Net draft (MCM/year) | Balance ground water resource for future use (MCM/year) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| **Madhya Pradesh** | | | | | | | | | | |
| Bhupal | 23.86 | 61.61 | 3.17 | 64.78 | 9.72 | 55.06 | 49.56 | 37.82 | 26.47 | 28.59 |
| Guna | 41.30 | 361.62 | 27.34 | 388.96 | 58.34 | 330.62 | 297.55 | 68.76 | 48.13 | 282.48 |
| Morena | 10.19 | 187.49 | 86.57 | 274.06 | 41.11 | 232.95 | 209.66 | 36.85 | 25.80 | 207.16 |
| Rajgarh | 12.72 | 133.75 | 9.37 | 143.12 | 21.47 | 121.65 | 109.49 | 42.20 | 29.54 | 92.11 |
| Sehore | 44.09 | 255.10 | 13.27 | 268.37 | 40.26 | 228.11 | 205.30 | 96.12 | 67.28 | 160.83 |
| Shajapur | 8.74 | 34.79 | 3.45 | 38.24 | 5.74 | 32.50 | 29.25 | 21.12 | 14.78 | 17.72 |
| Shivapuri | 0.23 | 1.83 | 0.10 | 1.93 | 0.29 | 1.64 | 1.48 | 0.54 | 0.38 | 1.26 |
| Vidisha | 5.23 | 35.12 | 7.26 | 42.38 | 6.36 | 36.02 | 32.42 | 4.31 | 3.02 | 33.01 |
| **Rajasthan** | | | | | | | | | | |
| Jhalowar | 0.64 | 2.43 | 0.14 | 2.57 | 0.39 | 2.18 | 1.97 | 2.00 | 1.40 | 0.78 |
| Kota | 39.52 | 343.03 | 275.85 | 618.88 | 92.83 | 526.05 | 473.44 | 73.07 | 51.15 | 474.90 |
| Total | | 1416.77 | 426.52 | 1843.29 | 276.49 | 1566.80 | 1410.12 | 382.79 | 267.95 | 1298.84 |

**Note:** Column (5)= Column (3) + Column (4); Column (6)= 15% of Column (5); Column (7)= Column (5) – Column (6); Column (8)= 90% of Column (7); Column (10)= 70% of Column (9); Column (11)= Column (7) – Column (10).

***Annexure-V***

# MONTHLY NET WATER REQUIREMENTS FOR DIFFERENT CROPS

**Table V.1** Monthly net water requirement for different crops in Upper Chambal basin (Unit: mm/month)

| Crop | Croping period | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Kharif** | | | | | | | | | | | | | | |
| Paddy<br>(122 days) | 1 Jun-30 Sep | 191.1 | 212.4 | 209.4 | 110.6 | | | | | | | | | 723.5 |
| Jowar/Foddar<br>(107 DAYS) | 1 Jul-15 Oct | | 10.5 | 18.6 | 15.1 | 26.1 | | | | | | | | 70.3 |
| Maize<br>(102 days) | 1 Jul-10 Oct | | 10.5 | 19.5 | 16.1 | 15.2 | | | | | | | | 61.3 |
| Oil seeds<br>(130 days) | 1 Jul-7 Nov | | 8.5 | 13.0 | 19.1 | 77.0 | 9.7 | | | | | | | 127.3 |
| Pulses<br>(107 days) | 16 Jun-30 Sep | 5.7 | 14.9 | 19.5 | 9.1 | | | | | | | | | 49.2 |
| **Rabi** | | | | | | | | | | | | | | |
| Wheat<br>(135 days) | 1 Nov-15 Mar | | | | | | 18.7 | 53.3 | 82.0 | 89.0 | 14.0 | | | 257.0 |
| Gram and other pulses<br>(141 days) | 21 Oct-10 Mar | | | | | 8.3 | 55.4 | 53.3 | 82.0 | 67.7 | 11.9 | | | 278.6 |
| Oil seed<br>(120 days) | 15 Oct-11 Feb | | | | | 21.1 | 55.4 | 72.7 | 56.3 | 22.4 | | | | 227.9 |
| Barley<br>(130 days) | 6 Nov-15 Mar | | | | | | 18.7 | 53.3 | 82.0 | 89.0 | 14.0 | | | 257.0 |
| Vegetables<br>(123 days) | 1 Oct-31 Jan | | | | | 38.4 | 55.4 | 80.5 | 75.6 | | | | | 249.9 |
| **Perrenial** | | | | | | | | | | | | | | |
| Sugarcane<br>(335 days) | 1 Feb-31 Dec | 69.2 | 21.3 | 10.6 | 20.1 | 93.4 | 60.0 | 37.8 | | 41.0 | 60.4 | 134.4 | 169.6 | 717.8 |

Stations: Neemuch (Latitude 240 28/ N, Longitude 740 54/ E); Indore (Latitude 220 43/ N, Longitude 750 48/ E); Ratlam (Latitude 230 19/ N, Longitude 750 03/ E).

**Table V.2** Monthly net water requirement for different crops in Lower Chambal basin (Unit: mm/month)

| Crop | Croping period | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Kharif** | | | | | | | | | | | | | | |
| Paddy (123 days) | 1Jul-31 Oct | | 166.6 | 211.9 | 232.3 | 194.9 | | | | | | | | 805.7 |
| Foddar (92 Days) | 1Jul-30 Sep | | 12.2 | 20.8 | 20.6 | | | | | | | | | 53.6 |
| Maize (102 days) | 1Jul-10Oct | | 12.2 | 21.8 | 34.2 | 16.2 | | | | | | | | 84.4 |
| Groundnut (130 days) | 1Jul-7Nov | | 9.7 | 14.5 | 49.5 | 73.9 | 8.7 | | | | | | | 156.3 |
| Pulses (90 days) | 1 Jul-7 Nov | | 12.2 | 21.8 | 19.8 | 3.7 | | | | | | | | 57.5 |
| Cotton (214 days) | 1 Jun-31 Dec | 40.5 | 17.2 | 14.5 | 60.5 | 108.9 | 56.3 | 35.6 | | | | | | 333.5 |
| Jowar (107 days) | 1Jul-15 Oct | | 12.2 | 20.8 | 29.3 | 21.6 | | | | | | | | 83.9 |
| Bajra (123 days) | 1 Jul-31 Oct | | 7.3 | 14.5 | 54.7 | 58.8 | | | | | | | | 135.3 |
| **Rabi** | | | | | | | | | | | | | | |
| Wheat (130 days) | 16 Nov-25 Mar | | | | | | 9.2 | 38.5 | 56.5 | 66.7 | 17.3 | | | 188.2 |
| Gram (141 days) | 22 Oct-10 Mar | | | | | 7.8 | 38.6 | 38.5 | 56.5 | 46.5 | 9.1 | | | 197.0 |
| Mustard (130 days) | 15 Oct-21 Feb | | | | | 12.1 | 48.8 | 59.0 | 34.3 | 18.9 | | | | 173.1 |
| Barley (130 days) | 6 Nov-15 Mar | | | | | | 15.3 | 53.5 | 51.5 | 56.7 | 10.4 | | | 187.4 |
| Foddar (182 days) | 15 Oct-15 Apr | | | | | 12.1 | 48.8 | 38.5 | 53.3 | 79.1 | 96 | 41.1 | | 368.9 |
| Vegetables (125 days) | 10 Nov-14 Mar | | | | | | 18.2 | 38.5 | 56.5 | 79.1 | 55.6 | | | 247.9 |
| **Perrenial** | | | | | | | | | | | | | | |
| Sugarcane (321 days) | 14 Feb-31 Dec | 153.4 | 24.2 | 20.8 | 29.3 | 73.9 | 33.6 | 26.8 | | 15.8 | 48.6 | 116.4 | 150.5 | 693.3 |

Stations: Kota (Latitude 250 11/N, Longitude 750 56/E); Sheopur (Latitude 25040/N, Longitude 76041/E).

### Table V.3 Monthly net water requirement for different crops in Kalisindh basin (Unit: mm/month)

| Crop | Croping period | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Kharif** | | | | | | | | | | | | | | |
| **Paddy (122 days)** | 1 Jun-30 Sep | 194.4 | 209.5 | 212.3 | 123.0 | | | | | | | | | 739.2 |
| **Jowar/Foddar (107 DAYS)** | 1 Jul-15 Oct | | 9.2 | 21.1 | 17.3 | 21.3 | | | | | | | | 68.9 |
| **Maize (102 days)** | 1 Jul-10 Oct | | 9.2 | 22.2 | 20.1 | 16.1 | | | | | | | | 67.6 |
| **Oil seeds (130 days)** | 1 Jul-7 Nov | | 7.4 | 14.8 | 31.5 | 65.2 | 7.7 | | | | | | | 126.6 |
| **Pulses (107 days)** | 16 Jun-30 Sep | 6.7 | 13.0 | 22.2 | 10.0 | | | | | | | | | 51.9 |
| **Rabi** | | | | | | | | | | | | | | |
| **Wheat (135 days)** | 1 Nov-15 Mar | | | | | | 14.0 | 37.7 | 58.8 | 71.3 | 11.5 | | | 193.3 |
| **Gram and other pulses (141 days)** | 21 Oct-10 Mar | | | | | 7.2 | 44.0 | 37.7 | 58.8 | 53.9 | 9.9 | | | 211.5 |
| **Oil seed (120 days)** | 15 Oct-11 Feb | | | | | 17.7 | 44.0 | 52.9 | 38.8 | 17.8 | | | | 171.2 |
| **Barley (130 days)** | 6 Nov-15 Mar | | | | | | 11.7 | 37.7 | 58.8 | 71.3 | 11.5 | | | 191.0 |
| **Vegetables (123 days)** | 1 Oct-31 Jan | | | | | 32.2 | 44.0 | 58.9 | 53.9 | | | | | 189.0 |
| **Perrenial** | | | | | | | | | | | | | | |
| **Sugarcane (321 days)** | 14 Feb-31 Dec | 81.2 | 18.6 | 21.1 | 36.8 | 73.6 | 47.8 | 25.6 | | 17.3 | 51.1 | 117.0 | 156.2 | 646.3 |

Station: Jhalawar (Latitude 240 32/N, Longitude 760 10/E).

**Table V.4** Monthly net water requirement for different crops in Parbati basin (Unit: mm/month)

| Crop | Croping period | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Kharif** | | | | | | | | | | | | | | 0.00 |
| Paddy (122 days) | 1Jun-30 Sep | 299.68 | 217.86 | 210.14 | 113.96 | | | | | | | | | |
| Maize (102 days) | 1 Jul-10 Oct | | 12.97 | 23.39 | 18.96 | 16.04 | | | | | | | | 71.36 |
| Oil seed (130 days) | 1 Jul-7 Nov | | 10.50 | 15.60 | 22.52 | 64.21 | 7.76 | | | | | | | 120.59 |
| Pulses (108 days) | 15 Jun-30 Sep | 6.75 | 18.38 | 23.39 | 10.66 | | | | | | | | | 59.18 |
| Jowar (107 days) | 1 Jul-15 Oct | | 13.30 | 22.28 | 17.78 | 21.38 | | | | | | | | 74.74 |
| Bajra (107 days) | 1 Jul-15 Oct | | 13.30 | 22.28 | 17.78 | 21.38 | | | | | | | | 74.74 |
| **Rabi** | | | | | | | | | | | | | | |
| Wheat (135 days) | 1 Nov-15 Mar | | | | | | 15.72 | 36.87 | 58.57 | 68.91 | 10.37 | | | 190.44 |
| Gram (141 days) | 21 Oct-10 Mar | | | | | 7.96 | 34.70 | 36.87 | 58.57 | 42.21 | 9.11 | | | 189.42 |
| Oil seed (120 days) | 15 Oct-11 Feb | | | | | 12.31 | 44.19 | 57.37 | 36.03 | 10.23 | | | | 160.13 |
| Barley (130 days) | 6 Nov-15 Mar | | | | | | 13.10 | 36.87 | 58.57 | 68.91 | 10.37 | | | 187.82 |
| Pulses (141 days) | 21 Oct-10 Mar | | | | | 7.96 | 34.70 | 36.87 | 58.57 | 42.21 | 9.11 | | | 189.42 |
| Vegetables (125 days) | 10 Nov-14 Mar | | | | | 50.39 | 69.35 | 54.47 | 52.13 | | | | | 226.34 |
| **Perrenial** | | | | | | | | | | | | | | |
| Sugarcane (321 days) | 14 Feb-31 Dec | 72.47 | 26.26 | 22.28 | 23.70 | 72.19 | 47.77 | 24.99 | | 16.27 | 48.55 | 118.96 | 150.65 | 624.09 |

Station: Guna (Latitude 240 39/ N, Longitude 770 19/E).

*Annexure-VI*

# WATER REQUIREMENT FOR THE FUTURE IRRIGATION PROJECTS IN VARIOUS BASINS IN CHAMBAL

**Table VI.1** Water requirement for the future irrigation projects in Upper Chambal basin

| Crops | Crop area (ha) | | Net water requirement (mm) | Net water requirement (ham) | |
|---|---|---|---|---|---|
| | Medium projects | Minor projects | | Medium projects | Minor projects |
| **Kharif** | | | | | |
| Paddy | 8826.0 | 3763.2 | 723.50 | 6385.61 | 2722.68 |
| Jowar | 1765.2 | 896.0 | 70.30 | 124.09 | 62.99 |
| Maize | 1765.2 | 716.8 | 61.30 | 108.21 | 43.94 |
| Oilseeds | 1765.2 | 716.8 | 127.30 | 224.71 | 91.25 |
| Pulses | 1765.2 | 716.8 | 49.20 | 86.85 | 35.27 |
| Fodder | 1765.2 | 716.8 | 70.30 | 124.09 | 50.39 |
| **Rabi** | | | | | |
| Wheat | 10591.2 | 5376.0 | 257.00 | 2721.94 | 1381.63 |
| Barley | 3530.4 | 1433.6 | 257.00 | 907.31 | 368.44 |
| Gram | 3530.4 | 716.8 | 278.60 | 983.57 | 199.70 |
| Pulses | 3530.4 | 716.8 | 278.60 | 983.57 | 199.70 |
| Oilseed | 1765.2 | 896.0 | 227.90 | 402.29 | 204.20 |
| Vegetable | 1765.2 | 716.8 | 249.90 | 441.12 | 179.13 |
| **Perennial** | | | | | |
| Sugarcane | 1765.2 | 537.6 | 717.80 | 1267.06 | 385.89 |
| Pre sowing water requirement (assumed 50 mm/ha for 20% of the rabi area) | | | | 247.13 | 98.56 |
| Net water requirement (including pre sowing water requirement) | | | | 15007.55 | 6023.75 |
| Gross irrigation requirement (55% and 70% irrigation efficiency for medium and minor projects, respectively) | | | | 27286.46 | 8605.36 |
| Evaporation loss (20% for medium and minor projects) | | | | 5457.29 | 1721.07 |
| Total water requirement | | | | 32743.75 | 10326.44 |
| Total water requirement for future irrigation projects in the basin | | | | | 43070.19 |

**Table VI.2** Water requirement for the future irrigation projects in Lower Chambal basin

| Crops | Crop area (ha) | | | Net water require -ment (mm) | Net water requirement (ham) | | |
|---|---|---|---|---|---|---|---|
| | Major projects | Medium projects | Minor projects | | Major projects | Medium projects | Minor Projects |
| **Kharif** | | | | | | | |
| Paddy | 6232.2 | 4981.4 | 1795.2 | 805.70 | 5021.32 | 4013.55 | 1446.41 |
| Jowar | 2492.9 | 1992.6 | 769.4 | 83.90 | 209.15 | 167.18 | 64.55 |
| Maize | 3116.1 | 2490.7 | 769.4 | 84.40 | 263.00 | 210.22 | 64.94 |
| Oilseeds | 3739.3 | 2988.9 | 1538.8 | 156.30 | 584.46 | 467.16 | 240.51 |
| Pulses | 3739.3 | 2988.9 | 1538.8 | 57.50 | 215.01 | 171.86 | 88.48 |
| Fodder | 2492.9 | 1992.6 | 769.4 | 53.60 | 133.62 | 106.80 | 41.24 |
| Cotton | 2492.9 | 1992.6 | 769.4 | 333.50 | 831.38 | 664.52 | 256.59 |
| Bajra | 2492.9 | 1992.6 | 769.4 | 135.30 | 337.29 | 269.60 | 104.10 |
| **Rabi** | | | | | | | |
| Wheat | 31161.2 | 24907.2 | 8976.1 | 188.20 | 5864.54 | 4687.54 | 1689.302 |
| Barley | 1869.7 | 1494.4 | 769.4 | 187.40 | 350.38 | 280.06 | 144.18 |
| Gram | 3116.1 | 2490.7 | 1282.3 | 197.00 | 613.88 | 490.67 | 252.61 |
| Oilseed | 6232.2 | 4981.4 | 2564.6 | 173.10 | 1078.80 | 862.29 | 443.93 |
| Vegetable | 3116.1 | 2490.7 | 1282.3 | 247.90 | 772.49 | 617.45 | 317.88 |
| Fodder | 1869.7 | 1494.4 | 769.4 | 368.90 | 689.72 | 551.30 | 283.82 |
| **Perennial** | | | | | | | |
| Sugarcane | 3739.3 | 2988.9 | 1282.3 | 693.30 | 2592.49 | 2072.18 | 889.02 |
| Pre sowing water requirement (assumed 50 mm/ha for 20% of the rabi area) | | | | | 1083.31 | 417.65 | 158.78 |
| Net water requirement (including pre sowing water requirement) | | | | | 20640.83 | 16050.01 | 6486.34 |
| Gross irrigation requirement (55%, 55% and 70% irrigation efficiency for major, medium and minor projects, respectively) | | | | | 37528.78 | 29181.84 | 9266.20 |
| Evaporation loss (10% for major and 20% for medium and minor projects) | | | | | 3752.88 | 5836.37 | 1853.24 |
| Total water requirement | | | | | 41281.65 | 35018.20 | 11119.44 |
| Total water requirement for future irrigation projects in the basin | | | | | | | 87419.29 |

**Table VI.3** Water requirement for the future irrigation projects in Kalisindh basin

| Crops | Crop area (ha) | | | Net water require -ment (mm) | Net water requirement (ham) | | |
|---|---|---|---|---|---|---|---|
| | Major projects | Medium projects | Minor projects | | Major projects | Medium projects | Minor Projects |
| **Kharif** | | | | | | | |
| Paddy | 42601.6 | 21630.0 | 19480.4 | 739.20 | 31491.10 | 15988.90 | 14399.94 |
| Jowar | 8520.3 | 4326.0 | 4638.2 | 68.90 | 587.05 | 298.06 | 319.57 |
| Maize | 8520.3 | 4326.0 | 3710.6 | 67.60 | 575.97 | 292.44 | 250.83 |
| Oilseeds | 8520.3 | 4326.0 | 3710.6 | 126.60 | 1078.67 | 547.67 | 469.76 |
| Pulses | 8520.3 | 4326.0 | 3710.6 | 51.90 | 442.20 | 224.52 | 192.58 |
| Fodder | 8520.3 | 4326.0 | 3710.6 | 68.90 | 587.05 | 298.06 | 255.66 |
| **Rabi** | | | | | | | |
| Wheat | 51121.9 | 25956.0 | 27829.2 | 193.30 | 9881.87 | 5017.29 | 5379.38 |
| Barley | 17040.6 | 8652.0 | 7421.1 | 191.00 | 3254.76 | 1652.53 | 1417.43 |
| Gram | 17040.6 | 8652.0 | 3710.6 | 211.50 | 3604.10 | 1829.90 | 784.78 |
| Pulses | 17040.6 | 8652.0 | 3710.6 | 211.50 | 3604.10 | 1829.90 | 784.78 |
| Oilseed | 8520.3 | 4326.0 | 4638.2 | 171.20 | 1458.68 | 740.61 | 794.06 |
| Vegetable | 8520.3 | 4326.0 | 3710.6 | 189.00 | 1610.34 | 817.61 | 701.30 |
| **Perennial** | | | | | | | |
| Sugarcane | 8520.3 | 4326.0 | 2782.9 | 646.30 | 5506.68 | 2795.89 | 1798.60 |
| Pre sowing water requirement (assumed 50 mm/ha for 20% of the rabi area) | | | | | 1192.84 | 605.64 | 510.20 |
| Net water requirement (including pre sowing water requirement) | | | | | 64875.42 | 32939.03 | 28058.88 |
| Gross irrigation requirement (55%, 55% and 70% irrigation efficiency for major, medium and minor projects, respectively) | | | | | 117955.31 | 59889.14 | 40084.12 |
| Evaporation loss (10% for major and 20% for medium and minor projects) | | | | | 11795.53 | 11977.83 | 8016.82 |
| Total water requirement | | | | | 129750.84 | 71866.97 | 48100.94 |
| Total water requirement for future irrigation projects in the basin | | | | | | | 249718.75 |

**Table VI.4** Water requirement for the future irrigation projects in Parbati basin

| Crops | Crop area (ha) | | | Net water require-ment (mm) | Net water requirement (ham) | | |
|---|---|---|---|---|---|---|---|
| | Major projects | Medium projects | Minor projects | | Major projects | Medium projects | Minor Projects |
| **Kharif** | | | | | | | |
| Paddy | 44216.0 | 9729.0 | 12672.2 | 841.64 | 37213.96 | 8188.32 | 10665.46 |
| Jowar | 8843.2 | 1945.8 | 3017.2 | 74.74 | 660.94 | 145.43 | 225.51 |
| Maize | 8843.2 | 1945.8 | 2413.8 | 71.36 | 631.05 | 138.85 | 172.25 |
| Oilseeds | 8843.2 | 1945.8 | 2413.8 | 120.59 | 1066.40 | 234.64 | 291.08 |
| Pulses | 8843.2 | 1945.8 | 2413.8 | 59.18 | 523.34 | 115.15 | 142.85 |
| Fodder | 8843.2 | 1945.8 | 2413.8 | 74.74 | 660.94 | 145.43 | 180.40 |
| **Rabi** | | | | | | | |
| Wheat | 53059.2 | 11674.8 | 18103.2 | 190.44 | 10104.59 | 2223.35 | 3447.57 |
| Barley | 17686.4 | 3891.6 | 4827.5 | 187.82 | 3321.86 | 730.92 | 906.70 |
| Gram | 17686.4 | 3891.6 | 2413.8 | 189.42 | 3350.16 | 737.15 | 457.21 |
| Pulses | 17686.4 | 3891.6 | 2413.8 | 189.42 | 3350.16 | 737.15 | 457.21 |
| Oilseed | 8843.2 | 1945.8 | 3017.2 | 160.13 | 1416.06 | 311.58 | 483.14 |
| Vegetable | 8843.2 | 1945.8 | 2413.8 | 226.34 | 2001.57 | 440.41 | 546.33 |
| **Perennial** | | | | | | | |
| Sugarcane | 8843.2 | 1945.8 | 1810.3 | 624.09 | 5518.95 | 1214.35 | 1129.80 |
| Pre sowing water requirement (assumed 50 mm/ha for 20% of the rabi area) | | | | | 1238.05 | 272.41 | 331.89 |
| Net water requirement (including pre sowing water requirement) | | | | | 71058.03 | 15635.15 | 19437.42 |
| Gross irrigation requirement (55%, 55% and 70% irrigation efficiency for major, medium and minor projects, respectively) | | | | | 129196.42 | 28427.54 | 27767.74 |
| Evaporation loss (10% for major and 20% for medium and minor projects) | | | | | 12919.64 | 5685.51 | 5553.55 |
| Total water requirement | | | | | 142116.06 | 34113.04 | 33321.29 |
| Total water requirement for future irrigation projects in the basin | | | | | | | 209550.40 |

# COMPUTER PROGRAM FOR PROCUREMENT PROBLEM MODEL

```
C     *****************************************************************
C       PROCUREMENT PROBLEM MODEL (PPM)
C     *****************************************************************
C       INFLOW, DEMAND, ACTIVE CAPACITY ARE KNOWN.
C       DECISION VARIABLE-WATER IMPORT AT ALL STAGES TO MEET
C       DEMANDS FULLY
C     *****************************************************************

C      PLSTI = PERMISSIBLE LOWER LIMIT ON INITIAL STATE AT 'T'
C      PUSTI = PERMISSIBLE UPPER LIMIT ON INITIAL STATE AT 'T'
C      PLSTF = PERMISSIBLE LOWER LIMIT ON FINAL STATE AT 'T'
C      PUSTF = PERMISSIBLE UPPER LIMIT ON FINAL STATE AT 'T'
C      PLSII = PERMISSIBLE LOWER LIMIT ON INITIAL STATE FOR
C          'ISTGO' STAGES TO GO
C      PUSII = PERMISSIBLE UPPER LIMIT ON INITIAL STATE FOR
C          'ISTGO' STAGES TO GO
C      PLSIF = PERMISSIBLE LOWER LIMIT ON FINAL STATE FOR
C          'ISTGO' STAGES TO GO
C      PUSIF = PERMISSIBLE UPPER LIMIT ON FINAL STATE FOR
C          'ISTGO' STAGES TO GO
C      GI = COST FUNCTION
C      CIT = UNIT COST AT STATE 'T'
C      CI = UNIT COST FOR 'ISTGO' STAGES TO GO
C      FLOWT = INFLOW AT STATE 'T'
C      FLOWI = INFLOW AT 'ISTGO' STAGES TO GO
C      PLLOT = PERMISSIBLE LOWER LIMIT ON OUTFLOW 'T'
C      PLLOI = PERMISSIBLE LOWER LIMIT ON OUTFLOW AT 'ISTGO'
C            STAGES TO GO.
C      PULOT = PERMISSIBLE UPPER LIMIT ON OUTFLOW 'T'
C      PULOI = PERMISSIBLE UPPER LIMIT ON OUTFLOW AT 'ISTGO'
C            STAGES TO GO.
C       PROPT = PRINT OPTION, '1' FOR PRINTING.
C                      1st=INPUT DATA
C                      2nd=PERMISSIBLE STATES.
C                      3rd=OPTIMAL FUNCTION VALUE
C                      4th=TABLE OF FEASIBLES
C                      5th=VALUES OF F
C                      6th=CONNECTIONS
C                      7th=OPTIMAL PATH TABLE
C      NOLOT = NO LIMIT ON OUTFLOW AT TIME 'T'
C      NOLOI = NO LIMIT ON OUTFLOW AT 'ISTGO' STAGES TO GO
```

```
C     ISTGO =  STAGES TO GO
C     FOT = FUNCTION VALUE AT THE END OF 'N'TH TIME PERIOD
C     F0I  = FUNCTION VALUE AT 0 STAGES TO GO
C     F   = OPTIMAL OBJECTIVE FUNCTION VALUE AT 'I'TH
C         INITIAL STATE
C     FMAX = MIXIMUM VALUE OF 'F'
C     FIMI1 = FUNCTION VALUE OF '(I-1)'TH STATE
C     OI=CURRENT DECISION AT 'I'TH INITIAL STATE (IN TERMS
C       OF CONNECTION WITH FIANL RESULTING 'II'TH STATE)
C     OIMI=OPTIMAL DECISIONS AT 'I'TH INITIAL STATE (IN TERMS
C        OF CONNECTION WITH FIANL RESULTING 'II'TH STATE)
C     NOI = NUMBER OF DECISIONS
C     N = NUMBER OF TIME PERIODS
C     IT = NUMBER OF TIME PERIODS
C     OIMIN= DECISION REGARDING STATE (RESULTING STATE)
      INTEGER delin, PROPT
      REAL LFAC
      DIMENSION  STORC(70), AREAC(70),ELEC(70),EDEP(204)
      DIMENSION FOT(250),F0I(250),FLOWT(204),STATA(250),EVDEP(204)
      DIMENSION GI(204,250),F(204,250),PROPT(10)
      DIMENSION PLSTI(204),PLSII(204),PUSTI(204),PUSII(204),PLSTF(204)
      DIMENSION PLSIF(204),PUSTF(204),PUSIF(204),NOI(204,250),NOLOI(204)
      DIMENSION OIMI(204,250,250),STATG(250),PLLOT(204),PULOT(204)
      DIMENSION PLLOI(204),PULOI(204),NOLOT(204),COSTTI(204)
      DIMENSION FLOWI(204),demndt(204),demndi(204),COSTTR(204)
      DIMENSION COSTSR(204),COSTSI(204),COSTSP(204),COSTSPI(204)
      DIMENSION DEMIRR(204), DEMIRRI(204),DEMSWI(204),DEMSW(204)
      DIMENSION DEMYEN(12),DEMEN(204),DEMENI(204),DEMEXPI(204)
      DIMENSION DEMYSW(12),DEMYIR(12),DEMEXP(204)
      DIMENSION DEMWIR(204),EVDEPT(12)

      COMMON/BLK1/FLOWI
      COMMON/BLK2/DELIN
      COMMON/BLK4/GI
      COMMON/BLK5/PLLOI,PULOI
      COMMON/BLK6/NOLOI
      COMMON/BLK7/F
      COMMON/BLK8/NOI,OIMI
      COMMON/BLK12/STATG
      COMMON/blk60/demndi,DEMSWI,DEMIRRI,DEMEXPI
      COMMON/BLK91/DEMSW,DEMIRR,DEMEXP,DEMWIR
      COMMON/blk61/COSTTI,COSTSI,COSTSPI
      COMMON/blk64/it,iopt
      COMMON/BLK70/STORC
      COMMON/BLK71/AREAC
      COMMON/BLK72/ELEC
      COMMON/BLK73/EDEP
      COMMON/BLK74/NPART
      COMMON/BLK75/DEADST
      COMMON/BLK80/PROPT
```

```
      COMMON/BLK81/PUSTI
      COMMON/BLK83/POPTION
      COMMON/BLK84/TWL,PCAP,LFAC,EFF
      COMMON/BLK85/DEMENI

      OPEN (unit=1, FILE='MAIN-FILE.dat', STATUS='OLD')
      OPEN (unit=2, FILE='PATH.out', STATUS='UNKNOWN')
      OPEN (unit=3, FILE='MAIN.OUT', STATUS='UNKNOWN')
      OPEN (unit=4, FILE='EV-AR-EL-CAP-FILE.dat', STATUS='OLD')
      READ(1,*)(PROPT(K),K=1,7)
      READ(1,67)CF
67    FORMAT(E10.2)
      READ(1,*)N
      READ(1,*)MAXNS
      READ(1,*)iobj
      READ(1,*)PLSTI(1),PUSTI(1)
      READ(1,*)(PLSTF(IT),IT=1,N)
      READ(1,*)(PUSTF(IT),IT=1,N)
      READ(1,*)DELIN
      READ(1,*)iopt
      if(iopt.eq.1)go to 5001
      if(iopt.eq.2)go to 5003
      GOTO 5003
5001  READ(1,*)(COSTTR(IT),IT=1,N)
      READ(1,*)(COSTSR(IT),IT=1,N)
      READ(1,*)(COSTSP(IT),IT=1,N)

      istgo=n
      DO 602 it=1,n
            COSTTI(istgo)=COSTTR(it)
            COSTSI(ISTGO)=COSTSR(IT)
            COSTSPI(ISTGO)=COSTSP(IT)
            istgo=istgo-1
602   CONTINUE

5003  READ(1,*)(NOLOT(IT),IT=1,N)
      DO 24 IT=1,N
            IF(NOLOT(IT).EQ.-1) GO TO 24
            READ(1,*)PLLOT(IT), PULOT(IT)
24    CONTINUE
      READ(1,*)(FLOWT(IT),IT=1,N)
      READ (1,*)(EVDEPT(MONTH),MONTH=1,12)
      READ(1,*)(DEMYSW(MONTH), MONTH=1,12)
      READ(1,*)(DEMYIR(MONTH), MONTH=1,12)
      READ(1,*)(DEMEXP(IT), IT=1,N)
      READ(1,*)(DEMYEN(MONTH),MONTH=1,12)

      MONTH=1
      DO IT=1,N
            DEMSW(IT)=DEMYSW(MONTH)
```

```
            DEMIRR(IT)=DEMYIR(MONTH)
            DEMEN(IT)=DEMYEN(MONTH)
            DEMNDT(IT)=DEMSW(IT)+DEMIRR(IT)+DEMEXP(IT)
            DEMWIR(IT)=DEMSW(IT)+DEMIRR(IT)
            EVDEP(IT)=EVDEPT(MONTH)
            MONTH=MONTH+1
            IF (MONTH.EQ.13) MONTH=1
      ENDDO
      DO 25 I3=1,N
            EDEP(I3)=EVDEP(N+1-I3)
 25   CONTINUE

      READ(1,*)(FOT(IR),IR=1,MAXNS)
      READ(1,*)ISG
      READ(1,*)(STATA(IL),IL=1,ISG)
      READ(1,*)POPTION

      IF (PROPT(1).NE.1)GOTO 240
      WRITE(2,*)'Number of Periods=',n
      WRITE(2,*)'Max. number of states=',maxns
      IF (iobj.eq.1)WRITE(2,*)'Objective Function is Maximizing'
      IF (iobj.eq.-1)WRITE(2,*)'Objective Function is Minimizing'
      WRITE(2,*)'Permissible Lower Limit on Initial State at (T)=',plsti
      1(1)
      WRITE(2,*)'Permissible Upper Limit on Initial State at (T)=',plsti
      1(1)
      WRITE(2,*)'State Increment is =',delin
      L=0
      DO 233 K=1,N
            J=0
            IF (NOLOT(K).EQ.-1)GOTO 233
            L=1
            IF (J.EQ.0)WRITE(2,*)'=================================='
            IF (J.EQ.0)WRITE(2,*)'  IT      UP.LIMIT       LO.LIMIT'
            IF (J.EQ.0)WRITE(2,*)'=================================='
            J=1
            WRITE(2,*)IT,PLLOT(K),PULOT(K)
233   CONTINUE
      IF (L.EQ.0)WRITE(2,*)'NO LIMITATIONS ON OUTPUT'
      WRITE(2,*)'NUMBER OF INITIAL STATES=',ISG
240   IF(N.EQ.1)GO TO 510
      DO 502 IT=2,N
            PLSTI(IT)=PLSTF(IT-1)
            PUSTI(IT)=PUSTF(IT-1)
 502  CONTINUE
 510  IF (PROPT(2).NE.1)GOTO 650
      WRITE(2,126)
 126  FORMAT(2X,'THE PERMISSIBLE STATES ARE'/)
      DO 501 IT=1,N
      WRITE(2,*)PLSTI(IT),PUSTI(IT)
```

```
      WRITE(2,*)PLSTF(IT),PUSTF(IT)
501   CONTINUE
650   READ (4,*) NPART
      READ (4,*)(STORC(J),J=1,NPART)
      READ (4,*)(AREAC(J),J=1,NPART)
      READ (4,*)(ELEC(J),J=1,NPART)
      READ (4,*)DEADST
      READ (4,*) TWL,PCAP,LFAC,EFF
      DO 100 IR=1,MAXNS
              F0I(IR)=FOT(IR)
100   CONTINUE
      IF (PROPT(3).NE.1) GOTO 651
      WRITE(2,128)
128   FORMAT(2X,'OPTIMAL FUNCTION VALUE FOR 0 STAGE TO GO'/)
      WRITE(2,*)(F0I(I),I=1,MAXNS)
651    IF (PROPT(4).NE.1) GOTO 652
      WRITE(2,129)
129   FORMAT(2X,60('=')/,8x,'IT',6X,'ISTGO',8X,'I',6X,'II'
     1, 8X,'NOFEA',8X,'GI(ISTGO,I)',/,2X,60('-')//)
652   IT=N
      ISTGO=1

5   DO 400 IR=1,MAXNS
              F(ISTGO,IR)=-1
              DO 4 K=1,MAXNS
                     OIMI(ISTGO,IR,K)=-1
4             CONTINUE
400    CONTINUE
       PLSII(ISTGO)=(PLSTI(IT)/delin)+1
       PUSII(ISTGO)=(PUSTI(IT)/delin)+1
       PLSIF(ISTGO)=(PLSTF(IT)/delin)+1
       PUSIF(ISTGO)=(PUSTF(IT)/delin)+1
       PLLOI(ISTGO)=(PLLOT(IT)/DELIN)
       PULOI(ISTGO)=(PULOT(IT)/DELIN)
       FLOWI(ISTGO)=(FLOWT(IT)/DELIN)
       DEMNDI(ISTGO)=DEMNDT(IT)/DELIN
       DEMSWI(ISTGO)=DEMSW(IT)/DELIN
       DEMIRRI(ISTGO)=DEMIRR(IT)/DELIN
       DEMEXPI(ISTGO)=DEMEXP(IT)/DELIN
       DEMENI(ISTGO)=DEMEN(IT)
       NOLOI(ISTGO)=NOLOT(IT)
       SI=PLSII(ISTGO)
       I=SI
3      II=PLSIF(ISTGO)
       NOI(ISTGO,I)=0
       if(iobj.eq.1)fmax=-CF
       if(iobj.eq.-1)fmax=CF
2      IF(PLSIF(ISTGO).NE.PUSIF(ISTGO))GO TO 20
       CALL CONNECT(I,II,ISTGO,NOFEA)
       IF(NOFEA.EQ.-1)GO TO 19
```

```
      SIMI1=PUSIF(ISTGO)
      IMI1=II
      OI=II
      CALL FUNCT(I,II,ISTGO)
      IF(ISTGO.EQ.1)FIMI1=F0I(IMI1)
      IF(ISTGO.GT.1)FIMI1=F(ISTGO-1,IMI1)
      IF (PROPT(4).EQ.1)write (2,*) fimi1
      IF(fimi1.eq.-1)nofea=-2
      IF (PROPT(4).NE.1) GOTO 653
      WRITE(2,131)it,istgo,i,ii,nofea,gi(istgo,i)
 131  FORMAT (5I10,F15.2)
 653  IF(fimi1.eq.-1)go to 19
      X=GI(ISTGO,I)+FIMI1
      NOI(ISTGO,I)=1
      FMAX=X
      OIMI(ISTGO,I,NOI(ISTGO,I))=OI
      GO TO 1
 20   CALL CONNECT(I,II,ISTGO,NOFEA)
      IF(NOFEA.EQ.-1)GO TO 19
      SIMI1=II
      IMI1=II
      OI=II
      CALL FUNCT(I,II,ISTGO)
      IF(ISTGO.EQ.1)FIMI1=F0I(IMI1)
      IF(ISTGO.GT.1)FIMI1=F(ISTGO-1,IMI1)
      IF (PROPT(4).EQ.1) write (2,*) fimi1
      IF(fimi1.eq.-1)nofea=-2
      IF (PROPT(4).NE.1) GOTO 654
      WRITE(2,131)it,istgo,i,ii,nofea,gi(istgo,i)
 654  IF(fimi1.eq.-1)go to 19
      X=GI(ISTGO,I)+FIMI1
      IF(iobj.eq.1.and.x.gt.fmax)go to 16
      IF(iobj.eq.-1.and.x.lt.fmax)go to 16
      IF(X.EQ.FMAX)GO TO 17
      GO TO 19
 16   NN=NOI(ISTGO,I)
      NOI(ISTGO,I)=0
      FMAX=X
      OIMIN=OI
      NOI(ISTGO,I)=NOI(ISTGO,I)+1
      DO 18 N1=1,NN
              OIMI(ISTGO,I,N1)=0.0
 18   CONTINUE
      OIMI(ISTGO,I,NOI(ISTGO,I))=OIMIN
      GO TO 19
 17   NOI(ISTGO,I)=NOI(ISTGO,I)+1
      OIMI(ISTGO,I,NOI(ISTGO,I))=OI
 19   II=II+1

      OI=II
```

```
        IF(II.LE.PUSIF(ISTGO))GO TO 2
1       IF(iobj.eq.1.and.fmax.eq.-CF)f(istgo,i)=-1
        IF(iobj.eq.1.and.fmax.ne.-CF)f(istgo,i)=fmax
        IF(iobj.eq.-1.and.fmax.eq.CF)f(istgo,i)=-1
        IF(iobj.eq.-1.and.fmax.ne.CF)f(istgo,i)=fmax
        1000 I=I+1
        SI=SI+1
        IF(I.LE.PUSII(ISTGO))GO TO 3
        IT=IT-1
        ISTGO=ISTGO+1
        IF(ISTGO.LE.N)GO TO 5
        ISTGO=0
        IF (PROPT(5).NE.1) GOTO 655
        WRITE(2,103)
 103    FORMAT(2X,50('=')/,5X,'ISTGO',4X,'I',12X,
      1 'F',8X,'NOI',4X,'OIMI'/,2X,50('-')//)
 655    DO 40 KJ=1,N
                ISTGO=ISTGO+1
                SI=PLSII(ISTGO)
                I=SI
41              IF (PROPT(5).NE.1) GOTO 656
                IF(NOI(ISTGO,I).EQ.0)WRITE(2,43)ISTGO,I
 43             FORMAT ('ISTGO=',I3,3X,'I=',I3,5X,'INFEASIBLE')
                IF(NOI(ISTGO,I).NE.0)WRITE(2,*)ISTGO,I,
       1        F(ISTGO,I),NOI(ISTGO,I),
       2        (OIMI(ISTGO,I,KKK),KKK=1,NOI(ISTGO,I))
                IF(NOI(ISTGO,I).EQ.-1)WRITE(2,*)'ISTG0=',ISTGO,'I=',I,
       1        'INFEASIBLE due to istgo-1 path infeasible'
656             SI=SI+1
                I=SI
                IF(I.LE.PUSII(ISTGO))GO TO 41
 40     CONTINUE
        DO 50 IL=1,ISG
                STATG(IL)=(STATA(IL)/DELIN)+1
 50     CONTINUE
        IF (PROPT(6).NE.1) GOTO 666

666     IF (PROPT(7).NE.1) GOTO 667
        WRITE(3,*)'TABLE OF OPTIMAL PATHS'
        WRITE(3,705)
 705    FORMAT(2x,127('-'))
        IF(POPTION.EQ.1)GOTO 702
        WRITE(3,701)
 701    FORMAT(4x,'IT',8x,'ISTGO',8x,'SI',8x,'OI',8x,'SF',8x,'Ev',8X,
      1 'INFLOW',4X,'DEMEND',4X,'SPILL',6X,'TRCOST',5X,'SRCOST',5X
      1 ,'SPCOST')
        GOTO 668
702     WRITE(3,703)
 703    FORMAT(4x,'IT',8x,'ISTGO',8x,'SI',8x,'OI',8x,'SF',8x,'Ev',8X,
      1 'INFLOW',4X,'TDEMEND',4X,'POWVDEM',3X,'SPILL',6X,'TRCOST',5X,
```

```
     1 'SRCOST',5X,'SPCOST')
 668   WRITE(3,705)
 667   CALL OPTPA(isg,n,maxns)
       STOP
       END
c      END OF THE MAIN PROGRAM
c *******************************************************
c  SUBROUTINE FUNCT(I,II,IT,ISTGO)
C *******************************************************
       SUBROUTINE FUNCT(I,II,ISTGO)
       integer delin
       DIMENSION GI(204,250),FLOWI(204),demndi(204),puloi(204),
     1 plloi(204),COSTTI(204),EDEP(204),
      1AREAC(70),STORC(70),ELEC(70),COSTSPI(204)
       DIMENSION  DEMIRRI(204), DEMSWI(204)
       DIMENSION COSTSI(204),DEMENI(204),DEMEXPI(204)
       COMMON/BLK1/FLOWI
       COMMON/BLK2/DELIN
       COMMON/BLK4/GI
       COMMON/blk60/demndi,DEMSWI,DEMIRRI,DEMEXPI
       COMMON/blk5/plloi,puloi
       COMMON/blk61/COSTTI,COSTSI,COSTSPI
       COMMON/blk64/it,iopt
       COMMON/BLK70/STORC
       COMMON/BLK71/AREAC
       COMMON/BLK72/ELEC
       COMMON/BLK73/EDEP
       COMMON/BLK74/NPART
       COMMON/BLK75/DEADST
       COMMON/BLK83/POPTION
       COMMON/BLK85/DEMENI

       IF(iopt.eq.1)go to 5000
       GI(ISTGO,I)=0.
       CALL EVAPO(I,II,ISTGO,EVAVOL,ACEVVL)
       OI=II-I-FLOWI(ISTGO)+DEMNDI(ISTGO)+EVAVOL
       IF (OI.LT.0)THEN
             SPILL=-OI
             OI=0.0
       ENDIF
       OI=OI*DELIN
       RETURN
5000   GI(ISTGO,I)=0.
       CALL EVAPO(I,II,ISTGO,EVAVOL,ACEVVL)
       IF(POPTION.NE.1)GOTO 8
       ENDEM=DEMENI(ISTGO)


       CALL PVOLDEM(I,II,ENDEM,PDEM)
```

```
C       ASSUMED THAT IRR. AND EXP. WATER CAN BE USED FOR POWER
C       GENERATION
        IF((PDEM-DEMSWI(ISTGO)*DELIN).GT.(DEMIRRI
 1(ISTGO)*DELIN+DEMEXPI(ISTGO)*DELIN)) DEMNDI(ISTGO)=DEMSWI(ISTGO)+
 1PDEM/DELIN
8       OI=II-I-FLOWI(ISTGO)+DEMNDI(ISTGO)+EVAVOL
        IF (OI.LT.0)THEN
              SPILL=-OI
              OI=0.0
        ENDIF
        OI=OI*DELIN
        iii=oi/delin
        GI(ISTGO,I)=GI(ISTGO,I)+OI*COSTTI(ISTGO)+(II-1)*COSTSI(ISTGO)
        1*DELIN+SPILL*DELIN*COSTSPI(ISTGO)
        RETURN
        END
C***********************************************************
C  SUBROUTINE CONNECT(ISTGO,I,II,NOFEA)
C***********************************************************
C       SUBROUTINE CONNECT FOR FINDING CONNECTED STATES
        SUBROUTINE CONNECT(I,II,ISTGO,NOFEA)
        INTEGER delin
        DIMENSION PLLOI(204),PULOI(204),FLOWI(204),NOLOI(204),demndi(204)
        DIMENSION EDEP(204),AREAC(70),STORC(70),ELEC(70),PUSTI(204)
        DIMENSION  DEMIRRI(204), DEMSWI(204),DEMENI(204),DEMEXPI(204)
        COMMON/BLK1/FLOWI
        COMMON/BLK2/DELIN
        COMMON/BLK5/PLLOI,PULOI
        COMMON/BLK6/NOLOI
        COMMON/blk60/demndi,DEMSWI,DEMIRRI,DEMEXPI
        COMMON/BLK70/STORC
        COMMON/BLK71/AREAC
        COMMON/BLK72/ELEC
        COMMON/BLK73/EDEP
        COMMON/BLK74/NPART
        COMMON/BLK75/DEADST
        COMMON/BLK81/PUSTI
        COMMON/BLK83/POPTION
        COMMON/BLK85/DEMENI


        CALL EVAPO(I,II,ISTGO,EVAVOL,ACEVVL)
        IF(POPTION.NE.1)GOTO 7
        ENDEM=DEMENI(ISTGO)
        CALL PVOLDEM(I,II,ENDEM,PDEM)
C       ASSUMED THAT IRR. AND EXP. WATER CAN BE USED FOR POWER
C       GENERATION
        IF((PDEM-DEMSWI(ISTGO)*DELIN).GT.(DEMIRRI
       1 (ISTGO)*DELIN+DEMEXPI(ISTGO)*DELIN))
       1 DEMNDI(ISTGO)=DEMSWI(ISTGO)+
```

```
     1 PDEM/DELIN
 7     OI=II-I-FLOWI(ISTGO)+DEMNDI(ISTGO)+EVAVOL
       IF(NOLOI(ISTGO).EQ.-1) GO TO 2
       IF(OI.LT.PLLOI(ISTGO).OR.OI.GT.PULOI(ISTGO)) GOTO 1
 2     NOFEA=1
       RETURN
 1     NOFEA=-1
       RETURN
       END
C*********************************************************************
C      SUBROUTINE OPTPA(ISG,N,MAXNS)
C*********************************************************************
C      SUBROUTINE FOR FINDING THE OPTIMAL PATH
C
       SUBROUTINE OPTPA(ISG,N,MAXNS)
C      ISG = POSSIBLE NUMBER OF STARTING STATES AT 'T=0'
C      STATA = ACTUAL VALUE OF POSSIBLE STARTING STATES AT 'T=0'
C      STATG = INDICES OF THOSE POSSIBLE STARTING STATES AT 'T=0'
C      STATI = INITIAL STARTING STATE AT 'ISTGO=N'
C      STATF = OPTIMAL RESULTING STATE FOR 'ISTGO=N'
C      NOINS = NUMBER OF DECISION FOR 'ISTGO'
C      NOFLS = NUMBER OF OPTIMAL RESULTING STATES
C      NCCUI = NUMBER OF CONNECTING CUMULATIVE INITIAL STATE
C      NCCUF = NUMBER OF CONNECTING CUMULATIVE FINAL STATE

       INTEGER DELIN,PROPT

       DIMENSION F(204,250),NOI(204,250),OIMI(204,250,250),EDEP(204)
       DIMENSION STATG(250),STATI(204,250),STATF(204,250)
       DIMENSION NOINS(204),NCCUI(204,250,250),NCCUF(204,250,250)
       DIMENSION NOFLS(204),demndi(204),flowi(204)
       DIMENSION DEMIRR(204), DEMIRRI(204), DEMSWI(204), DEMSW(204),
     1 AREAC(70),STORC(70),ELEC(70),PROPT(10)
       DIMENSION DEMWIR(204),COSTTI(204),COSTSI(204)
     1 ,DEMEXP(204),COSTSPI(204),DEMENI(204),DEMEXPI(204)
       COMMON/blk1/flowi
       COMMON/blk2/delin
       COMMON/BLK7/F
       COMMON/BLK8/NOI,OIMI
       COMMON/BLK10/NCCUI,NCCUF
       COMMON/BLK11/NOINS,NOFLS
       COMMON/BLK12/STATG
       COMMON/blk60/demndi,DEMSWI,DEMIRRI,DEMEXPI
       COMMON/BLK61/COSTTI,COSTSI,COSTSPI
       COMMON/BLK91/DEMSW,DEMIRR,DEMEXP,DEMWIR
       COMMON/BLK70/STORC
       COMMON/BLK71/AREAC
       COMMON/BLK72/ELEC
       COMMON/BLK73/EDEP
       COMMON/BLK74/NPART
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      COMMON/BLK75/DEADST
      COMMON/BLK80/PROPT
      COMMON/BLK83/POPTION
      COMMON/BLK85/DEMENI

      K11=1
      DO 33 IL=1,ISG
      IT=1
      ISTGO=N
      K2=0
      STATI(ISTGO,1)=STATG(IL)
      I=STATI(ISTGO,1)
      FMAX=F(ISTGO,I)
      IF (PROPT(6).EQ.1) WRITE(2,*)'FMAX=',FMAX
      IF(NOI(ISTGO,I).NE.0) NOINS(ISTGO)=1
      IF(NOI(ISTGO,I).EQ.0) NOINS(ISTGO)=0
25    IF(NOINS(ISTGO).EQ.0) GO TO 33
      DO 22 K1=1,NOINS(ISTGO)
            I=STATI(ISTGO,K1)
            DO 21 N1=1,NOI(ISTGO,I)
                  K2=K2+1
                  STATF(ISTGO,K2)=OIMI(ISTGO,I,N1)
                  NOFLS(ISTGO)=K2
21          CONTINUE
22    CONTINUE
      IF (istgo.eq.1)GOTO 100
      NOINS(ISTGO-1)=NOFLS(ISTGO)
      DO 23 K1=1,NOFLS(ISTGO)
            STATI(ISTGO-1,K1)=STATF(ISTGO,K1)
23    CONTINUE
      IT=IT+1
      ISTGO=ISTGO-1
      K2=0
      IF(ISTGO.NE.1)GO TO 25
100   IT=1
      ISTGO=N
      IF (PROPT(6).NE.1) GOTO 669
      WRITE(2,410)
410   FORMAT(1X,55('=')/,2x,'IT',3X,'ISTGO',3X,'STATI',
     1 3X,'NCCUI',3X,'OIMI',3X,'STATF',3X,'NCCUF'/,1X,
     2 55('-')//)
669   K5=0
      K6=MAXNS
      K55=K5
      K66=K6
      DO 42 IJ=1,N
      DO 50 K1=1,NOINS(ISTGO)
      I=STATI(ISTGO,K1)
      K5=K5+I
      DO 51 N1=1,NOI(ISTGO,I)
```

```
      STATF(ISTGO,N1)=OIMI(ISTGO,I,N1)
      II=STATF(ISTGO,N1)
      K6=K6+II
      NCCUI(ISTGO,I,II)=K5
      NCCUF(ISTGO,I,II)=K6
      IF (PROPT(6).NE.1) GOTO 670
      WRITE(2,600)IT,ISTGO,STATI(ISTGO,K1),NCCUI(ISTGO,I,II),
     1 OIMI(ISTGO,I,N1), STATF(ISTGO,N1),NCCUF(ISTGO,I,II)
 600  FORMAT(2(I3,2X),3X,F6.2,3X,I5,4X,2(F6.2,3X),1x,I5)
 670  K6=K66
      CALL EVAPO(I,II,ISTGO,EVAVOL,ACEVVL)
      IF (POPTION .NE.1) GOTO 9
      ENDEM=DEMENI(ISTGO)
      CALL PVOLDEM(I,II,ENDEM,PDEM)
C     ASSUMED THAT IRR. AND EXP. WATER CAN BE USED FOR POWER
C     GENERATION
      IF((PDEM-DEMSWI(ISTGO)*DELIN).GT.(DEMIRRI
     1 (ISTGO)*DELIN+DEMEXPI(ISTGO)*DELIN)) DEMNDI(ISTGO) = DEMSWI
     1 (ISTGO)+PDEM/DELIN

9     OI=STATF(ISTGO,N1)-STATI(ISTGO,K1)-FLOWI(ISTGO)+DEMNDI(ISTGO)
     1 +EVAVOL

      IF (OI.LT.0)THEN
            SPILL=-OI
            OI=0.0
      ENDIF
      SPILL=SPILL*DELIN
      IF (OI.GT.0) SPILL=0
      si=(stati(istgo,k1)-1)*DELIN
      oi=oi*delin
      sf=(statf(istgo,n1)-1)*DELIN

      AINFLW=FLOWI(ISTGO)*DELIN
      DEM=DEMNDI(ISTGO)*DELIN
      TRCOST=COSTTI(ISTGO)
      SRCOST=COSTSI(ISTGO)
      SPCOST=COSTSPI(ISTGO)
      IF(POPTION.EQ.1)GOTO 47
      IF (PROPT(7).EQ.1)write(3,700)it,istgo,si,oi,sf,ACEVVL,AINFLW,DEM
     1 ,SPILL,TRCOST,SRCOST,SPCOST
C    1 ,EXPREL(IT),IRRDEF(IT),EXPDEF(IT)
700   FORMAT(2x,2(i4,4X),2x,10(f7.2,4X))
      GOTO 51
47    IF (PROPT(7).EQ.1)write(3,701)it,istgo,si,oi,sf,ACEVVL,AINFLW,DEM,
      1PDEM,SPILL,TRCOST,SRCOST,SPCOST
C    1 ,EXPREL(IT),IRRDEF(IT),EXPDEF(IT)

 701  FORMAT(2x,2(i4,4X),2x,11(f7.2,4X))
 51   CONTINUE
```

```
      K5=K55
50    CONTINUE
      K5=IT*MAXNS
      K6=(IT+1)*MAXNS
      K55=K5
      K66=K6
      IT=IT+1
      ISTGO=ISTGO-1
42    CONTINUE
      IF (PROPT(7).EQ.1) write(3,703)
703   FORMAT(2x,56('.'))
33    CONTINUE

      IF (PROPT(6).EQ.1) WRITE(3,*)'FMAX=',FMAX
      RETURN
      END
C   ******************************************
C   ******************************************
      FUNCTION YINTP(XG,XX,YY,I5)
      DIMENSION XX(70), YY(70)
      X1=XG-XX(I5-1)
      Z1=XX(I5)-XX(I5-1)
      Y1=YY(I5)-YY(I5-1)
      YINTP=YY(I5-1)+(X1/Z1)*Y1
      RETURN
      END
C   ******************************************
C   ******************************************
      SUBROUTINE INTP2(XG,XX,NNN,L)
      DIMENSION XX(70)
      DO 1 L=2,NNN
            IF (XG.LE.XX(L)) GOTO 2
            GOTO 1
2           RETURN
1     CONTINUE
      RETURN
      END
C   ******************************************
C   ******************************************
      SUBROUTINE EVAPO(I,II,ISTGO,EVAVOL,ACEVVL)
      DIMENSION EDEP(204),STORC(70),AREAC(70),ELEC(70)
      COMMON/BLK70/STORC
      COMMON/BLK71/AREAC
      COMMON/BLK72/ELEC
      COMMON/BLK2/DELIN
      COMMON/BLK73/EDEP
      COMMON/BLK74/NPART
      COMMON/BLK75/DEADST
      INTEGER DELIN
      STOVOL=((I+II)-2)*DELIN/2.0 + DEADST
```

```
      CALL INTP2(STOVOL,STORC,NPART,I5)
      AREA=YINTP(STOVOL,STORC,AREAC,I5)
      ELE=YINTP(STOVOL,STORC,ELEC,I5)
      EVAVOL=AREA*EDEP(ISTGO)/DELIN
      ACEVVL=AREA*EDEP(ISTGO)
      RETURN
      END
C   ******************************************
C   ******************************************
      SUBROUTINE HPHEAD(I,II,HPH)
      DIMENSION STORC(70),ELEC(70)
      COMMON/BLK2/DELIN
      COMMON/BLK70/STORC
      COMMON/BLK72/ELEC
      COMMON/BLK74/NPART
      COMMON/BLK75/DEADST
      COMMON/BLK84/TWL,PCAP,LFAC,EFF
      STOVOL=((I+II-2)*DELIN)/2.0+DEADST
      DO 900 L=2,NPART
          IF(STOVOL.LE.STORC(L)) GOTO 910
900   CONTINUE
910   X1=STOVOL-STORC(L-1)
      Z1=STORC(L)-STORC(L-1)
      Y1=ELEC(L)-ELEC(L-1)
      EL=ELEC(L-1)+(X1/Z1)*Y1
      HPH=EL-TWL
      RETURN
      END
C   ******************************************
C   ******************************************
      SUBROUTINE PVOLDEM(I,II,ENDEM,PDEM)
      REAL LFAC
      COMMON/BLK84/TWL,PCAP,LFAC,EFF
      CALL HPHEAD(I,II,HPH)
      PDEM=ENDEM/(2.7222*HPH*EFF)
      RETURN
      END
C   ******************************************
C   ******************************************
      SUBROUTINE POWER(OP,I,II,MWHr)
      COMMON/BLK84/TWL,PCAP,LFAC,EFF
      REAL MWHr,LFAC
      CALL HPHEAD(I,II,HPH)
      MWHr=2.7222*OP*HPH*EFF
      IF(MWHr.GT.(LFAC*PCAP*730))MWHr=LFAC*PCAP*730
      RETURN
      END
C   ******************END*****************
```

*Annexure-VIII*

# COMPUTER PROGRAM FOR CONTROLLED INPUT MODEL

```
C    *************************************************************
C    CONTROL INPUT MODEL (CIM) PROGRAM
C    *************************************************************
C    INFLOW, DEMAND, ACTIVE CAPACITY ARE KNOWN.
C    DECISION VARIABLE IS THE CONTROLLED INFLOW.
C    DEMAND IS REVISED SO THAT IT CAN BE MET
C    *************************************************************
C      PLSTI = PERMISSIBLE LOWER LIMIT ON INITIAL STATE AT 'T'
C      PUSTI = PERMISSIBLE UPPER LIMIT ON INITIAL STATE AT 'T'
C      PLSTF = PERMISSIBLE LOWER LIMIT ON FINAL STATE AT 'T'
C      PUSTF = PERMISSIBLE UPPER LIMIT ON FINAL STATE AT 'T'
C      PLSII = PERMISSIBLE LOWER LIMIT ON INITIAL STATE FOR
C           'ISTGO' STAGES TO GO
C      PUSII = PERMISSIBLE UPPER LIMIT ON INITIAL STATE FOR
C           'ISTGO' STAGES TO GO
C      PLSIF = PERMISSIBLE LOWER LIMIT ON FINAL STATE FOR
C           'ISTGO' STAGES TO GO
C      PUSIF = PERMISSIBLE UPPER LIMIT ON FINAL STATE FOR
C           'ISTGO' STAGES TO GO
C      GI = COST FUNCTION
C      CIT = UNIT COST AT STATE 'T'
C      CI = UNIT COST FOR 'ISTGO' STAGES TO GO
C      FLOWT = INFLOW AT STATE 'T'
C      FLOWI = INFLOW AT 'ISTGO' STAGES TO GO
C      PLLOT = PERMISSIBLE LOWER LIMIT ON OUTFLOW 'T'
C      PLLOI = PERMISSIBLE LOWER LIMIT ON OUTFLOW AT 'ISTGO'
C           STAGES TO GO.
C      PULOT = PERMISSIBLE UPPER LIMIT ON INFLOW 'T'
C      PULOI = PERMISSIBLE UPPER LIMIT ON INFLOW AT 'ISTGO'
C           STAGES TO GO.
C      PROPT = PRINT OPTION, '1' FOR YES.
C                         1st=INPUT DATA
C                         2nd=PERMISSIBLE STATES.
C                         3rd=OPTIMAL FUNCTION VALUE
C                         4th=TABLE OF FEASIBLES
C                         5th=VALUES OF F
C                         6th=CONNECTIONS
C                         7th=OPTIMAL PATH TABLE
C      NOLOT = NO LIMIT ON INFLOW AT TIME 'T'
C      NOLOI = NO LIMIT ON INFLOW AT 'ISTGO' STAGES TO GO
C      ISTGO =  STAGES TO GO
C      FOT = FUNCTION VALUE AT THE END OF 'N'TH TIME PERIOD
C      F0I  = FUNCTION VALUE AT 0 STAGES TO GO
C      F   = OPTIMAL OBJECTIVE FUNCTION VALUE AT 'I'TH
C          INITIAL STATE
C      FMAX = MIXIMUM VALUE OF 'F'
C      FIMI1 = FUNCTION VALUE OF '(I-1)'TH STATE
C      OI=CURRENT DECISION AT 'I'TH INITIAL STATE (IN TERMS
C        OF CONNECTION WITH FIANL RESULTING 'II'TH STATE)
C      OIMI=OPTIMAL DECISIONS AT 'I'TH INITIAL STATE (IN TERMS
```

```
C         OF CONNECTION WITH FIANL RESULTING 'II'TH STATE)
C       NOI = NUMBER OF DECISIONS
C       N = NUMBER OF TIME PERIODS
C       IT = NUMBER OF TIME PERIODS
C       OIMIN= DECISION REGARDING STATE (RESULTING STATE)
C       ALIR=PERMISSIBLE IRRIGATION FAILURE ALLOWANCE
C       ALEXP=PERMISSIBLE WATER EXPORT FAILURE ALLOWANCE
C       ALPOW=PERMISSIBLE HYDROPOWER FAILURE ALLOWANCE
          INTEGER delin, PROPT
          REAL LFAC
          DIMENSION STORC(70), AREAC(70),ELEC(70),EDEP(204)
          DIMENSION FOT(250),F0I(250),FLOWT(204),STATA(250),EVDEP(204)
          DIMENSION GI(204,250),F(204,250),PROPT(10)
          DIMENSION PLSTI(204),PLSII(204),PUSTI(204),PUSII(204),PLSTF(204)
          DIMENSION PLSIF(204),PUSTF(204),PUSIF(204),NOI(204,250),NOLOI(204)
          DIMENSION OIMI(204,250,250),STATG(250),PLLOT(204),PULOT(204)
          DIMENSION PLLOI(204),PULOI(204),COSTINI(204)
          DIMENSION FLOWI(204),demndt(204),demndi(204),COSTIN(204)
          DIMENSION COSTSR(204),COSTSI(204),COSTSP(204),COSTSPI(204)
          DIMENSION DEMIRR(204), DEMIRRI(204),DEMSWI(204),DEMSW(204)
          DIMENSION DEMWIRI(204),COSTEND(204),COSTENDI(204),DEMENI(204)
          DIMENSION   DEMYSW(12),DEMYIR(12),DEMEXP(204),DEMYEN(12), DEMEN(204)
          DIMENSION DEMWIR(204),EVDEPT(12),DEMEXPI(204)
          DIMENSION COSTWSD(204),COSTIRD(204),COSTEXD(204)
          DIMENSION COSTWSDI(204),COSTIRDI(204),COSTEXDI(204)
          COMMON/BLK1/FLOWI
          COMMON/BLK2/DELIN
          COMMON/BLK4/GI
          COMMON/BLK5/PLLOI,PULOI
          COMMON/BLK6/NOLOI
          COMMON/BLK7/F
          COMMON/BLK8/NOI,OIMI
          COMMON/BLK12/STATG
          COMMON/blk60/demndi,DEMSWI,DEMIRRI,DEMWIRI,DEMEXPI
          COMMON/BLK91/DEMSW,DEMIRR,DEMEXP,DEMWIR
          COMMON/blk61/COSTINI,COSTSI,COSTSPI,COSTWSDI,COSTIRDI,
1         COSTEXDI,COSTENDI
          COMMON/blk64/it,iopt
          COMMON/BLK70/STORC
          COMMON/BLK71/AREAC
          COMMON/BLK72/ELEC
          COMMON/BLK73/EDEP
          COMMON/BLK74/NPART
          COMMON/BLK75/DEADST
          COMMON/BLK80/PROPT
          COMMON/BLK81/PUSTI
          COMMON/BLK82/ALIR,ALEXP,ALPOW
          COMMON/BLK83/POPTION
          COMMON/BLK84/TWL,PCAP,LFAC,EFF
          COMMON/BLK85/DEMENI

          OPEN (unit=1, FILE='MAIN-FILE.DAT', STATUS='OLD')
          OPEN (unit=2, FILE='PATH.OUT', STATUS='UNKNOWN')
          OPEN (unit=3, FILE='MONTHLY-DETAIL.OUT', STATUS='UNKNOWN')
          OPEN (unit=4, FILE='EV-AR-CAP-ELE.DAT', STATUS='OLD')
          OPEN (unit=5,FILE= 'YEARLY-DETAIL.OUT', STATUS='UNKNOWN')

          READ(1,*)(PROPT(K),K=1,7)
          READ(1,67)CF
67        FORMAT(E10.2)
```

```
      READ(1,*)N
      READ(1,*)MAXNS
      READ(1,*)iobj
      READ(1,*)PLSTI(1),PUSTI(1)
      READ(1,*)(PLSTF(IT),IT=1,N)
      READ(1,*)(PUSTF(IT),IT=1,N)
      READ(1,*)DELIN
      READ(1,*)iopt
      IF(iopt.eq.1)go to 5001
      IF(iopt.eq.2)go to 5003
      GOTO 5003
5001  READ(1,*)(COSTIN(it),it=1,N)
      READ(1,*)(COSTSR(IT),IT=1,N)
      READ(1,*)(COSTSP(IT),IT=1,N)
      READ(1,*)(COSTWSD(IT),IT=1,N)
      READ(1,*)(COSTIRD(IT),IT=1,N)
      READ(1,*)(COSTEXD(IT),IT=1,N)
      READ(1,*)(COSTEND(IT),IT=1,N)
      istgo=n
      DO 602 it=1,n
              COSTINI(istgo)=COSTIN(it)
              COSTSI(ISTGO)=COSTSR(IT)
              COSTSPI(ISTGO)=COSTSP(IT)
              COSTWSDI(ISTGO)=COSTWSD(IT)
              COSTIRDI(ISTGO)=COSTIRD(IT)
              COSTEXDI(ISTGO)=COSTEXD(IT)
              COSTENDI(ISTGO)=COSTEND(IT)
              istgo=istgo-1
 602  continue
 5003 READ(1,*)(PLLOT(IT),IT=1,N)
      READ(1,*)(PULOT(IT),IT=1,N)
      READ(1,*)(FLOWT(IT),IT=1,N)
      READ (1,*)(EVDEPT(MONTH),MONTH=1,12)
      READ(1,*)(DEMYSW(MONTH), MONTH=1,12)
      READ(1,*)(DEMYIR(MONTH), MONTH=1,12)
      READ(1,*)(DEMEXP(IT), IT=1,N)
      READ(1,*)(DEMYEN(MONTH),MONTH=1,12)

      MONTH=1
      DO IT=1,N
              DEMSW(IT)=DEMYSW(MONTH)
              DEMIRR(IT)=DEMYIR(MONTH)
              DEMEN(IT)=DEMYEN(MONTH)
              DEMNDT(IT)=DEMSW(IT)+DEMIRR(IT)+DEMEXP(IT)
              DEMWIR(IT)=DEMSW(IT)+DEMIRR(IT)
              EVDEP(IT)=EVDEPT(MONTH)
              MONTH=MONTH+1
              IF (MONTH.EQ.13) MONTH=1
      ENDDO
      DO 25 I3=1,N
              EDEP(I3)=EVDEP(N+1-I3)
 25   CONTINUE

      READ(1,*)(FOT(IR),IR=1,MAXNS)
      READ(1,*)ISG
      READ(1,*)(STATA(IL),IL=1,ISG)
      READ(1,*)ALIR,ALEXP,ALPOW
      READ(1,*)POPTION

      IF (PROPT(1).NE.1)GOTO 240
```

```
        WRITE(2,*)'Number of Periods=',n
        WRITE(2,*)'Max. number of states=',maxns
        IF (iobj.eq.1)WRITE(2,*)'Objective Function is Maximizing'
        IF (iobj.eq.-1)WRITE(2,*)'Objective Function is Minimizing'
        WRITE(2,*)'Permissible Lower Limit on Initial State at (T)=',plsti
        1(1)
        WRITE(2,*)'Permissible Upper Limit on Initial State at (T)=',plsti
        1(1)
        WRITE(2,*)'State Increment is =',delin
        L=0
        DO 233 K=1,N
        J=0
        L=1
         IF (J.EQ.0)WRITE(2,*)'=================================='
        IF (J.EQ.0)WRITE(2,*)'  IT            UP.LIMIT         LO.LIMIT'
        IF (J.EQ.0)WRITE(2,*)'=================================='
        J=1
        WRITE(2,*)IT,PLLOT(K),PULOT(K)
233     CONTINUE
        IF (L.EQ.0)WRITE(2,*)'NO LIMITATIONS ON OUTPUT'
        WRITE(2,*)'NUMBER OF INITIAL STATES=',ISG
240     IF(N.EQ.1)GO TO 510
        DO 502 IT=2,N
                PLSTI(IT)=PLSTF(IT-1)
                PUSTI(IT)=PUSTF(IT-1)
502     CONTINUE
510     IF (PROPT(2).NE.1)GOTO 650
        WRITE(2,126)
126     FORMAT(2X,'THE PERMISSIBLE STATES ARE'/)
        DO 501 IT=1,N
                WRITE(2,*)PLSTI(IT),PUSTI(IT)
                WRITE(2,*)PLSTF(IT),PUSTF(IT)
501     CONTINUE

650     READ (4,*) NPART
        READ (4,*)(STORC(J),J=1,NPART)
        READ (4,*)(AREAC(J),J=1,NPART)
        READ (4,*)(ELEC(J),J=1,NPART)
        READ (4,*)DEADST
        READ (4,*)TWL,PCAP,LFAC,EFF

        DO 100 IR=1,MAXNS
                F0I(IR)=FOT(IR)
100     CONTINUE
        IF (PROPT(3).NE.1) GOTO 651
        WRITE(2,128)
128     FORMAT(2X,'OPTIMAL FUNCTION VALUE FOR 0 STAGE TO GO'/)
        WRITE(2,*)(F0I(I),I=1,MAXNS)
651     IF (PROPT(4).NE.1) GOTO 652
        WRITE(2,129)
129     FORMAT(2X,60('=')/,8x,'IT',6X,'ISTGO',8X,'I',6X,'II'
       1,8X,'NOFEA',8X,'GI(ISTGO,I)',/,2X,60('-')//)
652     IT=N
        ISTGO=1
5       DO 400 IR=1,MAXNS
                F(ISTGO,IR)=-1
                DO 4 K=1,MAXNS
                        OIMI(ISTGO,IR,K)=-1
4               CONTINUE
400     CONTINUE
```

```
      PLSII(ISTGO)=(PLSTI(IT)/delin)+1
      PUSII(ISTGO)=(PUSTI(IT)/delin)+1
      PLSIF(ISTGO)=(PLSTF(IT)/delin)+1
      PUSIF(ISTGO)=(PUSTF(IT)/delin)+1
      PLLOI(ISTGO)=(PLLOT(IT)/DELIN)
      PULOI(ISTGO)=(PULOT(IT)/DELIN)
      FLOWI(ISTGO)=(FLOWT(IT)/DELIN)
      DEMNDI(ISTGO)=DEMNDT(IT)/DELIN
      DEMSWI(ISTGO)=DEMSW(IT)/DELIN
      DEMIRRI(ISTGO)=DEMIRR(IT)/DELIN
      DEMWIRI(ISTGO)=DEMWIR(IT)/DELIN
      DEMEXPI(ISTGO)=DEMEXP(IT)/DELIN
      DEMENI(ISTGO)=DEMEN(IT)
      SI=PLSII(ISTGO)
      I=SI
3     II=PLSIF(ISTGO)
      NOI(ISTGO,I)=0
      IF(iobj.eq.1)fmax=-CF
      IF(iobj.eq.-1)fmax=CF
2     IF(PLSIF(ISTGO).NE.PUSIF(ISTGO))GO TO 20
      CALL CONNECT(I,II,ISTGO,NOFEA)
      IF(NOFEA.EQ.-1)GO TO 19
      SIMI1=PUSIF(ISTGO)
      IMI1=II
      OI=II
      CALL FUNCT(I,II,ISTGO)
      IF(ISTGO.EQ.1)FIMI1=F0I(IMI1)
      IF(ISTGO.GT.1)FIMI1=F(ISTGO-1,IMI1)
      IF (PROPT(4).EQ.1)write (2,*) fimi1
      IF(fimi1.eq.-1)nofea=-2
      IF (PROPT(4).NE.1) GOTO 653
      WRITE(2,131)it,istgo,i,ii,nofea,gi(istgo,i)
131   FORMAT (5I10,F15.2)
653   IF(fimi1.eq.-1)go to 19
      X=GI(ISTGO,I)+FIMI1
      NOI(ISTGO,I)=1
      FMAX=X
      OIMI(ISTGO,I,NOI(ISTGO,I))=OI
      GO TO 1
20    CALL CONNECT(I,II,ISTGO,NOFEA)
      IF(NOFEA.EQ.-1)GO TO 19
      SIMI1=II
      IMI1=II
      OI=II
      CALL FUNCT(I,II,ISTGO)
      IF(ISTGO.EQ.1)FIMI1=F0I(IMI1)
      IF(ISTGO.GT.1)FIMI1=F(ISTGO-1,IMI1)
      IF (PROPT(4).EQ.1) write (2,*) fimi1
      if(fimi1.eq.-1)nofea=-2
      IF (PROPT(4).NE.1) GOTO 654
      write(2,131)it,istgo,i,ii,nofea,gi(istgo,i)
654   if(fimi1.eq.-1)go to 19
      X=GI(ISTGO,I)+FIMI1
      if(iobj.eq.1.and.x.gt.fmax)go to 16
      if(iobj.eq.-1.and.x.lt.fmax)go to 16
      IF(X.EQ.FMAX)GO TO 17
      GO TO 19
16    NN=NOI(ISTGO,I)
      NOI(ISTGO,I)=0
      FMAX=X
```

```
        OIMIN=OI
        NOI(ISTGO,I)=NOI(ISTGO,I)+1
        DO 18 N1=1,NN
        OIMI(ISTGO,I,N1)=0.0
 18     CONTINUE
        OIMI(ISTGO,I,NOI(ISTGO,I))=OIMIN
        GO TO 19
 17     NOI(ISTGO,I)=NOI(ISTGO,I)+1
        OIMI(ISTGO,I,NOI(ISTGO,I))=OI
 19     II=II+1
        OI=II
        IF(II.LE.PUSIF(ISTGO))GO TO 2
 1      IF(iobj.eq.1.and.fmax.eq.-CF)f(istgo,i)=-1
        IF(iobj.eq.1.and.fmax.ne.-CF)f(istgo,i)=fmax
        IF(iobj.eq.-1.and.fmax.eq.CF)f(istgo,i)=-1
        IF(iobj.eq.-1.and.fmax.ne.CF)f(istgo,i)=fmax
        1000 I=I+1
        SI=SI+1
        IF(I.LE.PUSII(ISTGO))GO TO 3
        IT=IT-1
        ISTGO=ISTGO+1
        IF(ISTGO.LE.N)GO TO 5
        ISTGO=0
        IF (PROPT(5).NE.1) GOTO 655
        WRITE(2,103)
 103    FORMAT(2X,50('=')/,5X,'ISTGO',4X,'I',12X,
      1 'F',8X,'NOI',4X,'OIMI'/,2X,50('-')//)
 655    DO 40 KJ=1,N
        ISTGO=ISTGO+1
        SI=PLSII(ISTGO)
        I=SI
 41     IF (PROPT(5).NE.1) GOTO 656
        IF(NOI(ISTGO,I).EQ.0)WRITE(2,43)ISTGO,I
 43     format ('ISTGO=',I3,3X,'I=',I3,5X,'INFEASIBLE')
        IF(NOI(ISTGO,I).NE.0)WRITE(2,*)ISTGO,I,
      1 F(ISTGO,I),NOI(ISTGO,I),
      2 (OIMI(ISTGO,I,KKK),KKK=1,NOI(ISTGO,I))
        IF(NOI(ISTGO,I).EQ.-1)WRITE(2,*)'ISTG0=',ISTGO,'I=',I,
      1 'INFEASIBLE due to istgo-1 path infeasible'
 656    SI=SI+1
        I=SI
        IF(I.LE.PUSII(ISTGO))GO TO 41
 40     CONTINUE
        DO 50 IL=1,ISG
                STATG(IL)=(STATA(IL)/DELIN)+1
 50     CONTINUE
        IF (PROPT(6).NE.1) GOTO 666
        WRITE(2,*)'================================================'

 666    IF (PROPT(7).NE.1) GOTO 667
        WRITE(3,*)'TABLE OF OPTIMAL PATHS'
        WRITE(3,705)
 705    FORMAT(2x,127('-'))
        IF(POPTION.EQ.1)GOTO 702
        WRITE(3,701)
 701    FORMAT(4x,'IT',4x,'ISTGO',5x,'SI',6x,'OI',7x,'SF',7x,'Ev',5X
      1 ,'INFLOW',4X,'DEMAND',5X,'REVDEM',7X,'SSPILL',3X,'TSPILL',5X,
      1 'WSDEM',5X,'WSREL', 4X,'DEFWS',3X,'IRRDEM',5X,'IRRREL',5X,'DEFIRR'
      1 ,4X,'EXPDEM',4X,'EXPREL',4X,'DEFEXP', 3X,
      1 'INFCOST',4X,'SRCOST',4X,'SPCOST',3X,'WSDCOST',3X,'IRDCOST',3X,
```

```
      1 'EXDCOST')
        GOTO 668
702     WRITE(3,703)
 703    FORMAT(4x,'IT',4x,'ISTGO',5x,'SI',6x,'OI',7x,'SF',7x,'Ev',5X
      1 ,'INFLOW',4X,'DEMAND',5X,'REVDEM',7X,'SSPILL',3X,'TSPILL',5X,
      1 'WSDEM',5X,'WSREL', 4X,'DEFWS',3X,'IRRDEM',5X,'IRRREL',5X,'DEFIRR'
      1 ,4X,'EXPDEM',4X,'EXPREL',4X,'DEFEXP', 3X,'PDEM',4X,'POWER',6X,
      1 'DEFPOW',4X,'SURPOW',4X,'POWVOL',3X,'INFCOST',4X,'SRCOST',4X,
      1 'SPCOST',3X,'WSDCOST',3X,'IRDCOST',3X,'EXDCOST',3X,'PWDCOST')
668     WRITE(3,705)
        WRITE(*,*)'YES'
667     CALL optpa(isg,n,maxns)
        STOP
        END
c       END OF THE MAIN PROGRAM
c **********************************************************
c       SUBROUTINE FUNCT(I,II,IT,ISTGO)
C **********************************************************
        SUBROUTINE FUNCT(I,II,ISTGO)
        INTEGER delin
        DIMENSION GI(204,250),FLOWI(204),demndi(204),puloi(204),
      1 plloi(204),COSTINI(204),EDEP(204),REVDEMI(204),
      1 AREAC(70),STORC(70),ELEC(70),COSTSPI(204)
        DIMENSION DEMIRRI(204), DEMSWI(204),COSTWSDI(204),COSTIRDI(204)
        DIMENSION DEMEXPI(204),COSTSI(204),DEMWIRI(204),COSTEXDI(204)
        DIMENSION WSREL(204),IRRREL(204),EXPREL(204),COSTENDI(204)
        DIMENSION DEFWS(204),DEFIRR(204),DEFEXP(204)
        DIMENSION WSIRDEM(204),WSDEM(204),IRRDEM(204),EXPDEM(204)
        DIMENSION DEFPOW(204),POWREL(204),DEMENI(204)
        COMMON/BLK1/FLOWI
        COMMON/BLK2/DELIN
        COMMON/BLK4/GI
        COMMON/blk60/demndi,DEMSWI,DEMIRRI,DEMWIRI,DEMEXPI
        COMMON/blk5/plloi,puloi
        COMMON/blk61/COSTINI,COSTSI,COSTSPI,COSTWSDI,COSTIRDI,
      1 COSTEXDI,COSTENDI
        COMMON/blk64/it,iopt
        COMMON/BLK70/STORC
        COMMON/BLK71/AREAC
        COMMON/BLK72/ELEC
        COMMON/BLK73/EDEP
        COMMON/BLK74/NPART
        COMMON/BLK75/DEADST
        COMMON/BLK85/DEMENI
        COMMON/BLK83/POPTION

        if(iopt.eq.1)go to 5000
        GI(ISTGO,I)=0.
        CALL EVAPO(I,II,ISTGO,EVAVOL,ACEVVL)
        OI=II-I+DEMNDI(ISTGO)+EVAVOL
        IF (OI.LT.0)THEN
                SSPILL=-OI
                OI=0.0
                REVDEMI(ISTGO)=DEMNDI(ISTGO)
                GOTO 12
        ENDIF
        IF (OI.LE.PULOI(ISTGO)) GOTO 13
        REVDEMI(ISTGO)=PULOI(ISTGO)-II+I-EVAVOL
        OI=PULOI(ISTGO)
        SSPILL=0.0
```

```
      GOTO 12
13    REVDEMI(ISTGO)=DEMNDI(ISTGO)
12    OI=OI*DELIN
      DEMDIFF=(DEMNDI(ISTGO)-REVDEMI(ISTGO))*DELIN
      GI(ISTGO,I)=GI(ISTGO,I)+DEMDIFF**2
      RETURN
5000  GI(ISTGO,I)=0.
      CALL EVAPO(I,II,ISTGO,EVAVOL,ACEVVL)
      IF(POPTION.NE.1)GOTO 8
      ENDEM=DEMENI(ISTGO)
      CALL PVOLDEM(I,II,ENDEM,PDEM)
C     ASSUMED THAT IRR. AND EXP. WATER CAN BE USED FOR POWER GENERATION
      IF((PDEM-DEMSWI(ISTGO)*DELIN).GT.(DEMIRRI
     1(ISTGO)*DELIN+DEMEXPI(ISTGO)*DELIN)) DEMNDI(ISTGO)=DEMSWI(ISTGO)+
     1 PDEM/DELIN
8     OI=II-I+DEMNDI(ISTGO)+EVAVOL
      IF (OI.LT.0)THEN
            SSPILL=-OI
            OI=0.0
            REVDEMI(ISTGO)=DEMNDI(ISTGO)
            GOTO 14
      ENDIF
      IF (OI.LE.PULOI(ISTGO)) GOTO 15
      REVDEMI(ISTGO)=PULOI(ISTGO)-II+I-EVAVOL
      OI=PULOI(ISTGO)
      SSPILL=0.0
      GOTO 14
15    REVDEMI(ISTGO)=DEMNDI(ISTGO)
14    DEMDIFF=(DEMNDI(ISTGO)-REVDEMI(ISTGO))*DELIN
      UNUSEINF=PULOI(ISTGO)-OI
      TSPILL=SSPILL+UNUSEINF
      OI=OI*DELIN
      AINFLW=FLOWI(ISTGO)*DELIN
      DEM=DEMNDI(ISTGO)*DELIN
      REVDEM=REVDEMI(ISTGO)*DELIN
      PULIF=PULOI(ISTGO)*DELIN

      WSIRDEM(ISTGO)=DEMWIRI(ISTGO)*DELIN
      WSDEM(ISTGO)=DEMSWI(ISTGO)*DELIN
      IRRDEM(ISTGO)=DEMIRRI(ISTGO)*DELIN
      EXPDEM(ISTGO)=DEMEXPI(ISTGO)*DELIN

      IF(REVDEM.GE.WSIRDEM(ISTGO)) THEN
            WSREL(ISTGO)=WSDEM(ISTGO)
            IRRREL(ISTGO)=IRRDEM(ISTGO)
            EXPREL(ISTGO)=REVDEM-WSREL(ISTGO)-IRRREL(ISTGO)
            IF(EXPREL(ISTGO).LT.0.0001)EXPREL(ISTGO)=0.0
      ELSE
            IF(REVDEM.GE.WSDEM(ISTGO))THEN
                  WSREL(ISTGO)=WSDEM(ISTGO)
                  IRRREL(ISTGO)=REVDEM-WSREL(ISTGO)
                  EXPREL(ISTGO)=0.0
            ELSE
                  WSREL(ISTGO)=REVDEM
                  IRRREL(ISTGO)=0.0
                  EXPREL(ISTGO)=0.0
            ENDIF
      ENDIF
      POWREL(ISTGO)=REVDEM-WSREL(ISTGO)
      DEFWS(ISTGO)=WSREL(ISTGO)-WSDEM(ISTGO)
```

```
      DEFIRR(ISTGO)=IRRREL(ISTGO)-IRRDEM(ISTGO)
      DEFEXP(ISTGO)=EXPREL(ISTGO)-EXPDEM(ISTGO)
      IF(POWREL(ISTGO).GT.PDEM)THEN
              DEFPOW(ISTGO)=0.0
      ELSE
              DEFPOW(ISTGO)=PDEM-POWREL(ISTGO)
      ENDIF

      IF(DEFWS(ISTGO).LT.0.0)        THEN
              DEFWS(ISTGO)=-DEFWS(ISTGO)
      ELSE
              DEFWS(ISTGO)=0
      ENDIF

      IF(DEFIRR(ISTGO).LT.0.0)        THEN
              DEFIRR(ISTGO)=-DEFIRR(ISTGO)
      ELSE
              DEFIRR(ISTGO)=0
      ENDIF

      IF(DEFEXP(ISTGO).LT.0.0)        THEN
              DEFEXP(ISTGO)=-DEFEXP(ISTGO)
      ELSE
              DEFEXP(ISTGO)=0
      ENDIF
      GI(ISTGO,I)=GI(ISTGO,I)+OI*COSTINI(ISTGO)+(II-1)*COSTSI(ISTGO)
     1 *DELIN+TSPILL*DELIN*COSTSPI(ISTGO)+DEFWS(ISTGO)*COSTWSDI(ISTGO)
     1 +DEFIRR(ISTGO)*COSTIRDI(ISTGO)+DEFEXP(ISTGO)*COSTEXDI(ISTGO)+
     1 DEFPOW(ISTGO)*COSTENDI(ISTGO)
      RETURN
      END
c*************************************************************
c  SUBROUTINE CONNECT(ISTGO,I,II,NOFEA)
c*************************************************************
C       SUBROUTINE CONNECT FOR FINDING CONNECTED STATES
        SUBROUTINE CONNECT(I,II,ISTGO,NOFEA)
        INTEGER DELIN
        DIMENSION PLLOI(204),PULOI(204),FLOWI(204),NOLOI(204),demndi(204)
        DIMENSION EDEP(204),AREAC(70),STORC(70),ELEC(70),PUSTI(204)
        DIMENSION DEMIRRI(204), DEMSWI(204),DEMENI(204),
        1DEMEXPI(204),REVDEMI(204),DEMWIRI(204)
        COMMON/BLK1/FLOWI
        COMMON/BLK2/DELIN
        COMMON/BLK5/PLLOI,PULOI
        COMMON/BLK6/NOLOI
        COMMON/blk60/demndi,DEMSWI,DEMIRRI,DEMWIRI,DEMEXPI
        COMMON/BLK70/STORC
        COMMON/BLK71/AREAC
        COMMON/BLK72/ELEC
        COMMON/BLK73/EDEP
        COMMON/BLK74/NPART
        COMMON/BLK75/DEADST
        COMMON/BLK81/PUSTI
        COMMON/BLK85/DEMENI
        COMMON/BLK83/POPTION

        CALL EVAPO(I,II,ISTGO,EVAVOL,ACEVVL)
        IF(POPTION.NE.1)GOTO 7
        ENDEM=DEMENI(ISTGO)
        CALL PVOLDEM(I,II,ENDEM,PDEM)
```

```
C       ASSUMED THAT IRR. AND EXP. WATER CAN BE USED FOR POWER GENERATION
        IF((PDEM-DEMSWI(ISTGO)*DELIN).GT.(DEMIRRI
        1(ISTGO)*DELIN+DEMEXPI(ISTGO)*DELIN)) DEMNDI(ISTGO)=DEMSWI(ISTGO)+
        1PDEM/DELIN

 7      OI=II-I+DEMNDI(ISTGO)+EVAVOL
        IF (OI.LE.PULOI(ISTGO)) GOTO 2
        REVDEMI(ISTGO)=PULOI(ISTGO)-II+I-EVAVOL
        IF(REVDEMI(ISTGO).LT.0.0) GOTO 1
 2      NOFEA=1
        RETURN
 1      NOFEA=-1
        RETURN
        END

C**********************************************************************
c     SUBROUTINE OPTPA(ISG,N,MAXNS)
c**********************************************************************
c     SUBROUTINE FOR FINDING THE OPTIMAL PATH
C
        SUBROUTINE OPTPA(ISG,N,MAXNS)
C        ISG = POSSIBLE NUMBER OF STARTING STATES AT 'T=0'
C       STATA = ACTUAL VALUE OF POSSIBLE STARTING STATES AT 'T=0'
C       STATG = INDICES OF THOSE POSSIBLE STARTING STATES AT 'T=0'
C       STATI = INITIAL STARTING STATE AT 'ISTGO=N'
C       STATF = OPTIMAL RESULTING STATE FOR 'ISTGO=N'
C       NOINS = NUMBER OF DECISION FOR 'ISTGO'
C       NOFLS = NUMBER OF OPTIMAL RESULTING STATES
C       NCCUI = NUMBER OF CONNECTING CUMULATIVE INITIAL STATE
C       NCCUF = NUMBER OF CONNECTING CUMULATIVE FINAL STATE

        INTEGER DELIN,PROPT
        REAL INFCOST,IRRREL(204),IRRDEM(204),IRDMON1,IRDMON2,IRDMON3,
       1 IRDMON4,IRDMON5,IRDMON6,IRDMON7,IRDMON8,IRDMON9,IRDMON10,IRDMON11
       1 ,IRDMON12,MWHr,IRDCOST
        DIMENSION F(204,250),NOI(204,250),OIMI(204,250,250),EDEP(204)
        DIMENSION STATG(250),STATI(204,250),STATF(204,250)
        DIMENSION NOINS(204),NCCUI(204,250,250),NCCUF(204,250,250)
        DIMENSION NOFLS(204),demndi(204),flowi(204),PULOI(204),PLLOI(204)
        DIMENSION DEMIRR(204), DEMIRRI(204), DEMSWI(204), DEMSW(204),
      1 AREAC(70),STORC(70),ELEC(70),PROPT(10),REVDEMI(204),DEMWIRI(204)
        DIMENSION DEMWIR(204),COSTINI(204),COSTSI(204)
      1 ,DEMEXP(204),COSTSPI(204),DEMEXPI(204),DEMENI(204),
      1 COSTWSDI(204),COSTIRDI(204),COSTEXDI(204),COSTENDI(204)
        DIMENSION WSIRDEM(204),WSDEM(204),EXPDEM(204)
        DIMENSION WSREL(204),EXPREL(204),DEFWS(204),RELEXP(20)
        DIMENSION DEFIRR(204),DEFEXP(204),YIRD(20),YWSD(20),YEXPD(20)
        DIMENSION FWS(204),FIR(204),FEXP(204),RELWS(20),RELIR(20)
        DIMENSION FAIR(204),FAEXP(204),RELAIR(20),RELAEX(20)
        DIMENSION YWSDEM(20),YEXDEM(20),YEXREL(20),YIRREL(20),YIRDEM(20),
        1FYAIR(20),FYAEX(20),RELAPOW(20),SURPOW(204)
        DIMENSION POWREL(204),DEFPOW(204),POW(204),FYAPOW(20),RELPOW(20)
        DIMENSION FPOW(204),FAPOW(204),YPWDEM(20),YMWHr(20),YPOWDF(20)
        COMMON/blk1/flowi
        COMMON/blk2/delin
        COMMON/BLK5/PLLOI,PULOI
        COMMON/BLK7/F
        COMMON/BLK8/NOI,OIMI
        COMMON/BLK10/NCCUI,NCCUF
        COMMON/BLK11/NOINS,NOFLS
```

```
      COMMON/BLK12/STATG
      COMMON/blk60/demndi,DEMSWI,DEMIRRI,DEMWIRI,DEMEXPI
      COMMON/blk61/COSTINI,COSTSI,COSTSPI,COSTWSDI,COSTIRDI,
     1COSTEXDI,COSTENDI
      COMMON/BLK91/DEMSW,DEMIRR,DEMEXP,DEMWIR
      COMMON/BLK70/STORC
      COMMON/BLK71/AREAC
      COMMON/BLK72/ELEC
      COMMON/BLK73/EDEP
      COMMON/BLK74/NPART
      COMMON/BLK75/DEADST
      COMMON/BLK80/PROPT
      COMMON/BLK82/ALIR,ALEXP,ALPOW
      COMMON/BLK83/POPTION
      COMMON/BLK85/DEMENI
      K11=1
      DO 33 IL=1,ISG
      IT=1
      ISTGO=N
      K2=0
      STATI(ISTGO,1)=STATG(IL)
       I=STATI(ISTGO,1)
      FMAX=F(ISTGO,I)
      IF (PROPT(6).EQ.1) WRITE(2,*)'FMAX=',FMAX
      IF(NOI(ISTGO,I).NE.0) NOINS(ISTGO)=1
      IF(NOI(ISTGO,I).EQ.0) NOINS(ISTGO)=0
      WRITE(*,*)NOI(ISTGO,I)
25    IF(NOINS(ISTGO).EQ.0) GO TO 33

      DO 22 K1=1,NOINS(ISTGO)
              I=STATI(ISTGO,K1)
              DO 21 N1=1,NOI(ISTGO,I)
                        K2=K2+1
                        STATF(ISTGO,K2)=OIMI(ISTGO,I,N1)
                        NOFLS(ISTGO)=K2
21            CONTINUE
22     CONTINUE
       IF (istgo.eq.1)go to 100
       NOINS(ISTGO-1)=NOFLS(ISTGO)
       DO 23 K1=1,NOFLS(ISTGO)
       STATI(ISTGO-1,K1)=STATF(ISTGO,K1)
23     CONTINUE
       IT=IT+1
       ISTGO=ISTGO-1
       K2=0
       IF(ISTGO.NE.1)GO TO 25
100    IT=1
       ISTGO=N
       IF (PROPT(6).NE.1) GOTO 669
       WRITE(2,410)
410    FORMAT(1X,55('=')/,2x,'IT',3X,'ISTGO',3X,'STATI',
      1 3X,'NCCUI',3X,'OIMI',3X,'STATF',3X,'NCCUF'/,1X,
      2 55('-')//)
669    K5=0
       K6=MAXNS
       K55=K5
       K66=K6
       DO 42 IJ=1,N
       DO 50 K1=1,NOINS(ISTGO)
       I=STATI(ISTGO,K1)
```

```
      K5=K5+I
      DO 51 N1=1,NOI(ISTGO,I)
      STATF(ISTGO,N1)=OIMI(ISTGO,I,N1)
      II=STATF(ISTGO,N1)
      K6=K6+II
      NCCUI(ISTGO,I,II)=K5
      NCCUF(ISTGO,I,II)=K6
      IF (PROPT(6).NE.1) GOTO 670
      WRITE(2,600)IT,ISTGO,STATI(ISTGO,K1),NCCUI(ISTGO,I,II),
     1 OIMI(ISTGO,I,N1), STATF(ISTGO,N1),NCCUF(ISTGO,I,II)
 600  FORMAT(2(I3,2X),3X,F6.2,3X,I5,4X,2(F6.2,3X),1x,I5)
 670  K6=K66
      CALL EVAPO(I,II,ISTGO,EVAVOL,ACEVVL)
      IF (POPTION .NE.1) GOTO 9
      ENDEM=DEMENI(ISTGO)
      CALL PVOLDEM(I,II,ENDEM,PDEM)
C     ASSUMED THAT IRR. AND EXP. WATER CAN BE USED FOR POWER GENERATION
      IF((PDEM-DEMSWI(ISTGO)*DELIN).GT.(DEMIRRI
      1(ISTGO)*DELIN+DEMEXPI(ISTGO)*DELIN)) DEMNDI(ISTGO)=DEMSWI(ISTGO)+
     1 PDEM/DELIN

9     OI=STATF(ISTGO,N1)-STATI(ISTGO,K1)+DEMNDI(ISTGO)
      1+EVAVOL
      IF (OI.LT.0)THEN
            SSPILL=-OI
            OI=0.0
            REVDEMI(ISTGO)=DEMNDI(ISTGO)
            GOTO 12
      ENDIF
      IF (OI.LE.PULOI(ISTGO)) GOTO 13
      REVDEMI(ISTGO)=PULOI(ISTGO)-II+I-EVAVOL
      OI=PULOI(ISTGO)
      SSPILL=0.0
      GOTO 12
13    REVDEMI(ISTGO)=DEMNDI(ISTGO)
12    DEMDIFF=(DEMNDI(ISTGO)-REVDEMI(ISTGO))*DELIN

      IF (OI.GT.0) SSPILL=0
      UNUSEINF=PULOI(ISTGO)-OI
      OI=OI*DELIN
      TSPILL=SSPILL+UNUSEINF
      SSPILL=SSPILL*DELIN
      TSPILL=TSPILL*DELIN
      si=(stati(istgo,k1)-1)*DELIN
      sf=(statf(istgo,n1)-1)*DELIN
      AINFLW=FLOWI(ISTGO)*DELIN
      DEM=DEMNDI(ISTGO)*DELIN
      REVDEM=REVDEMI(ISTGO)*DELIN
      PULIF=PULOI(ISTGO)*DELIN
      INFCOST=COSTINI(ISTGO)
      SRCOST=COSTSI(ISTGO)
      SPCOST=COSTSPI(ISTGO)
      WSDCOST=COSTWSDI(ISTGO)
      IRDCOST=COSTIRDI(ISTGO)
      EXDCOST=COSTEXDI(ISTGO)
      ENDCOST=COSTENDI(ISTGO)
      WSIRDEM(ISTGO)=DEMWIRI(ISTGO)*DELIN
      WSDEM(ISTGO)=DEMSWI(ISTGO)*DELIN
      IRRDEM(ISTGO)=DEMIRRI(ISTGO)*DELIN
      EXPDEM(ISTGO)=DEMEXPI(ISTGO)*DELIN
```

```
IF(REVDEM.GE.WSIRDEM(ISTGO)) THEN
        WSREL(ISTGO)=WSDEM(ISTGO)
        IRRREL(ISTGO)=IRRDEM(ISTGO)
        EXPREL(ISTGO)=REVDEM-WSREL(ISTGO)-IRRREL(ISTGO)
        IF(EXPREL(ISTGO).LT.0.0001)EXPREL(ISTGO)=0.0
        IF(EXPDEM(ISTGO).EQ.0.0) EXPREL(ISTGO)=0.0
ELSE
        IF(REVDEM.GE.WSDEM(ISTGO))THEN
                WSREL(ISTGO)=WSDEM(ISTGO)
                IRRREL(ISTGO)=REVDEM-WSREL(ISTGO)
                EXPREL(ISTGO)=0.0
        ELSE
                WSREL(ISTGO)=REVDEM
                IRRREL(ISTGO)=0.0
                EXPREL(ISTGO)=0.0
        ENDIF
ENDIF
POWREL(ISTGO)=REVDEM-WSREL(ISTGO)
OP=POWREL(ISTGO)
CALL POWER(OP,I,II,MWHr)
POW(ISTGO)=MWHr
DEFWS(ISTGO)=WSREL(ISTGO)-WSDEM(ISTGO)
DEFIRR(ISTGO)=IRRREL(ISTGO)-IRRDEM(ISTGO)
DEFEXP(ISTGO)=EXPREL(ISTGO)-EXPDEM(ISTGO)
IF(MWHr.GE.DEMENI(ISTGO))THEN
        DEFPOW(ISTGO)=0.0
        SURPOW(ISTGO)=MWHr-DEMENI(ISTGO)
ELSE
        DEFPOW(ISTGO)=DEMENI(ISTGO)-MWHr
        SURPOW(ISTGO)=0.0
ENDIF

IF(DEFWS(ISTGO).LT.0.0)         THEN
        FWS(ISTGO)=0
        DEFWS(ISTGO)=-DEFWS(ISTGO)
ELSE
        FWS(ISTGO)=1
ENDIF
IF(DEFIRR(ISTGO).LT.0.0)THEN
        FIR(ISTGO)=0
        DEFIRR(ISTGO)=-DEFIRR(ISTGO)
        IF(DEFIRR(ISTGO).GT.ALIR*IRRDEM(ISTGO))THEN
                FAIR(ISTGO)=0
        ELSE
                FAIR(ISTGO)=1
        ENDIF
ELSE
        FIR(ISTGO)=1
        FAIR(ISTGO)=1
ENDIF
IF(DEFEXP(ISTGO).LT.0.0) THEN
        FEXP(ISTGO)=0
        DEFEXP(ISTGO)=-DEFEXP(ISTGO)
        IF(DEFEXP(ISTGO).GT.ALEXP*EXPDEM(ISTGO))THEN
                FAEXP(ISTGO)=0
        ELSE
                FAEXP(ISTGO)=1
        ENDIF
```

```
      ELSE
              FEXP(ISTGO)=1
              FAEXP(ISTGO)=1
      ENDIF
      IF(DEFPOW(ISTGO).EQ.0.0) THEN
              FPOW(ISTGO)=1
      ELSE
              FPOW(ISTGO)=0
      ENDIF
      IF(DEFPOW(ISTGO).LE.ALPOW*DEMENI(ISTGO))THEN
              FAPOW(ISTGO)=1
      ELSE
              FAPOW(ISTGO)=0
      ENDIF
      IF(POPTION.EQ.1)GOTO 704

      IF (PROPT(7).EQ.1)WRITE(3,700)it,istgo,si,oi,sf,ACEVVL,PULIF,DEM
     1 ,REVDEM,SSPILL,TSPILL,WSDEM(ISTGO),WSREL(ISTGO),DEFWS(ISTGO),
     1 IRRDEM(ISTGO),IRRREL(ISTGO),DEFIRR(ISTGO),EXPDEM(ISTGO),
     1 EXPREL(ISTGO),DEFEXP(ISTGO),
     1 INFCOST,SRCOST,SPCOST,WSDCOST,IRDCOST,EXDCOST
700   FORMAT(2x,2(i4,2X),2x,6(f7.2,2X),3X,F8.2,2X,F8.2,2X,F8.2,2X,
     1 15(F8.2,2X))
      GOTO 51
704   IF (PROPT(7).EQ.1)write(3,705)it,istgo,si,oi,sf,ACEVVL,PULIF,DEM
     1 ,REVDEM,SSPILL,TSPILL,WSDEM(ISTGO),WSREL(ISTGO),DEFWS(ISTGO),
     1 IRRDEM(ISTGO),IRRREL(ISTGO),DEFIRR(ISTGO),EXPDEM(ISTGO),
     1 EXPREL(ISTGO),DEFEXP(ISTGO),DEMENI(ISTGO),MWHr,DEFPOW(ISTGO),
     1 SURPOW(ISTGO),OP,INFCOST,SRCOST,SPCOST,WSDCOST,IRDCOST,EXDCOST,
     1 ENDCOST
705   format(2x,2(i4,2X),2x,6(f7.2,2X),3X,F8.2,2X,F8.2,2X,F8.2,2X,
     1 21(F8.2,2X))
 51   CONTINUE
      K5=K55
 50   CONTINUE
      K5=IT*MAXNS
      K6=(IT+1)*MAXNS
      K55=K5
      K66=K6
      IT=IT+1
      ISTGO=ISTGO-1
 42   CONTINUE
      IF (PROPT(7).EQ.1) write(3,703)
703   FORMAT(2x,56('.'))
 33   CONTINUE
      JJJJ=1
      DO JJJ=1,N/12
              YIRD(JJJ)=0.0
              YWSD(JJJ)=0.0
              YEXPD(JJJ)=0.0
              YIRDEM(JJJ)=0.0
              YIRREL(JJJ)=0.0
              YEXDEM(JJJ)=0.0
              YEXREL(JJJ)=0.0
              YWSDEM(JJJ)=0.0
              YPWDEM(JJJ)=0.0
              YMWHr(JJJ)=0.0
              YPOWDF(JJJ)=0.0
      ENDDO
      DO 66 JJJ=1,N/12
```

```
        DO 76 MMM=JJJJ,JJJJ+11
               YIRD(JJJ)=YIRD(JJJ)+DEFIRR(MMM)
               YWSD(JJJ)=YWSD(JJJ)+DEFWS(MMM)
               YEXPD(JJJ)=YEXPD(JJJ)+DEFEXP(MMM)
               YIRDEM(JJJ)=YIRDEM(JJJ)+IRRDEM(MMM)
               YIRREL(JJJ)=YIRREL(JJJ)+IRRREL(MMM)
               YEXDEM(JJJ)=YEXDEM(JJJ)+EXPDEM(MMM)
               YEXREL(JJJ)=YEXREL(JJJ)+EXPREL(MMM)
               YWSDEM(JJJ)=YWSDEM(JJJ)+WSDEM(MMM)
               YPOWDF(JJJ)=YPOWDF(JJJ)+DEFPOW(MMM)-SURPOW(MMM)
               YPWDEM(JJJ)=YPWDEM(JJJ)+DEMENI(MMM)
               YMWHr(JJJ)=YMWHr(JJJ)+POW(MMM)
76      CONTINUE
        IF(YIRREL(JJJ).LT.(1-ALIR)*YIRDEM(JJJ))THEN
               FYAIR(JJJ)=0.0
        ELSE
               FYAIR(JJJ)=1
        ENDIF
        IF(YEXREL(JJJ).LT.(1-ALEXP)*YEXDEM(JJJ))THEN
               FYAEX(JJJ)=0
        ELSE
               FYAEX(JJJ)=1
        ENDIF
        IF(YMWHr(JJJ).LT.(1-ALPOW)*YPWDEM(JJJ))THEN
               FYAPOW(JJJ)=0.0
        ELSE
               FYAPOW(JJJ)=1
        ENDIF
        JJJJ=JJJJ+12
66    CONTINUE
      WRITE (5,70)
70    FORMAT (4X,115('='))
      WRITE (5,71)
71    FORMAT(4X,'YEAR',4X,'WSDEM',5X,'WSDEF',4X,'IRDEM',4X,'IRREL',5X,
     1 'IRRDEF',4X,'EXPDEM',4X,'EXPREL',4X,'EXPDEF',6X,'PDEM',7X,'MWHr',
     1 7X,'PDEF')
      WRITE (5,70)
      IPPP=1
      DO 1111 LLL=(N/12),1,-1
           WRITE(5,633) IPPP,YWSDEM(LLL),YWSD(LLL),YIRDEM(LLL),YIRREL(LLL),
     1     YIRD(LLL),YEXDEM(LLL),YEXREL(LLL),YEXPD(LLL),
     1     YPWDEM(LLL),YMWHr(LLL),YPOWDF(LLL)
633        format (3x,I3,3X,8(F7.2,3X),3(F10.2,2X)/)
           IPPP=IPPP+1
1111  CONTINUE

      WSDMON12=0.0
      IRDMON12=0.0
      EXDMON12=0.0
      PWDMON12=0.0
      DO LL=1,N,12
            WSDMON12=WSDMON12+DEFWS(LL)
            IRDMON12=IRDMON12+DEFIRR(LL)
            EXDMON12=EXDMON12+DEFEXP(LL)
            PWDMON12=PWDMON12+DEFPOW(LL)-SURPOW(LL)
      ENDDO
      WSDMON11=0.0
      IRDMON11=0.0
      EXDMON11=0.0
      PWDMON11=0.0
```

```
DO LL=2,N,12
        WSDMON11=WSDMON11+DEFWS(LL)
        IRDMON11=IRDMON11+DEFIRR(LL)
        EXDMON11=EXDMON11+DEFEXP(LL)
        PWDMON11=PWDMON11+DEFPOW(LL)-SURPOW(LL)
ENDDO
WSDMON10=0.0
IRDMON10=0.0
EXDMON10=0.0
PWDMON10=0.0
DO LL=3,N,12
        WSDMON10=WSDMON10+DEFWS(LL)
        IRDMON10=IRDMON10+DEFIRR(LL)
        EXDMON10=EXDMON10+DEFEXP(LL)
        PWDMON10=PWDMON10+DEFPOW(LL)-SURPOW(LL)
ENDDO
WSDMON9=0.0
IRDMON9=0.0
EXDMON9=0.0
PWDMON9=0.0
DO LL=4,N,12
        WSDMON9=WSDMON9+DEFWS(LL)
        IRDMON9=IRDMON9+DEFIRR(LL)
        EXDMON9=EXDMON9+DEFEXP(LL)
        PWDMON9=PWDMON9+DEFPOW(LL)-SURPOW(LL)
ENDDO
WSDMON8=0.0
IRDMON8=0.0
EXDMON8=0.0
PWDMON8=0.0
DO LL=5,N,12
        WSDMON8=WSDMON8+DEFWS(LL)
        IRDMON8=IRDMON8+DEFIRR(LL)
        EXDMON8=EXDMON8+DEFEXP(LL)
        PWDMON8=PWDMON8+DEFPOW(LL)-SURPOW(LL)
ENDDO
WSDMON7=0.0
IRDMON7=0.0
EXDMON7=0.0
PWDMON7=0.0
DO LL=6,N,12
        WSDMON7=WSDMON7+DEFWS(LL)
        IRDMON7=IRDMON7+DEFIRR(LL)
        EXDMON7=EXDMON7+DEFEXP(LL)
        PWDMON7=PWDMON7+DEFPOW(LL)-SURPOW(LL)
ENDDO
WSDMON6=0.0
IRDMON6=0.0
EXDMON6=0.0
PWDMON6=0.0
DO LL=7,N,12
        WSDMON6=WSDMON6+DEFWS(LL)
        IRDMON6=IRDMON6+DEFIRR(LL)
        EXDMON6=EXDMON6+DEFEXP(LL)
        PWDMON6=PWDMON6+DEFPOW(LL)-SURPOW(LL)
ENDDO
WSDMON5=0.0
IRDMON5=0.0
EXDMON5=0.0
PWDMON5=0.0
```

```
DO LL=8,N,12
        WSDMON5=WSDMON5+DEFWS(LL)
        IRDMON5=IRDMON5+DEFIRR(LL)
        EXDMON5=EXDMON5+DEFEXP(LL)
        PWDMON5=PWDMON5+DEFPOW(LL)-SURPOW(LL)
ENDDO
WSDMON4=0.0
IRDMON4=0.0
EXDMON4=0.0
PWDMON4=0.0
DO LL=9,N,12
        WSDMON4=WSDMON4+DEFWS(LL)
        IRDMON4=IRDMON4+DEFIRR(LL)
        EXDMON4=EXDMON4+DEFEXP(LL)
        PWDMON4=PWDMON4+DEFPOW(LL)-SURPOW(LL)
ENDDO
WSDMON3=0.0
IRDMON3=0.0
EXDMON3=0.0
PWDMON3=0.0
DO LL=10,N,12
        WSDMON3=WSDMON3+DEFWS(LL)
        IRDMON3=IRDMON3+DEFIRR(LL)
        EXDMON3=EXDMON3+DEFEXP(LL)
        PWDMON3=PWDMON3+DEFPOW(LL)-SURPOW(LL)
ENDDO
WSDMON2=0.0
IRDMON2=0.0
EXDMON2=0.0
PWDMON2=0.0
DO LL=11,N,12
        WSDMON2=WSDMON2+DEFWS(LL)
        IRDMON2=IRDMON2+DEFIRR(LL)
        EXDMON2=EXDMON2+DEFEXP(LL)
        PWDMON2=PWDMON2+DEFPOW(LL)-SURPOW(LL)
ENDDO
WSDMON1=0.0
IRDMON1=0.0
EXDMON1=0.0
PWDMON1=0.0
DO LL=12,N,12
        WSDMON1=WSDMON1+DEFWS(LL)
        IRDMON1=IRDMON1+DEFIRR(LL)
        EXDMON1=EXDMON1+DEFEXP(LL)
        PWDMON1=PWDMON1+DEFPOW(LL)-SURPOW(LL)
ENDDO
AVMON1WD=WSDMON1*12./N
AVMON2WD=WSDMON2*12./N
AVMON3WD=WSDMON3*12./N
AVMON4WD=WSDMON4*12./N
AVMON5WD=WSDMON5*12./N
AVMON6WD=WSDMON6*12./N
AVMON7WD=WSDMON7*12./N
AVMON8WD=WSDMON8*12./N
AVMON9WD=WSDMON9*12./N
AVMON10WD=WSDMON10*12./N
AVMON11WD=WSDMON11*12./N
AVMON12WD=WSDMON12*12./N

AVMON1ID=IRDMON1*12./N
```

```
      AVMON2ID=IRDMON2*12./N
      AVMON3ID=IRDMON3*12./N
      AVMON4ID=IRDMON4*12./N
      AVMON5ID=IRDMON5*12./N
      AVMON6ID=IRDMON6*12./N
      AVMON7ID=IRDMON7*12./N
      AVMON8ID=IRDMON8*12./N
      AVMON9ID=IRDMON9*12./N
      AVMON10ID=IRDMON10*12./N
      AVMON11ID=IRDMON11*12./N
      AVMON12ID=IRDMON12*12./N

      AVMON1ED=EXDMON1*12./N
      AVMON2ED=EXDMON2*12./N
      AVMON3ED=EXDMON3*12./N
      AVMON4ED=EXDMON4*12./N
      AVMON5ED=EXDMON5*12./N
      AVMON6ED=EXDMON6*12./N
      AVMON7ED=EXDMON7*12./N
      AVMON8ED=EXDMON8*12./N
      AVMON9ED=EXDMON9*12./N
      AVMON10ED=EXDMON10*12./N
      AVMON11ED=EXDMON11*12./N
      AVMON12ED=EXDMON12*12./N

      AVMON1PD=PWDMON1*12./N
      AVMON2PD=PWDMON2*12./N
      AVMON3PD=PWDMON3*12./N
      AVMON4PD=PWDMON4*12./N
      AVMON5PD=PWDMON5*12./N
      AVMON6PD=PWDMON6*12./N
      AVMON7PD=PWDMON7*12./N
      AVMON8PD=PWDMON8*12./N
      AVMON9PD=PWDMON9*12./N
      AVMON10PD=PWDMON10*12./N
      AVMON11PD=PWDMON11*12./N
      AVMON12PD=PWDMON12*12./N

      WRITE(5,85)'AVERAGE MONTH1 WATER SUPPLY DEFICIT=',AVMON1WD
      WRITE(5,85)'AVERAGE MONTH2 WATER SUPPLY  DEFICIT=',AVMON2WD
      WRITE(5,85)'AVERAGE MONTH3 WATER SUPPLY DEFICIT=', AVMON3WD
      WRITE(5,85)'AVERAGE MONTH4 WATER SUPPLY DEFICIT=', AVMON4WD
      WRITE(5,85)'AVERAGE MONTH5 WATER SUPPLY DEFICIT=', AVMON5WD
      WRITE(5,85)'AVERAGE MONTH6 WATER SUPPLY  DEFICIT=',AVMON6WD
      WRITE(5,85)'AVERAGE MONTH7 WATER SUPPLY  DEFICIT=',AVMON7WD
      WRITE(5,85)'AVERAGE MONTH8 WATER SUPPLY DEFICIT=', AVMON8WD
      WRITE(5,85)'AVERAGE MONTH9 WATER SUPPLY DEFICIT=', AVMON9WD
      WRITE(5,85)'AVERAGE MONTH10 WATER SUPPLY DEFICIT=',AVMON10WD
      WRITE(5,85)'AVERAGE MONTH11 WATER SUPPLY DEFICIT=',AVMON11WD
      WRITE(5,86)'AVERAGE MONTH12 WATER SUPPLY DEFICIT=',AVMON12WD
86    FORMAT(A38,F11.4,/)

      WRITE(5,85)'AVERAGE MONTH1 IRRIGATION DEFICIT=',AVMON1ID
      WRITE(5,85)'AVERAGE MONTH2 IRRIGATION DEFICIT=',AVMON2ID
      WRITE(5,85)'AVERAGE MONTH3 IRRIGATION DEFICIT=',AVMON3ID
      WRITE(5,85)'AVERAGE MONTH4 IRRIGATION DEFICIT=',AVMON4ID
      WRITE(5,85)'AVERAGE MONTH5 IRRIGATION DEFICIT=',AVMON5ID
      WRITE(5,85)'AVERAGE MONTH6 IRRIGATION DEFICIT=', AVMON6ID
      WRITE(5,85)'AVERAGE MONTH7 IRRIGATION DEFICIT=', AVMON7ID
      WRITE(5,85)'AVERAGE MONTH8 IRRIGATION DEFICIT=', AVMON8ID
```

```
      WRITE(5,85)'AVERAGE MONTH9 IRRIGATION DEFICIT=', AVMON9ID
      WRITE(5,85)'AVERAGE MONTH10 IRRIGATION DEFICIT=',AVMON10ID
      WRITE(5,85)'AVERAGE MONTH11 IRRIGATION DEFICIT=', AVMON11ID
      WRITE(5,86)'AVERAGE MONTH12 IRRIGATION DEFICIT=', AVMON12ID

      WRITE(5,85)'AVERAGE MONTH1 EXPORT DEFICIT=',AVMON1ED
      WRITE(5,85)'AVERAGE MONTH2 EXPORT DEFICIT=',AVMON2ED
      WRITE(5,85)'AVERAGE MONTH3 EXPORT DEFICIT=',AVMON3ED
      WRITE(5,85)'AVERAGE MONTH4 EXPORT DEFICIT=',AVMON4ED
      WRITE(5,85)'AVERAGE MONTH5 EXPORT DEFICIT=', AVMON5ED
      WRITE(5,85)'AVERAGE MONTH6 EXPORT DEFICIT=', AVMON6ED
      WRITE(5,85)'AVERAGE MONTH7 EXPORT DEFICIT=', AVMON7ED
      WRITE(5,85)'AVERAGE MONTH8 EXPORT DEFICIT=', AVMON8ED
      WRITE(5,85)'AVERAGE MONTH9 EXPORT DEFICIT=', AVMON9ED
      WRITE(5,85)'AVERAGE MONTH10 EXPORT DEFICIT=',AVMON10ED
      WRITE(5,85)'AVERAGE MONTH11 EXPORT DEFICIT=',AVMON11ED
      WRITE(5,86)'AVERAGE MONTH12 EXPORT DEFICIT=',AVMON12ED

      WRITE(5,*)'NEGATIVE SIGN INDICATES SURPLUS'
      WRITE(5,85)'AVERAGE MONTH1 POWER DEFICIT=',AVMON1PD
      WRITE(5,85)'AVERAGE MONTH2 POWER DEFICIT=',AVMON2PD
      WRITE(5,85)'AVERAGE MONTH3 POWER DEFICIT=',AVMON3PD
      WRITE(5,85)'AVERAGE MONTH4 POWER DEFICIT=',AVMON4PD
      WRITE(5,85)'AVERAGE MONTH5 POWER DEFICIT=', AVMON5PD
      WRITE(5,85)'AVERAGE MONTH6 POWER DEFICIT=', AVMON6PD
      WRITE(5,85)'AVERAGE MONTH7 POWER DEFICIT=', AVMON7PD
      WRITE(5,85)'AVERAGE MONTH8 POWER DEFICIT=', AVMON8PD
      WRITE(5,85)'AVERAGE MONTH9 POWER DEFICIT=', AVMON9PD
      WRITE(5,85)'AVERAGE MONTH10 POWER DEFICIT=',AVMON10PD
      WRITE(5,85)'AVERAGE MONTH11 POWER DEFICIT=',AVMON11PD
      WRITE(5,86)'AVERAGE MONTH12 POWER DEFICIT=',AVMON12PD
85    FORMAT(A38,F11.4)

      JJJ=1
      DO JJ=1,N/12
            RELWS(JJ)=0
            RELIR(JJ)=0
            RELEXP(JJ)=0
            RELAIR(JJ)=0
            RELAEX(JJ)=0
            RELPOW(JJ)=0
            RELAPOW(JJ)=0
      ENDDO
      SYAIR=0
      SYAEX=0
      SYAPOW=0

      DO 73 JJ=N/12,1,-1
            DO 43 MM=JJJ,JJJ+11
                  RELWS(JJ)=RELWS(JJ)+FWS(MM)
                  RELIR(JJ)=RELIR(JJ)+FIR(MM)
                  RELEXP(JJ)=RELEXP(JJ)+FEXP(MM)
                  RELAIR(JJ)=RELAIR(JJ)+FAIR(MM)
                  RELAEX(JJ)=RELAEX(JJ)+FAEXP(MM)
                  RELPOW(JJ)=RELPOW(JJ)+FPOW(MM)
                  RELAPOW(JJ)=RELAPOW(JJ)+FAPOW(MM)
43          CONTINUE
            SYAIR=SYAIR+FYAIR(JJ)
            SYAEX=SYAEX+FYAEX(JJ)
            SYAPOW=SYAPOW+FYAPOW(JJ)
```

```
            JJJ=JJJ+12
73      CONTINUE
        SWS=0
        SIR=0
        SEXP=0
        SAIR=0
        SAEXP=0
        SPOW=0
        SAPOW=0
        DO 53 JJ=N/12,1,-1
            IF(RELWS(JJ).EQ.12) SWS=SWS+1
            IF(RELIR(JJ).EQ.12) SIR=SIR+1
            IF(RELEXP(JJ).EQ.12) SEXP=SEXP+1
            IF(RELAIR(JJ).EQ.12) SAIR=SAIR+1
            IF(RELAEX(JJ).EQ.12) SAEXP=SAEXP+1
            IF(RELPOW(JJ).EQ.12) SPOW=SPOW+1
            IF(RELAPOW(JJ).EQ.12) SAPOW=SAPOW+1
53      CONTINUE
        WRITE(5,*)'NO. OF SUCCESSFUL MONTHS FOR'
        WRITE(5,54)
54      FORMAT(2X,'YEAR',5X,'WSUP',6X,'IRGN',6X,'EXPT',6X,'POWER',5X,
      1 'IRWMA',5X,'EXPWA',5X,'POWWA')
        DO 63 JJ=N/12,1,-1
            WRITE(5,55)JJ,RELWS(JJ),RELIR(JJ),RELEXP(JJ),RELPOW(JJ),
      1 RELAIR(JJ),RELAEX(JJ),RELAPOW(JJ)
55          FORMAT(3X,I2,6X,7(F4.1,6X))
63      CONTINUE
        RELIBWS=(SWS/(N/12+1))*100
        RELIBIR=(SIR/(N/12+1))*100
        RELIBEX=(SEXP/(N/12+1))*100
        REAIR=(SAIR/(N/12+1))*100
        REAEX=(SAEXP/(N/12+1))*100
        REYAIR=(SYAIR/(N/12+1))*100
        REYAEX=(SYAEX/(N/12+1))*100
        RELIBPOW=(SPOW/(N/12+1))*100
        REAPOW=(SAPOW/(N/12+1))*100
        REYAPOW=(SYAPOW/(N/12+1))*100
        WRITE(5,*)'RELIABILITY OF WATER SUPPLY=',RELIBWS
        WRITE(5,*)'RELIABILITY OF IRRIGATION=',RELIBIR
        WRITE(5,*)'RELIABILITY OF WATER EXPORT=',RELIBEX
        WRITE(5,*)'RELIABILITY OF POWER=',RELIBPOW
        write(5,*)'PERMISSIBLE IRR. FAILURE PERCENTAGE=',ALIR*100
        write(5,*)'PERMISSIBLE EXP. FAILURE PERCENTAGE=',ALEXP*100
        write(5,*)'PERMISSIBLE POWER FAILURE PERCENTAGE=',ALPOW*100

        WRITE(5,*)'RELIABILITY OF IRR. AFTER ALLOWING MONTHLY ALLOWANCE=
        1',REAIR
        WRITE(5,*)'RELIABILITY OF EXPORT AFTER ALLOWING MONTHLY ALLOWANCE=
        1',REAEX
        WRITE(5,*)'RELIABILITY OF POWER AFTER ALLOWING MONTHLY ALLOWANCE=
        1',REAPOW

        WRITE(5,*)'RELIABILITY OF IRR. AFTER ALLOWING ANNUAL ALLOWANCE=',
        1REYAIR
        WRITE(5,*)'RELIABILITY OF EXPORT AFTER ALLOWING ANNUAL ALLOWANCE='
        1,REYAEX
        WRITE(5,*)'RELIABILITY OF POWER AFTER ALLOWING ANNUAL ALLOWANCE=',
        1REYAPOW

        IF (PROPT(6).EQ.1) WRITE(3,*)'FMAX=',FMAX
```

```
      RETURN
      END
C     *********************************
C     *********************************
      FUNCTION YINTP(XG,XX,YY,I5)
      DIMENSION XX(70), YY(70)
      X1=XG-XX(I5-1)
      Z1=XX(I5)-XX(I5-1)
      Y1=YY(I5)-YY(I5-1)
      YINTP=YY(I5-1)+(X1/Z1)*Y1
      RETURN
      END
C     *********************************
C  *********************************
      SUBROUTINE INTP2(XG,XX,NNN,L)
      DIMENSION XX(70)
      DO 1 L=2,NNN
             IF (XG.LE.XX(L)) GOTO 2
             GOTO 1
 2           RETURN
 1    CONTINUE
      RETURN
      END
C  *********************************
C  *********************************
      SUBROUTINE EVAPO(I,II,ISTGO,EVAVOL,ACEVVL)
      DIMENSION EDEP(204),STORC(70),AREAC(70),ELEC(70)
      COMMON/BLK70/STORC
      COMMON/BLK71/AREAC
      COMMON/BLK72/ELEC
      COMMON/BLK2/DELIN
      COMMON/BLK73/EDEP
      COMMON/BLK74/NPART
      COMMON/BLK75/DEADST
      INTEGER DELIN
      STOVOL=((I+II)-2)*DELIN/2.0 + DEADST
      CALL INTP2(STOVOL,STORC,NPART,I5)
      AREA=YINTP(STOVOL,STORC,AREAC,I5)
      ELE=YINTP(STOVOL,STORC,ELEC,I5)
      EVAVOL=AREA*EDEP(ISTGO)/DELIN
      ACEVVL=AREA*EDEP(ISTGO)
      RETURN
      END
C  *********************************
C  *********************************
      SUBROUTINE POWER(OP,I,II,MWHr)
      COMMON/BLK84/TWL,PCAP,LFAC,EFF
      REAL MWHr,LFAC
      CALL HPHEAD(I,II,HPH)
      MWHr=2.7222*OP*HPH*EFF
      IF(MWHr.GT.(LFAC*PCAP*730))MWHr=LFAC*PCAP*730
      RETURN
      END
C  *********************************
C  *********************************
      SUBROUTINE HPHEAD(I,II,HPH)
      DIMENSION STORC(70),ELEC(70)
      COMMON/BLK2/DELIN
      COMMON/BLK70/STORC
      COMMON/BLK72/ELEC
```

```
      COMMON/BLK74/NPART
      COMMON/BLK75/DEADST
      COMMON/BLK84/TWL,PCAP,LFAC,EFF
      STOVOL=((I+II-2)*DELIN)/2.0+DEADST
      DO 900 L=2,NPART
            IF(STOVOL.LE.STORC(L)) GOTO 910
900   CONTINUE
910   X1=STOVOL-STORC(L-1)
      Z1=STORC(L)-STORC(L-1)
      Y1=ELEC(L)-ELEC(L-1)
      EL=ELEC(L-1)+(X1/Z1)*Y1
      HPH=EL-TWL
      RETURN
      END
C  *********************************
C  *********************************
      SUBROUTINE PVOLDEM(I,II,ENDEM,PDEM)
      COMMON/BLK84/TWL,PCAP,LFAC,EFF
      CALL HPHEAD(I,II,HPH)
      PDEM=ENDEM/(2.7222*HPH*EFF)
      RETURN
      END
C  ***************END*************
```

*Annexure-IX*

# SYMBOLS FOR UNITS

| | |
|---|---|
| cumec | Cubic meters per second |
| ha | Hactare |
| ham | Hactare meter |
| km | Kilometer |
| KW | Kilowatt |
| KWhr | Kilowatt hour |
| m | meter |
| MCM | Million cubic meter |
| mm | Milimeter |
| MW | Megawatt |
| MWhr | Megawatt hour |
| sq km | Square kilometer |

# PUBLICATIONS

*The works related to the present study is reported as follows:*

1. **Sarma, B., and Srivastava, D.K.** (2003). "Dynamic programming models for inter-basin water transfer." In: Singh, V.P. and Yadava, R.N. (Ed), *Water Resources System Operation, Proceedings of the International Conference on Water and Environment (WE-2003),* Dec. 15-18, Bhopal, India, pp. 539-555.

2. **Sarma, B., and Srivastava, D.K.** (2005) "Simulation study of a river linking project." *Proc. of the International Conference on Hydrological Perspectives for Sustainable Development (HYPESD-2005)*, Indian Institute of Technology Roorkee, Feb.23-25, 2005, pp. 598-608.

3. **Sharma, N, and Sarma, B.** (2003). "Inter-basin water transfer - A critical study on basic approach with special reference to the Brahmaputra basin." *Proc. of the National Seminar on River Link Water Management-Its Necessity and Feasibility in East and Northeast India With or Without Bangladesh.* Centre for Research in Indo-Bangladesh Relations, ICCR, Dec. 6, Kolkata.

*The following papers are under preparation for submission:*

4. **Sarma, B., and Srivastava, D.K.** "An Improved Multireservoir Multiyield Preliminary Screening Model." Journal of Water Resources Planning and Management, ASCE.

5. **Sarma, B., and Srivastava, D.K.** "Dynamic programming models for planning and operation of reservoirs in a river linking project." Australian Journal of Water Resources (AJWR).

6. **Sarma, B., and Srivastava, D.K.** "Transboundary water transfers involving multireservoirs." Journal of Water Resources Planning and Management, ASCE.