OPTIMAL WATER USE AND CROPPING PATTERN FOR THRITHALA REGULATOR - CUM - BRIDGE PROJECT

By

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THESIS

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DECLARATION

I hereby declare that this thesis entitled "**O**ptimal water use and cropping pattern for Trithala Regulator-cum-bridge project" is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, associate ship, fellowship or other similar title of any other university or society.

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CERTIFICATE

Certified that this thesis entitled **"Optimal water use and cropping pattern for Trithala Regulator-cum-bridge project"** is a record of original work done independently by **Ms.** Saritha, E. K. under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associate ship to her.

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Saritha. E. K.

Dedicated to

My Loving Parents

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SYMBOLS AND ABBREVIATIONS

Agril.	-	agricultural
Apr	-	April
ASAE	-	American Society of Agricultural Engineers
Aug	-	August
AW	-	Available water
cm	-	centimetre(s)
cumec	-	cubic metres per second
Dec	-	December
Dept.	-	Department
DP	-	Dynamic programming
Ed.	-	Edition
Engg.	-	Engineering
ER	-	Effective rainfall
ET	-	Evapo- transpiration
et al.	-	and others
etc.	-	Etcetera
Feb	-	February
Fig.	-	figure
ha	-	hectare (s)
IARI	-	Indian Agricultural Research Institute
ID	-	Irrigation department
i.e.	-	that is
IIT	-	Indian Institute of Technology
Int.	-	international
IR	-	Irrigation requirement
Irrgn	-	Irrigation
ISAE	-	Indian Society of Agricultural Engineers
J.	-	Journal
Jan	-	January

Jul	-	July
Jun	-	June
KAU	-	Kerala Agricultural University
KCAET	-	Kelappaji College of Agricultural Engineering and Technology
Km	-	Kilometre
LDR	-	Linear Decision Rule
LP	-	Linear programming
m	-	metre (s)
Mar	-	March
mbar	-	millibar
Mha-m	-	Million hectare metre
mm	-	millimetre(s)
Mm	-	million metre
MOLP	-	Multiobjective linear program
MSL	-	Mean sea level
NLP	-	Network linear program
No.	-	*number*
Nov	-	November
Oct	-	October
pp.	-	pages
Proc.	-	proceedings
Res.	-	research
RH	-	relative humidity
SAC	-	Supportive and Allied Courses of Study
SCS	-	Soil Conservation Service
SDP	-	Stochastic dynamic programming
Sep	-	September
Sl No.	-	serial number
Soc.	-	society
Trans.	-	transactions
U. N.	-	United Nations

U. S.	-	United States
USDA	-	United States Department of Agriculture
Viz.	-	Namely
Vol.	-	Volume
Yr	-	year
°	-	degree (s)
'	-	minute (s)
"	-	second (s)
°C	-	Degree Celsius
/	-	per
%	-	per cent
η	-	efficiency
&	-	and

INTRODUCTION

INTRODUCTION

Soil and water are the two important basic natural resources for the existence of life on earth and among these, water is becoming increasingly scarce at a faster rate. We have to constantly remind ourselves that it is water which makes the earth so green and full of life, and so different from any other known planet in the Universe. Hence, we have to make it sure that we do not fritter away each drop of this immeasurable wealth, and use it for the best of developmental purposes, for sustaining human life and culture and enhancing it.

Due to rapid growth of population and increased demand of water for power generation, agriculture, industry, domestic uses and several other purposes water has become a critical factor in many areas both in quantity and quality. Considering the earth as a whole, the availability of water is practically constant whereas the population is on the increasing trend. Out of the world's total available water of 1400 million Km^3, about 95 per cent is contained in the oceans and seas as saline water and 4 per cent is in the form of snow and ice. Thus, the fresh and unfrozen water is only 1 per cent of the total availability, out of which 99 per cent is ground water and only 1 per cent is present as surface water in lakes, rivers, soil and atmosphere.

The total quantum of water available on an annual basis may be enough to meet all our demands, however it is not available in required quantities where and when we need it. This calls for scientific long-term planning for equitable and efficient utilization of the available water at the local, state, regional, national and sometimes even at international levels, both in time and space.

Agriculture sector has been playing a major role in the development of our Country. Water is vital for agriculture. The basic source of water in India is precipitation in the form of rainfall and snowfall. The country's average annual rainfall is about 119.4 cm which amounts to 400 Mha-m. Out of this, 70 Mha-m is lost to atmosphere, 215 Mha-m soaks into the ground and the remaining 115 Mha-m flows as surface runoff. But by the addition of 20 Mha-m by rivers from catchments lying outside the country and 45 Mha-m by the re-generated flow from groundwater, the total annual surface flow in the country has been estimated to be 180 Mha-m.

Out of this 180 Mha-m, 15 Mha-m is stored in various reservoirs and tanks and 15 Mha-m is utilized through diversion works and direct pumping. The remaining 150 Mha-m goes to the sea and to some adjoining countries. On full development, the use of water through diversion works or direct pumping is expected to increase to 45 Mha-m, the balance 105 Mha-m would even then continue to flow to the sea and neighbouring countries.

The state Kerala, having about 300 cm of average annual rainfall and with 44 rivers, chains of backwater bodies, reservoirs, tanks, ponds, springs and wells is often considered as a land of water. Yet Kerala is frequently facing severe droughts followed by acute drinking water scarcity. The rivers hardly contain any water during six months in a year. Kerala does not have a single major river, but has only 4 medium rivers and 40 minor rivers. The total catchment area of all the 44 rivers together is only $28739Km^2$ and the total discharge is $77900Mm^3$. Compared to the national average, Kerala receives 2.78 times more rainfall, but due to steep sloping and undulating topography rainwater is not much retained on the land. At the same time unit land of Kerala has to support 3.6 times population, when compared with the National level scenario. Hence for self-sufficiency, unit land of Kerala has to produce 3.6 times of drinking water, food, biomass and associated water requirements compared to the National average. The realization of the fact that, Kerala has the lowest per capita fresh water availability, we should correct the erroneous feeling that "Lot of water in Kerala". Proper management of the water resources of Kerala would certainly make the situation more comfortable than today.

Reservoirs are the most important elements of complex water resources development systems. They are used for spatial and temporal re-distribution of water in quantity as well as in quality and enhancing the ability of water to generate hydropower. The important characteristic of a reservoir is its potential to cater to multipurpose demands. By building the dam, storage created may be used for flood control, water conservation (municipal, industrial and agricultural water supply), low flow augmentation, hydroelectric power generation, navigation, recreation and fisheries.

The national water policy (1987) suggested that the water resources development projects should be planned and developed as far as possible as multi-objective projects with drinking water supply as top priority followed by irrigation, hydropower etc.

The multipurpose concept in reservoir systems is a sound one and it is finding increased use day by day due to the following reasons.

i) Multipurpose projects make the maximum use of the resources of a river valley in a unified and co-ordinated manner.
ii) In many cases, a mono-purpose reservoir project proves uneconomical and hence, the multipurpose concept has been found necessary in order to provide the much needed economic justification.

Reservoir operation policies contain inherent uncertainty. The random nature of reservoir inflows and other related hydrologic variables are important characteristics of reservoir operation. Hence, a reservoir operation plan is devised to achieve greatest value or benefit from the storage capacity. Optimizing reservoir operation involves allocating resources, developing stream flow regulation strategies and operating rules, and making real time release decisions within the guidelines of the operating rules. A reservoir system regulation plan or operating procedure or release policy is a set of rules for determining the quantity of water to be stored and to be released or withdrawn from a reservoir or system of several reservoirs under various conditions. In real world operations, the operating rules provide guidance to the operators who make the actual release decisions. The optimal operational plan must be formulated considering the following aspects.

1. Knowledge of the flow characteristics of the stream i.e., a history of its past performance.
2. The purpose or purposes of the reservoir must be analysed to determine as how the hydrograph of flow should be altered to produce the greatest benefits; and
3. Special considerations, such as the effect of sudden releases on stream banks, and of long sustained flows from the reservoir on agricultural developments in the valley below the reservoir.

In a multipurpose project the water management would require optimum use of water for various needs at different times. The need for an integrated and comprehensive planning of the limited water resources for maximum economic benefits emphasises the importance of systems analysis. Optimization techniques and use of fast digital computers have made it possible to use the systems analysis for solving the problems related with water resources planning.

The second important demand after drinking needs to be met from a reservoir is irrigation. Irrigation consumes a huge quantity of water and quite naturally the major allocation from a reservoir system goes to irrigation. Hence, our aim should be to increase the effectiveness of every drop of water used for irrigation in terms of economy. There lies the importance of cropwise and seasonwise allocation of area in the command. Here also, the systems analysis techniques play a vital role in optimizing the area allocation for different crops considering various socioeconomic constraints.

Systems analysis has been used in all the phases of water resources development say basin/ regional planning, project planning, design of project component, operation and maintenance of the project. The conflicts arising between various competing uses and the need for total water planning including allocation of water to different purposes, necessitates the system to be considered as a whole. A system may be considered as an aggregation or assemblage of components united by some form of interaction or interdependence. The procedures and techniques used to analyze the system under consideration as a whole, instead of each component separately, so as to improve the performance of the system is called systems analysis. Thus, progress can be achieved if we shift our mindset from a commodity-centered approach to an entire cropping or farming system based on an integrated natural resources management strategy.

There are different classes of models generally used in systems analysis. Among these, mathematical programming has considerable application in water resources planning for finding the minimum or maximum of a function of several variables under a prescribed set of constraints. The most widely used mathematical model in this class is linear programming model because of the easy availability of its software packages. The limitation of the linear programming model is the use of only linear objective function and constraint relationships in terms of decision variables.

From the above discussions, it is to be inferred that any proposed multi-objective storage reservoir with irrigation component should undergo thorough analysis in terms of optimum water allocation and most efficient cropping pattern for the command area. With this idea, a study has been carried out for the regulator-cum-bridge under construction at Thrithala in Palakkad district of Kerala state in Indian Peninsular.

The specific objectives of the study are:

i) To determine the optimum water allocation of the reservoir for meeting various demands on it and

ii) To obtain the optimal cropping pattern for the command area.

REVIEW OF LITERATURE

REVIEW OF LITERATURE

Application of systems engineering techniques to water resources management problems appears to have good potential, since it is possible to consider the complex issues in totality with systems approach. This technique not only deals with the engineering aspects of water resources planning and management, but also covers multi-disciplinary areas considering other relevant factors such as physical, social, economic, political, biological, and other characteristics of specific problems for which the techniques are to be applied.

Though "Systems approach" has been practiced for long period, its development can be traced from World War II. During the war, effort was made by the allies to solve very complex rescheduling problems, which fell outside the professional expertise of any one discipline or profession. It played an important role in post war military establishments. Soon after the war, principles of systems analysis were utilized for business decision making and now it is used in almost all complex decision making situations.

This chapter makes a brief review of the applications of systems analysis approach to the water resources problems faced round the world. In 1953 the U.S. Army Corps. of Engineers made a study of water resources system on the Missouri River. Studies were made on the Nile river basin in 1958. The U.S. Army Corps. of Engineers made a study of the Columbia River system with 25 storage dams and 45 runs of river facilities in 1962. The Harward water resources group (Maass *et al.*, 1962) had evaluated the merits of the systems approach as compared to traditional methods. Hufschmidt and Fiering (1966) used simulation in planning the multi-reservoir, multi-purpose Lehigh River system.

Systems analysis studies of Ganga-Brahmaputra basin were carried out at Harvard University Centre for population studies from 1966-69. This was an international basin study. Similar studies had carried out for Indus and Mekong basins. An optimizing simulation approach had been attempted under the framework of multi-objective to generate development alternatives for enhancing irrigation and power generation in Rio Colorado River basin (Major and Lento, 1975).

A number of studies have been carried out in Indian context also. Several studies were made to optimize the existing irrigation systems such as studies on reservoir operation of Mayurakshi project by Maji (1975), Upper Bari Doab command area studies by Lakshminarayanan and Rajagopalan (1977), Upper GangaCanal studies by Singh (1977) and Gupta (1984), Operation of Damodar basin reservoirs by Sinha and Rao (1984) and Cauvery basin studies by Vedula and Rogers (1985).

It is thus evident that systems analysis could improve the planning and operation of water resource projects because it permits the study of their behavior under varying conditions. It also provides a rational basis for selecting an action plan out of several alternatives. But the system analyst and the decision-maker should clearly understand the limitation of the technique. Systems analysis is a tool for the decision-maker and not a replacement of professional wisdom.

2.1 Optimization of multi objective reservoir operation using Systems Analysis

Several simple linear programming problems have been formulated by Thomas and Revelle (1966) to illustrate the interactive influence of irrigation and power. They have used distribution coefficients of water demand for each month for irrigation and power and the maximum level of farm power was calculated for different levels of agriculture. They have used linear programming to rank the many alternative operating schemes resulting from the different combinations of agriculture and power targets. They have also developed a realistic model for a multiple objective reservoir considering the constraints regarding flow continuity, irrigation release, and hydropower generation. The decision variables were the target outputs to be achieved for irrigation, hydropower and flood water storage, lower bound for storage during any month and cumulative release from the i th month of the jth year.

Becker and Yeh (1974) have developed a method for the determination of optimal operating rules for a multi-reservoir system. They utilized a form of dynamic programming for the selection of an optimal reservoir storage path policy through a specified number of policy periods and a linear programming model for period-by-period optimization. The method is easily adaptable to a great variety of situations, regarding only inflow predictions for the interval for which the optimal policy is to be determined and an end-of-period permissible storage vector space for the final period.

Srivastava and Tiwari (1978) have developed a two-season optimization model for optimal allocation of Narmada waters to the two beneficiary states namely, Madhya Pradesh and Gujarat using linear programming approach. Eighteen proposed design alternatives involving six major reservoirs have been examined in this study. The decision variables of the model were releases from different reservoirs during the season considered, storage of the reservoirs at the beginning of the season, the gross capacities of the reservoirs, the hydropower plant capacity at the reservoir sites, the irrigation demand and the hydropower targets of the season. The objective of the model was to maximise the net benefits from irrigated agriculture and power production from all reservoirs in the system. The constraints formulated were on reservoir release for irrigation, reservoir storage continuity, capacity of the reservoir, limitation of the flood through the turbines, and power produced at each reservoir site. Design constraints regarding the dead storage capacity of the reservoir, design load factor and total irrigation water used by each of the two states were included in the model. The linear programming model was solved using MPS/ 360 package.

A chance constrained linear programming model which employs multiple linear decision rule was developed by Houck (1979). The model incorporates, explicitly, the stochastic nature of the stream flow process. It can be used in design and/or management situations and it does not significantly restrict the operating policy prior to solution. It is also economically and computationally feasible.

Simonovic (1979) developed an algorithm for solving the problem of long-term control or planning the functioning of multi-purpose reservoir pool. The complexity of the problem was imposed by 2- step algorithm for solving the long-term optimal control: 1) Explication of all chance constraints on the state and control co-ordinates is being done at the first step; 2) the choice of optimum control is being done in the second step. The method of iterative evolution was chosen for the first step and the method of linear programming for the second step.

Bhaskar and Whitlatch (1980) analysed a single, multi- purpose reservoir using a backward looking dynamic programming algorithm to obtain optimal releases. The dynamic program was solved for both one sided and two sided quadratic loss functions. Linear and non-linear releases policies were developed, verified and compared through simulation. For a two-sided quadratic loss function, linear policies are as good as or better than non-linear policies.

Esmaeil-Beik and Yu (1980) used a stochastic dynamic programming to develop optimal policies for operating the Elkcity Lake in Kansas with serially correlated inflows. The model determines a long term operating policy to minimise the expected average annual loss. The developed optimal policy to operate the lake from 1967 to 1977 shows a marked reduction in the expected annual losses as compared with the historical operation.

Kandaiah (1982) has applied linear programming technique to develop the optimal operating policy for Sholayar reservoir of Tamilnadu in India which plays a twin role in the system operation namely i) diverting a fixed quantity of water to the Sholayar reservoir in Kerala state which is connected in parallel and ii) releasing a minimum quantity to Parambikkulam reservoir for riparian usage.

Yeh and Becker (1982) developed practical procedures for the analysis of a multiple purpose, multiple facility reservoir to guide real time decisions concerning the optimal operation of the system. Application is made to the California Central Valley project. The five purposes (benefits) treated as objectives in the multi-objective optimization, include 1) hydropower production 2) fish production 3) water quality maintenance 4) water supply and 5) recreation. The constraint method was used to develop the trade-offs while a specially modified linear programming and dynamic programming algorithm was used for optimization.

Yacigil *et al.* (1983) developed an optimization model that may be used by reservoir system operators to improve daily real time operations and to evolve better long term operating guidelines were developed and tested. The four multi-purpose reservoirs in the Green River Basin (GRB) of Kentucky were used for the case study. The GRB operation optimization model was a linear program constructed to imitate the decision making process that results in actual reservoir release decisions. The model is easily modifiable and very flexible, which allows sensitivity analysis and experimentation with new operating guidelines. This experimentation should permit the operators to evolve improved operating policies. The inputs to the model are data that are readily available and the inputs may be presented in easily interpreted graphical form.

Mohammadi and Marino (1984) presented an efficient algorithm for the real time monthly operation of multi-purpose reservoir. The model is a combination of linear programming and dynamic programming. The use of parametric linear programming, minimum required beginning of month storage and an iterative solution procedure resulted in low computer time and low computer requirements.

Grygier and Stedinger (1985) employed a successive linear programming, an optimal control algorithm and a combination of linear programming and dynamic programming (LP-DP) to optimize the operation of multi-reservoir hydrosystems given a deterministic inflow forecast. The algorithm maximizes the value of energy produced at on-peak and off-peak rates, plus the estimated value of water remaining in storage at the end of the 12-months planning period.

Chattopathyay (1988) presented a generalized linear decision rule, which takes into account the aspect of spill in a multi-lag LDR model. The proposed rule incorporates past inflow experience to determine the optimum release rules based on a stochastic (linear) programming optimization model. Two synthetic stream flow series of a duration of 50 years each were generated under lognormal flow assumption. The prescribed release rules were applied to a hypothetical reservoir with the optimum capacity determined by the linear programming method and the generated series as the inflow.

Kuczera (1989) formulated multi-reservoir, multi-period linear programming models as network linear programs (NLPs) for which computer codes about 100 times faster than general linear programming codes are available. A NLP formulation was presented for determining water assignments in multi-reservoir systems over some time horizon. It provides for demand zone shortfalls due to drought or transfer limitations, instream flow requirements which can be violated during droughts and seasonal reservoir target volumes. It also allows the trade-off between reliability and demand shortfall severity to be explored.

Loganathan and Bhattacharya (1989) studied the problem of optimal reservoir operation as it consists of obtaining optimal releases, reservoir storage and downstream reach routed flows based on forecasted inflows and precipitation. Five goal programming schemes that minimise deviations from a set of preferred target storage and flow values are considered. The reservoir operation is also formulated as a multi-objective linear program(MOLP). The optimal solutions of goal programs are contained among the efficient points of the MOLP. It is also shown that the min-max fuzzy goal programs can yield inefficient points as optima, however there exists efficient alternative optima.

Afshar *et al.* (1991) presented a mixed integer linear optimization model for river basin development for irrigation. The model is a chance- constrained optimization model that considers the interactions between design and operation parameters (reservoir capacity, delivery system capacity, hectares of land to be developed and planted to different crops etc.) The model is capable of integrating all decision variables in the design phase, thus accounting directly for any interdependency between design variables. 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 decision rule operational parameters.

Keskar and Mohan (1991) proposed a goal programming approach for multipurpose reservoir operation and it was applied to the Bhadra reservoir system having irrigation and hydropower production as dual purposes in India. The objective of the model was to satisfy sequentially a series of operating criteria. Two goal programming models, one with the objective of minimizing the deviations from storage targets and the other with the objective function as minimizing the deviations from release targets were formulated and applied to the reservoir under study. The results proved that the model with release targets is preferred over the model with storage targets for determining operational policies for multipurpose reservoir system.

Tao and Lennox (1991) described the solution procedure of the reservoir systems operation problem, which was formulated as a successive linear programming model. The algorithm was then applied to the operation of the High Aswan Dam (HAD) in the Nile river basin.

Mizyad *et al.* (1992) demonstrated the utility of optimal control theory for the deterministic operation of very large multi-reservoir systems for a real situation, the complex multi-reservoir Mahaveli system in Srilanka. The system includes 19 nodes or reservoirs and 35 release links. The model developed was designed to minimize a hydroelectric energy shortage objective and satisfy pre-specified irrigation demand constraints. Two alternative approaches were explored for optimal operation of the

Mahaveli system. The first involved monthly application of the optimal control algorithm to find an optimal policy for the next year, based on current shortage and forecasted or historical inflows and demands. The second alternative was an implicit stochastic approach, in which linear operating rules were derived using deterministic optimal control and historical data. Both of the alternatives gave reasonable and comparable results. The implicit stochastic optimization alternative has a good advantage regarding computer time and storage requirements. This makes it usable on a small personal computer, providing the system operator with decisions in a few seconds even with very large systems.

Mohan and Raipure (1992) developed a linear multi-objective programming model in which the constraint technique was used to derive the optimal releases for various purposes from a large-scale multi-reservoir system consisting of five reservoirs in India. Maximization of irrigation releases and maximization of hydropower production were considered as the twin objectives in the model subjected to constraints on physical limitations, environmental restrictions and storage continuity. The trade-off analysis between the conflicting objectives of irrigation and hydropower was also carried out and the transformation curve was plotted. The optimal point on this curve gives the best combination of the twin objectives considered in the model.

Simonovic (1992) presented a short review of the mathematical models used in reservoir management and operations to present conclusions reached by previous state- of- the- art reviews and to provide two ideas for closing the gap between theory and practice. First, a simple simulation- optimization model for reservoir sizing has been presented as an example of system approach which respond to practical needs of water resources engineers. The second example illustrated the benefits of knowledge-based technology with regard to single multi-purpose reservoir analysis.

Hajilal *et al.* (1995) presented the development of mathematical models for optimal reservoir operations for irrigation management. The problem of real time reservoir operation for optimizing the crop yield in the command area was considered to occur at two distinct stages, i.e., the planning stage and the real time management stage. The use of reservoir inflow forecasts in real time reservoir operation was also evaluated.

Randall *et al.* (1997) described the development of a water supply planning simulation model that uses a mixed- integer linear programming (LP) approach and demonstrated that this approach has more capability than similar models that use network formulations. Water supply operations for a single monthly time step are formulated as a mixed integer linear program. The LP was then embedded in a month-by-month simulation model. The LP was formulated using a priority based objective function. The model has been used successfully by the Alameda County Water District (California) staff for its long range, integrated planning.

Study conducted by Needham *et al.* (2000) dealt with questions related to flood control operating procedures followed by the U.S. Army Corps of Engineers, Rock Island district. Application was presented as a mixed integer linear programming model for a reservoir system analysis of three U.S. Army Corps of Engineers' projects on the Iowa and Des Moines rivers. A strategy for evaluating the value of coordinated reservoir operations was developed.

Verma and Shrivastava (2000) presented the application of weighted goal programming methodology to a system of multipurpose reservoirs for optimal monthly operation policy. The weighted goal programming model was developed and applied to the Mahanadi Reservoir Project complex comprising of six multi-purpose reservoirs.

2.2 Optimization of Cropping pattern

In general, crop planning procedures involves selection of crop activities from a number of feasible alternatives so as to satisfy the objectives of the planner under the limiting conditions of available land and water resources, social requirements and other physical and technological constraints in the planning environment. Crop planning is gaining importance due to the scarcity of farm resources and particularly so with the introduction of the high yielding crop varieties. Thus the optimal allocation of water for irrigation depends not only on the effective use of water, but also on other inputs such as fertilizer, labour etc. While obtaining the solution for the optimal cropping pattern for a particular region, factors like soils, topography, climate, agro-biology and socio-economy are also to be considered.

Dudly (1971) have dealt with the intermediate problem of deciding the area of a single crop to be planted at the beginning of an irrigation season by a single decision maker with full control on operation of the reservoir. They had treated the inflows into the reservoir and the crop water demand as stochastic variables. Their result indicated that the best acreage to be planted is an approximate linear function of the initial stage in the reservoir.

Clummings (1972) conducted a study to maximize the expected net revenue of reservoir release. He employed the linear and dynamic programming techniques in his study. Linear programming model estimates the optimal areas of feasible crop activities for an irrigation season. Expected net revenue in terms of the release from the reservoir for that season was obtained from the linear programming model assuming the crop water requirements to be deterministic. The results from the above models were used to obtain optimal annual reservoir releases as functions of initial reservoir level using dynamic programming.

Dudly (1972) have developed a model to solve the long run irrigation problem for determining the best size of area, which can be brought under irrigation in case of regulated stream flow. The releases from the reservoir of fixed capacity, the area to be planted and irrigation timings were assumed to be controlled by a single decision-maker. The demand and supply of water were considered as stochastic. The analysis indicated that the results were sensitive to the variation in the fixed costs of the alternatives in the system.

Anderson and Mass (1973) developed a digital model to approximate the critical operating decision variables of an irrigation system for both short and long run problems. In the short run, the model yields solution for the best way of water allocation for irrigation under water shortage conditions. The advantage of this model is its simple format of the decision output which enables farmers and operators of irrigation systems to make decisions on their own, regarding the effects on cropping patterns, crop production and farm income of different water supply restrictions and different rules for delivering water. On the other hand for the long run problem, the model aids in comparing alternative programs or designs for the development of new supplies of irrigation water and new distribution system.

Dudly and Burt (1973) have developed an integrated inter-seasonal stochastic dynamic programming model to determine an optimal decision rule with respect to the following three types of irrigation crop decisions.

i) Inter-temporal water application rates
ii) Whether or not a portion of the irrigated area should be abandoned from further irrigation for the remainder of the season and
iii) The optimal area to be planted for potential irrigation at the beginning of the irrigation season.

Solutions from the model indicated the influence of developed irrigation area, distribution system capacity and reservoir capacity in optimizing the design. A method was presented by them for incorporating the variance and expected value of net benefits into the decision criteria for optimal developed crop area.

Blank (1975) has described a linear programming model for determining the mix of crops so as to take advantage of the limited resources to produce the maximum economic return. The total number of crop activity levels accounted in the model was expressed as,

No of crop Activities = No. of crops x No. of methods of growing for each crop

Water activity levels of the model consider time period in the irrigation season.

Sowell *et al.* (1976) conducted studies on agricultural water demands in North Carolina. The objective of their studies was to determine the following.

i) total water requirement for a given level of agricultural activity in an area.

ii) the optimal level of agricultural activity for a given level of water available in a specified area.

iii) economically feasible irrigation water requirements for each crop grown in the area.

A linear programming optimization model has been developed to analyse large number of combinations of irrigation, soil type and crop activity.

Lakshminarayanan and Rajagopalan (1977) investigated the problem of optimal cropping pattern considering conjunctive use of releases from canals and tubewells in the Bari Doab basin in India using linear programming model. The objective function of the linear programming model contained 42 operating variables to be determined and 68 constraint equations. Simplex algorithm was used to solve the problem. Their result showed that an increase in the available area for irrigation would give rise to increased benefits from irrigation activity.

Maji (1977) applied linear programming models in optimal allocation of land, water and other farm resources in the command area of the Mayurakshi project in West Bengal. The objective of the study was to evolve an optimal cropping pattern. For this purpose, the monthly gross irrigation requirement of each crop was integrated with the monthly reservoir operations. The results indicated that the overall intensity of cropping in the command area could be increased from the existing level of 105% to 150%. They also suggested that the agricultural operations in the command area would be more efficient if the existing emphasis on kharif season irrigation is shifted to Rabi season irrigation.

Michael *et al.* (1978) reported that for a given set of crops that may be grown under the specified agro-climatic restrictions, an efficient crop planning must recognize the following often conflicting goals,

i) Optimal use of fixed as well as variable resources in production.

ii) Increase in employment opportunity and income for the agricultural labour, especially in a developing country like India, where unemployment is a severe problem.

iii) Attainment of the national objective of self-sufficiency in food production.

Shortcomings in anyone of the above mentioned goals will either lead to undesirable socioeconomic consequences, or a failure to bring out the cropping pattern into reality.

Efforts have been made by Saksena and Satish Chandra (1978) to study the then existed and future water balance in the command area of upper Ganga canal (U.P) to plan the conjunctive use and to obtain an optimal cropping pattern using linear programming model. The objective of the problem was to maximize the annual aggregate benefits considering the net benefits obtained from crops as well as the annual operating and maintenance costs of canal and tube well systems. The result of the study indicated that the intensity of irrigation in the command area would increase from 98% to 115%.

Matanga and Marino (1979) studied the irrigation programmes generated for each of the selected three crops to be planted, using an area allocation model to determine an optimal cropping pattern. The area allocation model is a linear optimization model to maximize gross margin from yields. The objective function was formulated taking into account the economic return from the cropped land, cost of production, water and labour which is subjected to the total water supply, maximum amount of water that can be delivered on any date of irrigation, yield limitation and labour. The results obtained by them included the cropping pattern, gross margin, total irrigation depth on each date of irrigation, total irrigation labour and crop yield.

Kumar and Singh (1980) studied the effect of interaction of irrigation and labour on optimal cropping pattern. A multi- crop optimization model was formulated and applied for the canal command area of Sirsa branch of Western

Jamuna canal system. The optimal cropping plans were determined with and without considering the labour constraints.

Venkatesan and Ramalingam (1980) applied linear programming model to plan the area under irrigation in the command of Bhadra-irrigation project of Gujarat with the objective of optimizing the benefits from irrigated crops.

Duggal and Khepar (1981) developed a linear programming model and it was applied to a canal command region of Punjab to examine the capacity and operation of an irrigation system consisting of canals and tube wells. The objective of the model was to determine the optimal cropping pattern subject to,

i) the water availability constraints regarding surface water, ground water and total water.
ii) the specification of the total land constraint, maximum and minimum crop land restrictions of certain crops grown specifically in the area maintaining the rigid institutional framework.

Vedula and Rogers (1981) developed a deterministic model for a four-reservoir system on a monthly basis using linear programming technique. This model was applied to the Cauvery river basin in South India with the aim of finding optimum cropping patterns subject to land, water and downstream release constraints. In this model, while considering the two objectives namely, maximizing net economic benefits and maximizing irrigated crop area they have analysed the resulting trade-offs in the context of multi-objective planning. In addition to crop area the other decision variables are storage at the beginning of each month and monthly downstream releases of each reservoir. Constraints have also been laid on limits of individual crops to be grown. Representative values of crop yields were used for calculating the net benefits from crops for the study region.

Kumar *et al.* (1982) developed an optimal cropping pattern for Gandak command area of Uttar Pradesh using linear programming. The benefits to cultivators were maximized in this study subject to constraints regarding upper limits of total land and water quantity. Optimal cropping patterns (with adequate quantity of water) were worked out for four different conditions for different limits of croplands.

English (1981) published a paper about economic optimization of irrigation water use. Statistical decision theory was applied in this analysis and particular attention was given to questions of uncertainty and utility. The theoretical framework was applied to a case study involving farmers with a limited water supply. Uncertainty was shown to be substantial and pervasive. Decision theory was used to select optimal cropping pattern for each of six farmers. The cropping patterns considered included various combinations of two different crops and fallow land. Case study results indicated optimal irrigation strategies selected for individual farmers in the face of the uncertainty in crop yield models may differ substantially from strategies selected without regard for uncertainty and utility. These optimal strategies will be more consistent with the preferences of the individual farmers.

Mohile and Jagannathan (1983) developed a linear programming model, which determines allocation of land to irrigated as well as non-irrigated crops. The yields and benefits resulting from irrigated as well as non- irrigated crops were considered in this model. The model also decides the reservoir releases, surface diversions and pumping and energy distribution. The benefits from different engineering designs effected by varying the system parameters such as capacities of reservoirs, canals and pumping capacities or the system constraints like required flows and water export were readily comparable without trial and error simulation based optimization. Existing and future conditions with and without the project were investigated in this study.

Panda and Khepar (1985) adopted a linear programming technique to maximize the net return from optimal irrigation planning. Both deterministic and chance constrained linear programming models were used.

Rao *et al.* (1988) conducted a study of irrigation scheduling under limited water supply. The problem of scheduling irrigation at weekly intervals for a single crop, when water supply is limited was considered. The mathematical formulation was based on a dated water production function, weekly soil water balance and a heuristic assumption that water stress in the early weeks of a crop growth stage leads to sub-optimal yields. The allocation problem is solved at two levels, growth stages and weeks. At the first level, the dated water production function was maximized by dynamic programming to obtain optimum allocations for growth stages. At the second level, the water allocated to each growth stage was reallocated to satisfy weekly water deficits within the stage. Water delivery and soil- water storage constraints were included at both levels. The model was applied to a field problem to derive weekly irrigation programs for cotton under various levels of seasonal water supply and initial soil moisture.

Ahmad and Heerman (1990) developed a model to simulate the irrigation scheduling of a water course command. The model was to predict cropping intensity, net farm returns, farm water use, percent water utilized, deep percolation at farm level, rainfall contribution and extra tube well water pumped. Schedules for these selected farms on a water course command in Sargodha, Pakistan were simulated with three fixed rotation strategies and compared with a demand strategy. The change of the fixed rotation system to demand system will significantly increase the net farm return in addition to improved water allocation to various farms in watercourse command. The demand strategy will provide saving in energy due to scheduled pumping operations and effective utilization of canal water supplies.

Paudyal and Gupta (1990) solved the complex problem of irrigation management in a large heterogeneous basin by using a multilevel optimization technique. The real problem consisted of determining the optimal cropping patterns in various sub-areas of the basin, the optimal design capacities of irrigation facilities including surface and ground water resources and the optimal water allocation policies for conjunctive use. However, the effects of stream flow or resources uncertainty with the year-to-year variability of crop water requirements were not considered in the model.

Dariane and Hughes (1991) developed a model for real time operation of an irrigation reservoir with the objective of maximizing the value of multiple crop yields during a growing season. The model employs monthly additive and product forms of crop yield functions for dry matter and grain crops respectively. The resulting non-linear optimization model uses a long transform to reduce non-linearities in the model. An application of the proposed model was compared to a common operating rule used in simulation models.

A multi-objective linear programming based planning model for irrigation development incorporating the integrated use of surface and ground water resources was developed by Onta *et al.* (1991). Evaluation of the objectives by compromise programming was carried out to indicate the optimal scale of development, cropping plans, system design capacities and water allocation planning. These related studies need to be extended to incorporate the reliability of the resources to consider the uncertainty in the natural phenomina.

Paul and Raman (1992) developed a linear programming model for obtaining an optimal cropping pattern from among the various alternatives for any command area by the conjunctive use of surface and ground water, for getting maximum net returns from the command area as well as for maximizing the area of cultivation. The study revealed that when the traditional cropping pattern was changed, the entire command area could be cultivated with the same available water and an increased net benefit was also obtained. It also revealed that when the objective was to maximize the area, a total of 19 Mm^3 of water left unused for irrigation purpose. This quantity was 28Mm^3 when the model was run for maximizing the net benefit. Since this surplus water was found during the summer months, this could be utilized for domestic and downstream releases.

Acharya and Gupta (1996) conducted a study for optimum resources utilization for increased agricultural activity in Som-Kagdar command area. The study was undertaken to investigate present status of resource utilization (land, water, human and capital) and to suggest alternative strategies for increased economic status of the population. Use of linear programming model has been made to arrive at optimal cropping pattern for upliftment of economic status of the population of the command area. The model provides an optimal cropping pattern through which judicious utilization of generated resource is made possible in the command area. The result showed that only 14.7, 19.0, and 22.0 percent area can be put under cultivation in Kharif, Rabi and Zaid seasons respectively and the labour utilization in agriculture is only 5 percent of total manpower available. The result also showed that more than 70 percent of water resources remained unutilized. A comprehensive study of optimal cropping patterns revealed that capital was acting as main constraint which restricted the utilization of other valuable resources in the command area.

Balasubramannian *et al.* (1996) established a linear programming analysis in a tank irrigation system for real representation and optimal allocation of area of Aralikattaitank system in Tamilnadu. The actual conditions were simulated at each sluice command level whereas the best operational policy was attempted for the entire system as a whole. The analysis was conducted separately for a drought year (1988) and a surplus year (1990) with the available five-year data from 1988 to 1992. The major conclusions indicated that the late transplantation of the rice crop and the excess water application during the period of water availability (leading to water stress during the last stages of crop maturity) were the causes of the meager benefits in a drought year. Also in a surplus year the excess water application over the entire cropping season resulted in under utilization of land resources and moderate benefits. The existing status of irrigation can be improved to obtain the maximum benefits from the tank command area based on the quantification done.

Juan *et al.* (1996) developed a model to determine optimal irrigation strategies for a single season. This has been achieved by using a simple relation between yield and amount of irrigation water which takes into account the effect of uniformity of water application. The main objective of the model was to provide a procedure by which farmers can evaluate and compare alternative assumptions on expected water regimes for the following year in order to optimize crop rotations, crop production and farm incomes and to obtain the optimum use of irrigation works, farmland and other resources. This requires data that are readily available to the farmer.

Vedula and Kumar (1996) developed an integrated model based on seasonal inputs of reservoir inflow and rainfall in the irrigated area to determine the optimal reservoir release policies and irrigation allocations to multiple crops. The model was conceptually made up of 2 modules. Module 1 was an intra-seasonal allocation model to maximize the sum of relative yields of all crops for a given state of the system using linear programming (LP). The module considered reservoir storage continuity, soil moisture balance and crop root growth with time. Module 2 was a seasonal allocation model to derive the steady state reservoir operating policy using stochastic dynamic programming (SDP). Reservoir storage, seasonal inflow and seasonal rainfall were the state variables in the SDP. The objective in SDP was to maximize the expected sum of relative yields of all crops in a year. The results of module 1 and the transition probabilities of seasonal inflow and rainfall form the input to module 2. The use of seasonal inputs coupled with the LP-SDP solution strategy in the present formulation facilitates in relaxing the limitations of an earlier study while effecting additional improvements. The model was applied to an existing reservoir in Karnataka State.

Mainuddin *et al.* (1997) formulated a monthly irrigation planning model for determining optimal cropping pattern and the ground water abstraction requirement in an existing ground water development project. Two objectives, maximization of net economic benefits and maximization of irrigated area aspired to by both the irrigation authority and the individual farmers in the Sukhothan Ground Water Development Project in Thailand were considered. To account the uncertainty in water resources availability the model was solved for three levels of reliability of rainfall and ground water resources (80, 50 and 20 percent). The effects of deficit irrigation on the net benefit and cropping intensity as well as on the yield of crop were also assessed by considering three levels (no deficit, 25 percent deficit and 50 percent deficit) of water application to the crops. To select best alternative plan, a multi- objective analysis was carried out using the Analysis Hierarchy process considering the preference of the decision-makers, including farmers and irrigation project managers.

Sunantara *et al.* (1997) studied optimal seasonal multi-crop irrigation water allocation and optimal stochastic intra- seasonal (daily) irrigation scheduling. They used a two-stage optimization approach based on a stochastic dynamic programming methodology. In the first stage, the optimal seasonal water and acreage allocation among several crops or fields was defined using deterministic dynamic programming with the objective of maximizing total benefits from all crops. The optimization was based on seasonal crop production functions. Seasonal crop production functions were obtained using single crop stochastic dynamic programming which incorporates the physics of soil moisture depletion and the stochastic properties of precipitation. In the second stage, optimal intra- seasonal scheduling performed using a single crop stochastic dynamic programming algorithm conditional on the optimal seasonal water allocation of stage one. Optimal daily irrigation decision functions were obtained as a function of root-zone soil moisture content and the currently available irrigation water. The methodology was applied to a case study characterized by four crops in which both the optimal irrigation applications and the optimal storage for each crop were determined.

Ravikumar and Venugopal (1999) conducted a study on optimal reservoir operation under cropping pattern uncertainty and an innovative three dimensional stochastic dynamic programming model was formulated to arrive at minimum initial storage that can meet demand at specified reliability for each cropping season. The applicability of the model to a typical southern Indian irrigation system, Krishnagiri Reservoir Project was demonstrated and the potential utility of the model were discussed in this study.

Bindhu (2000) formulated a monthly irrigation planning model for determining the optimal cropping pattern in an existing lift irrigation scheme at Thavanur in Malappuram district of Kerala. The study dealt with the use of linear programming technique for obtaining an optimal cropping pattern from various alternatives for a command area by the conjunctive use of surface and ground water. Three conditions were considered in the model formulation. In order to make the best use of the available water resources and to get the maximum benefits and to put maximum area under cultivation, different trials were conducted with different crop combinations subjected to the constraints identified using the model. Area maximization was found useful to provide more labour opportunities to the region even with a limited water supply. By using the developed model for area and benefit maximization, the decision makers can recommend a better cropping pattern to the farmers in advance which will satisfy both the objectives to the desired levels. The model is found very flexible to alter the constraints or to add more constraints according to the decision of policy makers from time to time based on socio- economic considerations.

Most of the river basin irrigation projects are aimed at providing supplemental or protective irrigation to the traditional crops grown in the command areas of the projects. But the introduction of high yielding varieties of crops has increased the choice set of the farmer and the planner. It is therefore important to examine, if a change in the traditional cropping pattern in the irrigation project area may result in a better use of the available resources. Cropping pattern in a particular region also depends on socioeconomic factors, soil, topography, climate etc. Thus, the cropping pattern should be viewed as a dynamic concept rather than a static concept.

MATERIALS AND METHODS

MATERIALS AND METHODS

The materials used and methodology adopted for the study are described in this chapter.

3.1 Description of the project selected for the study

3.1.1 Location

The water resources project selected for the study is the Regulator- Cum- Bridge under construction across Bharatapuzha. It is located at Thrithala in Palakkad district of Kerala. It is situated across Bharatapuzha at about 30 KM upstream side of Chamravattom project. In this forthcoming Regulator- Cum- Bridge, water will be stored up to a level of +15m MSL and can be regulated for various needs. The reservoir of the regulator is confined to the course of river by providing flood banks on either side. The bridge is aimed to connect the underdeveloped places such as Paradur and Pallippuram etc. to Thrithala and Kunnamkulam. The latitude and longitude of the site is 10^0 48'0" N and 76^0 8' 0" E respectively. The location and command area map of the project is shown in Fig. 1.

3.1.2 Major benefits from the project

The major benefits expected from the project are:

1. Assure irrigation to an area of 1303 ha in Ottappalam Taluk of Palakkad district.
2. Drinking water supply to Kunnamkulam, Guruvayur and Chavakkad municipalities in Trichur districts and a number of panchayats lying in Palakkad and Trichur districts.
3. Distance between Kozhikodu and Guruvayur via Valanchery will be shortened by 11 KM.

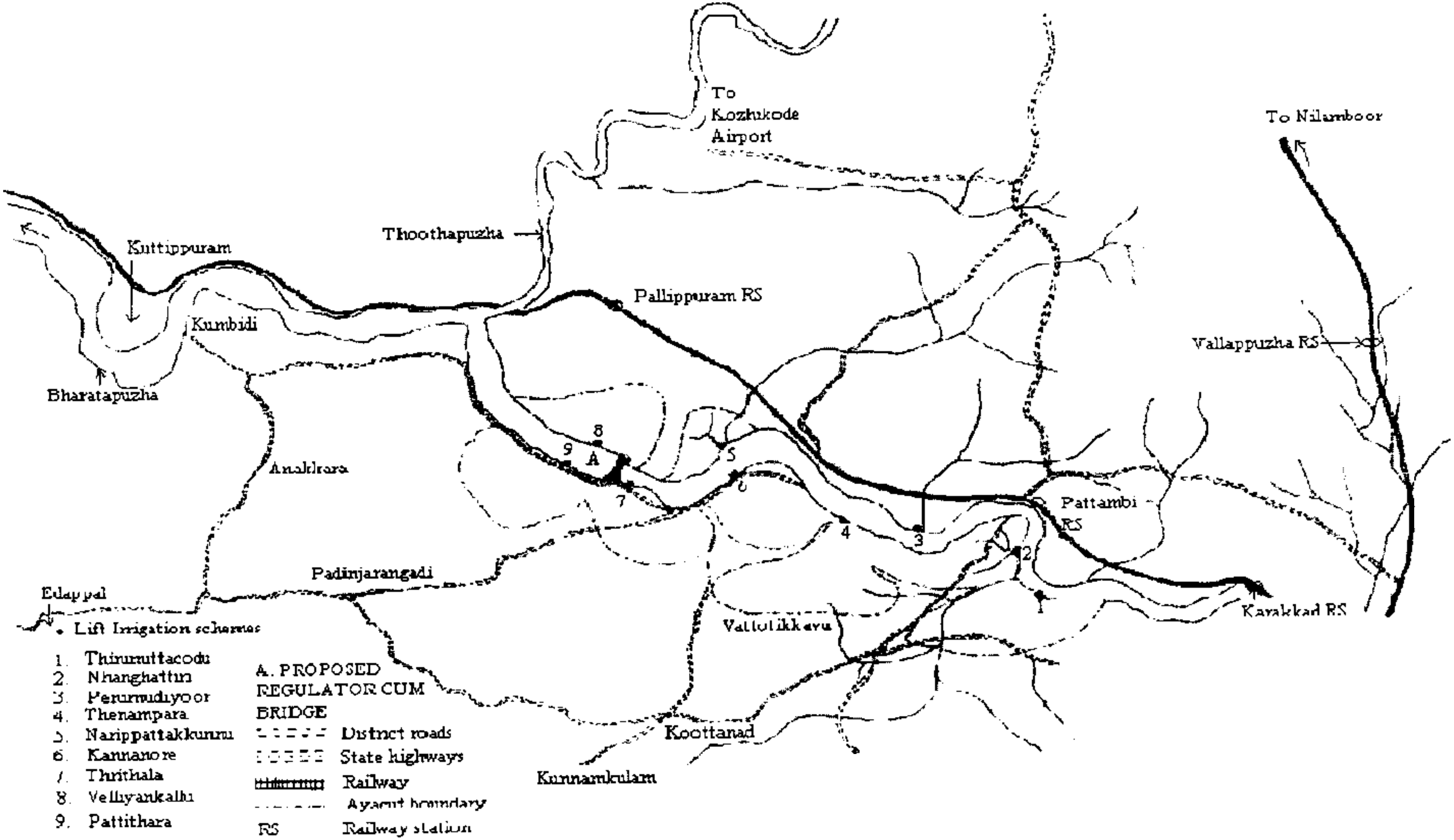

Fig. 1 Location and Ayacut map of Thrithala Regulator- cum-Bridge Project

4. The reservoirs shall help to raise the water table of nearby region.
5. The reservoirs will facilitate inland navigation and fish farming. The reservoir can be developed to a tourist centre by providing for water sporting, fishing and other recreational facilities.
6. The reservoir will help to retain the flora and fauna of the locality and to restore the environmental conditions of the area.
7. The sheet piles proposed in the upstream and downstream of the apron will facilitate storage of water under the ground forming an underground reservoir. This will further raise the water table in the locality.

3.1.3 Salient Features of the regulator

Location	:	Velliyankallu near Thrithala
River Basin	:	Bharatapuzha
State (Interstate)	:	Kerala and Tamilnadu
Length	:	300m
Height	:	5.5m
Drainage area of the River about the site	:	400Km^2
Available Catchment area	:	400Km^2
Mean annual rainfall in the Catchment	:	272.1cm
Max. Annual rainfall	:	452.78cm
Min. annual rainfall	:	179.27cm
Min dry weather flow	:	Nil
Type of Project	:	Multipurpose
Gross command area	:	3997ha
Culturable command area	:	1303ha

Names of villages and towns served :

Kunnamkulam, Chavakkadu, Guruvayur, Kadappuram, Thrithala, Orumanayur, Thirumittakkodu, Tholur , Nagalassery, Pattiathara, Chalissery, Kadavallur, Kattambakal, Vadakkekadu, Punnayur, Punnaurkulam, Porkulam, Chowannur, Arthat, Pookkodu, Thycaude.

3.1.4 Salient Features of the Reservoir

Max water level	:	+15m
Full reservoir level	:	+15m
Min drawdown level	:	+9.5m
Dead storage level	:	empty (+9.5m)
Free board	:	0.6m
Wave height	:	Nil
Live storage	:	13.3Mm^3
Capacity at Max. level	:	13.3Mm^3
Capacity at full reservoir level	:	13.3Mm^3
Annual Evaporation losses from reservoir		
Depth	:	996mm
Quantum	:	3.795Mm^3
Max. Discharging capacity	:	118.33 m^3/s

The maximum storage at full reservoir level of +15m is 13.3Mm^3 and the water spread area is 381 ha. No land will be submerged by the implementation of the scheme since necessary flood banks on either side of the river have been designed. The water spread area will confine more or less to the course of the river itself.

3.2 River systems and basin characteristics

The Bharatapuzha, the second longest river of the state takes its origin at an altitude of +1964m above MSL from Anamalai hills in Western ghats and flows through the districts of Coimbatore in Tamilnadu and Palakkad, Trichur and Malappuram in Kerala and joins the Arabian sea near the Ponnani town. Its four main tributaries are Gayatripuzha, Kannadipuzha, Kalpathypuzha and Thuthapuzha.

The Bharatapuzha river basin is bounded by Tirur, Chaliyar and Bhavani basins on the North and Kecheri river basin on the South. The catchment area of the Kanjiramukku stream lying between Kecheri River and Bharatapuzha is also included in the Bharatapuzha basin. This basin includes 1, 25, 700 ha of wetland, 46, 050 ha of garden land and 35, 400 ha of waste land. Out of these wasteland about 4300 ha can be converted to wetland and 25, 500 ha into garden land if adequate irrigation facilities are provided. At present, 9 major irrigation projects are existing in the basin in addition to a number of minor and lift irrigation projects. Combinely, these projects can serve only a little portion of the total irrigation requirement. Hence, to fulfill the total water needs in the basin additional schemes have to be thought of.

3. 3 Topography, Physiography and Geology of the area

Kerala State is bounded by Western Ghats in the East and Arabian Sea in the West. The average width of the state is nearly 100Km. The altitude varies from 0 m to 2000 m in the West and East respectively. Due to the steep sloping topography of the State towards the West, the rainfall received runs off into the Arabian Sea within a short period and when the rains are subsided, acute scarcity of water is experienced throughout the State.

The gross catchment area of the project is 6600 Km^2 . This is spread over Coimbatore, Palakkad and Trichur districts. About 4814 Km^2 drainage area of the catchment is in Kerala State and the remaining area of 1786 Km^2 is in Tamilnadu. The total length of the river is 209Km. The project site is about 32 Km upstream of the confluence of the river with the sea at Ponnani.The project area falls in the midland region of the State. The area is not affected by floods in normal conditions. The topography of the area is fairly uneven without many undulations.

Geologically the basin consists of low lying laterite table lands fringed the seaward side by a narrow belt of arenacious soil at the very shores of the sea. The soil of the basin belongs to the hard ferrugenous series composed of a mixture of clay and river sand in varying proportions. The command area is most suited for irrigated agriculture and the soil is most suited for paddy cultivation.

3.4 Major soil types

The soil in the command area can be broadly classified as follows:

1. Moderately deep to very deep, well-drained yellowish red to dark red gravely clay soils.
2. Very deep, imperfectly drained alluvial soils, brownish in colour.
3. Very deep brownish Grey to dark greyish coastal alluvial soils.

The pH of the soil varies from 5.5 to 6.2. The soil is generally deficient in all major nutrients.

3.5 Climate

Important climatological parameters of the command area is given in Table 1.

Table 1. Climatological data

	Mean	Maximum	Minimum
Annual rainfall (mm)	2480.73	4527.8	1792.7
Evaporation (mm/ day)	5	7	3.5
Air Temperature (^{0}C)	25.57	36.47	20.46
Relative humidity (%)	**	95.24	35.33
Wind velocity (Km/ h)	**	5.13	2.74

** data not available

3.6 Irrigation Potential

Table 2. Proposed cropping pattern of the cropping area

	Existing (ha)	Proposed (ha)
1.Wet land		
A. Area		
1. Total area	771.69	1303
2. Net area sown	771.69	1303
B. Seasonal crops		
Autumn		
1. Paddy	771.69	1303
Winter		
1. Paddy	771.69	1303
Summer		
1. Paddy	-----	600
2. sesamum	-----	500
3. Pulses	-----	100
4. Vegetables	-----	103
2. Dry land (Garden land)		
A. Area		
1. Total area	88	88
2. Irrigated area	----	88

The project envisages to irrigate an area of 1303 ha of wetland and 88 ha of dry land (garden land). Existing cropping pattern and the cropping pattern proposed by the Irrigation Department are given in Table 2. Under the existing cropping pattern, two crops of paddy is raised in the wetland. First crop is completely rainfed.

The yield of second crop will be severely affected if supplemental irrigation could not be provided and the third crop is impossible without irrigation facilities.

The proposed cropping pattern as suggested by the project authorities recommend raising of two paddy crops for an area of 1303 ha. And for summer, a crop combination of paddy, sesamum, pulses, and vegetables are suggested. Project also claims to provide irrigation to 88 ha of garden land with crops coconut, arecanut, banana, pepper etc.

The area under paddy cultivation is 1303 ha for first and second crops each and that earmarked for third crop is 600 ha. Sesamum, Pulses, green manure and vegetables can be cultivated in a total area of 703 ha. In the garden land coconut, arecanut, pepper etc. are proposed to be cultivated in an area of 88 ha.

3.7 Irrigation Requirements

Irrigation requirement was obtained by estimating the crop water requirement and then deducting the effective rainfall from that. Crop water requirement for different crops were computed using Modified Penman method. Effective rainfall in the case of paddy was taken as 75% of the 75%chance rainfall. 75% chance rainfall is that rainfall which is certain to occur with a probability of 0.75.

For the other crops, the method developed by USDA (SCS) was used to determine the effective rainfall. The gross irrigation requirement for each month is worked out taking the gross irrigation efficiency as 57%. The calculations are tabulated in Appendix IV. Table 3 shows reference crop evapotranspiration (ET_0) for different months and Table 4 shows the irrigation requirement for different crops during each month.

Table 3. Reference crop Evapotranspiration (ET_0) for different months (mm/ day)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET_0	3.88	4.15	4.5	4.4	3.7	2.3	2.2	2.9	3.1	3.1	3.2	3.0

3.8 Optimal water use of the reservoir

The multi-objectives of the reservoir system in the order of priority are:

1. Drinking water demand
2. Irrigation demand
3. Pisciculture demand
4. Downstream release

Table 4. Monthly irrigation requirement for different crops (m^3/ ha)

Months / Crops	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Coconut mix crop	2321	2253	2472	1576	498.4	---	---	---	---	99.68	203.4	1595
Paddy(Kh) Nursery	---	---	---	---	1262	---	---	---	---	---	---	---
Main field	---	---	---	---	---	612.6	---	1488	1266	---	---	---
Paddy(R) Nursery		---	---	---	---	---	---	307	2952	---	---	---
Main field	202.7	---	---	---	---	---	---	---	612.6	3272	4012	4861
Paddy(S) Nursery	3602	---	---	---	---	---	---	---	---	---	---	1430
Main field	2602	5205	5906	3216	---	---	---	---	---	---	---	---
Pulses	340.4	1423	2196	898.3	---	---	---	---	---	---	---	---
vegetables	340.7	1427	2214	1192	---	---	---	---	---	---	---	---
Sesamum	340.4	1488	2077	340.4	---	---	---	---	---	---	---	---

Monthly water demand for each objective was calculated using the available data from the region. The monthly water requirements for different purposes are given in Table 5.

Table 5. Monthly water demands for different purposes in Mm^3

Months	Drinking water	Irrigation demand as proposed by ID	Pisciculture	Downstream flow
Jun	1.5345	0.798	1	0.5
Jul	1.5345	0	1	0.5
Aug	1.5345	1.979	1	0.5
Sep	1.5345	2.832	1	0.5
Oct	1.5345	4.272	1	0.5
Nov	1.5345	5.246	1	0.5
Dec	1.5345	6.561	1	0.5
Jan	1.5345	2.484	1	0.5
Feb	1.5345	4.355	1	0.5
Mar	1.5345	5.248	1	0.5
Apr	1.5345	2.444	1	0.5
May	1.5345	0.208	1	0.5

3. 8. 1 Formulation of the problem

The problem has been formulated as a monthly operation model and the operating horizon has been taken as twelve months from June to May, which is generally considered as the water year. The water requirements for each purpose are taken as the targets or goals to be achieved by the model. The mathematical model has been formulated with all the known quantities on the right hand side of the constraint equations.

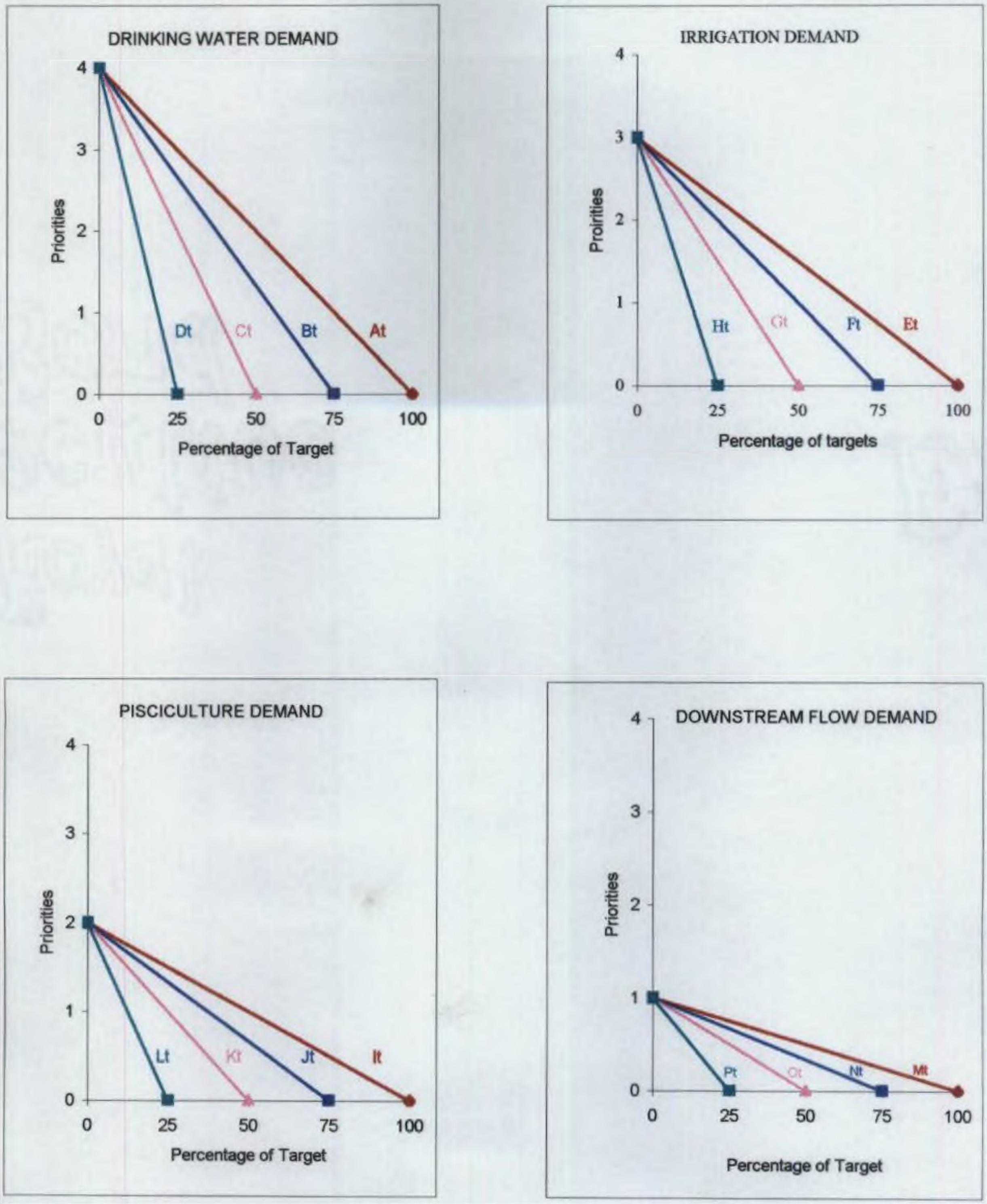

Fig. 2 Slopes for different objectives from their priorities and percentage targets

The goals and priorities of the reservoir operations can be represented systematically in a framework. For that the states of the system are divided into targets or ideal states and non-ideal states. Deviations from the ideal states are then incorporated with penalties, which may or may not be measured in economic units. By assigning different weights to different deviations from the ideal component values of the state vector and by aggregating these penalties over an operating horizon, a consistent, yet flexible frame work may be established for judging the relative merits of different operating policies.

In each of the objectives, the target is again divided into 25%, 50%, 75% and 100% of the target in order to minimize the deviations from the monthly target of each of the objectives and the slopes in each deviation is obtained from their priority levels. Since there are one irrigation release, one drinking water release, one pisciculture release and one downstream release from the reservoir in each month, altogether there are 4 targets and 16 subdivisions of targets. Fig. 2 shows how each target is subdivided to get the different slopes. The slopes of the lines drawn to each level of target from the priority points are taken as the penalty coefficients. The penalty coefficients considered for this study are given in Table 6.

Table 6. Penalty coefficients for linear programming

Variables	Slope/ Penalty coefficients	Variables	Slope/ Penalty coefficients
A1- A12	0.040	I1- I12	0.020
B1- B12	0.053	J1- J12	0.027
C1- C12	0.080	K1- K12	0.040
D1- D12	0.160	L1- L12	0.080
E1- E12	0.030	M1- M12	0.010
F1- F12	0.040	N1- N12	0.013
G1- G12	0.060	O1- O12	0.020
H1- H12	0.120	P1- P12	0.040

The objective of the model is to minimize the deviations from the targets for each objective. The objective function may be stated as:

$$\text{Minimize } Z = \sum_{t=1}^{T} At * P_{At} + Bt * P_{Bt} + Ct * P_{Ct} + Dt * P_{Dt} + Et * P_{Et} + Ft * P_{Ft}$$

$$+ Gt * P_{Gt} + Ht * P_{Ht} + It * P_{It} + Jt * P_{Jt} + Kt * P_{Kt} + Lt * P_{Lt}$$

$$+ Mt * P_{Mt} + Nt * P_{Nt} + Ot * P_{Ot} + Pt * P_{Pt}$$

Where

t = 1, 2, 3, -------, T and T= 12

At, Bt, Ct, ..., Qt = Deviations from the targets for t^{th} month

$P_{At}, P_{Bt}, \ldots, P_{Pt}$ = Penalty coefficients corresponding to At, Bt,...,Pt

The objective function Z aggregates all penalties associated with undesirable conditions, i.e., with deviations in allocations from the targets.

3. 8. 1. 1 Constraints

The constraints considered for the linear programming model were described below.

Continuity Equation constraints

$$S_{1,t+1} - S_{1,t} + R_{1,t} + M_{1,t} + D_{1,t} + E_{1,t} + Q_{1,t} = I_{1,t}$$

Where $S_{1,t}$ - Storage in the reservoir at the beginning of the t^{th} month

$S_{1,t+1}$ - Storage in the reservoir at the end of the t^{th} month

$R_{1,t}$ - Irrigation release in t^{th} month

$M_{1,t}$ - Drinking water release in t^{th} month

$D_{1,t}$ - Downstream release in t^{th} month

$E_{1,t}$ - Evaporation loss in t^{th} month

$I_{1,t}$ - Inflow to the reservoir in t^{th} month

$Q_{1,t}$ - Surplus flow in t^{th} month

Storage constraint

$$S_{1,t} \leq 13.3$$

$$S_{1,t} \geq 1$$

Release constraints

$$R_{1,t} \leq IR_{1,t}$$

Where, $IR_{1,t}$ = Monthly irrigation requirement in t^{th} month

$$M_{1,t} \leq 1.6$$

$$D_{1,t} \leq 0.5$$

Target constraints

$$M_{1,t} + A_t + B_t + C_t + D_t = 1.5345$$

$$R_{1,t} + E_t + F_t + G_t + H_t = IR_{1,t}$$

$$F_{1,t} + I_t + J_t + K_t + L_t = 1$$

$$D_{1,t} + M_t + N_t + O_t + P_t - Q_t = 0.5$$

$$A_t, B_t, C_t, D_t = 0 \text{ to } 0.4$$

$$E_t, F_t, G_t, H_t = 0 \text{ to } IR_{1,t} / 4$$

$$I_t, J_t, K_t, L_t = 0 \text{ to } 0.25$$

$$M_t, N_t, O_t, P_t = 0 \text{ to } 0.125$$

Where, F_t is the Pisciculture demand

$$Q_t \quad = \quad 0 \text{ to } \infty$$

There are 192 variables in the linear programming model when the operating horizon is taken as one year.

3.8.2 Solution of the Problem

The objective function is to minimize the sum of penalties associated with the reservoir releases. The linear programming model was solved with the above constraints using Excel solver software package.

75% chance inflow was considered for this study and the solution gives the optimal releases for each month for different purposes for the entire operating horizon.

3.9 Selection of optimal cropping pattern

Cropping pattern of an area means the cropping choices in favour of one or more preference of one crop over other competing crops. The procedure for cropping pattern selection involves selection of crop activities from a large number of feasible alternatives so as to satisfy the objectives of the planner under the conditions of limited availability of land and water resources, social requirements and other physical and technological constraints in the planning environment.

The dependability of the available water is an important criterion for planning water resources development. The water available for irrigation in the present study is obtained from the optimal irrigation releases. Table 4 gives the monthly irrigation requirement for different crops in m^3/ ha.

Here, the use of linear programming technique for obtaining an optimal cropping pattern from the various alternatives for the command area is dealt with. There are two objectives. They are:

i. to maximize the net profit from the command area for a year, and

ii. to maximize the net area put under cultivation in a year.

3.9.1 Assumptions made in the study

For the formulation of the problem the following assumptions have been made.

1. Only principal crops like three crops of rice, garden crops like coconut, arecanut and coconut mixed crops like pepper, vegetables, pulses and sesamum have been considered.
2. All inputs other than water , viz. good quality seeds, fertilizers, weedicides, pesticides etc. are available in adequate quantities.
3. Khariff and Rabi rice cultivation is essential.

3. 9. 2 Formulation of the problem

3. 9. 2. 1 Part I

This part of the problem deals with the maximization of the net returns from the command area.

Mathematically this can be expressed as,

$$\text{Max } Z = \sum_{j=1}^{n} P_j X_j$$

where, Z is the net benefit from the command area to be maximized, n the number of crops considered, X_j is the area under j^{th} crop and P_j is the net benefit from j^{th} crop.

$$\sum_{j=1}^{n} X_j Q_{jt} \leq Qt$$

where Q_{jt} is the quantity of water required for irrigating j^{th} crop per unit area in t^{th} month, n the number of crops in the area in a particular month and Qt is the total available water in t^{th} month.

In addition few other constraints are also considered such as:

1. Lower and upper bounds given for any particular crop as desired by the decision makers.
2. Lower and upper bounds given for the total area under cultivation in each month.

3. 9. 2. 1. 1 Analysis by linear programming:

The existing cropping pattern, alternatives and net return from each crop were collected from different agencies of the region. Different trials were done with different crop combinations and area constraints to make the best use of all the available water resources and to get maximum benefit. Six cases of constraint sets considered were shown in T

Let the areas allotted for different crops in ha are:

Coconut	-	X1
Paddy (Kharif)Nursery	-	X2
Paddy (Kharif) main field	-	X3
Paddy (Rabi) Nursery	-	X4
Paddy (Rabi) main field	-	X5
Paddy (summer) Nursery	-	X6
Paddy (summer) main field	-	X7
Pulses	-	X8

Vegetables - X9

Sesamum - X10

The area constraints for different crops for the 6 cases are shown in Table 7.

Table 7. Area constraints for different cases

Case1	Case 2	Case3	Case 4	Case 5	Case 6
$X1 \geq 88$	$X1 \geq 200$	$X1 \geq 150$	$X1 \geq 150$	$X1 \geq 100$	$X1 \geq 88$
$X2 = 0.1X3$	$X2 = 0.1X3$	$X2 = 0.1X3$	$X2 = 0.1X3$	$X2 = 0.1X3$	$X2 = 0.1X3$
$X3 \geq 1400$	$X3 \geq 0$	$X3 \geq 0$	$X3 \geq 1300$	$X3 \geq 1500$	$X3 \geq 1700$
$X4 = 0.1X5$	$X4 = 0.1X5$	$X4 = 0.1X5$	$X4 = 0.1X5$	$X4 = 0.1X5$	$X4 = 0.1X5$
$X5 \geq 1400$	$X5 \geq 0$	$X5 \geq 0$	$X5 \geq 0$	$X5 \geq 0$	$X5 \geq 0$
$X6 = 0.1X7$	$X6 = 0.1X7$	$X6 = 0.1X7$	$X6 = 0.1X7$	$X6 = 0.1X7$	$X6 = 0.1X7$
$X7 \geq 400$	$X7 \geq 200$	$X7 \geq 250$	$X7 \geq 100$	$X7 \geq 200$	$X7 \geq 300$
$X8 \geq 100$	$X8 \geq 300$	$X8 \geq 250$	$X8 \geq 300$	$X8 \geq 300$	$X8 \geq 150$
$X9 \geq 100$	$X9 \geq 300$	$X9 \geq 250$	$X9 \geq 300$	$X9 \geq 300$	$X9 \geq 150$
$X10 \geq 500$	$X9 \leq 500$	$X9 \leq 500$	$X9 \leq 500$	$X10 \geq 600$	$X10 \geq 700$
	$X10 \geq 600$	$X10 \geq 600$	$X10 \geq 600$		
			$X10 \leq 700$		

3.9.2.2 Part II

In this part, the area which can be brought under irrigation in a year is maximized. Here the profit variation between individual crops were not considered. The objective function can be written as:

$$\text{Max } A = \sum_{j=1}^{n} X_j$$

where, A is the area which can be put under cultivation in an year.

Table 8. Average net return from each crop (Rs/ ha)

Crop	Net return (Rs/ha)
Coconut	40000
Paddy(Khariff)	8000
Paddy (Rabi)	10000
Paddy (summer)	13000
Pulses	16560
Vegetables	20000
Sesamum	8900

All the constraints remained as that of Part I. Here also 6 cases of constraint sets same as that of Part I were tried to get the optimal solution. The average net return from each crop considered for the study is shown in Table 8.

RESULTS AND DISCUSSION

RESULTS AND DISCUSSION

The salient findings of the study conducted on the regulator- cum- bridge under construction at Thrithala giving focus to optimal water use and cropping pattern are described in this chapter.

4.1 River discharge at the site

River flow records obtained from the gauging station established near the regulator site for a period of 30 years, starting from 1968 to 1997 is given in Appendix I. The mean of monthly river discharge reveals that maximum flow occurs during the month of July followed by August and June (Table 9). Minimum flow occurs during March followed by April and February. Mean monthly maximum flow is 767 Mm^3 and mean monthly minimum flow is 5.01Mm^3. Variation of monthly flows as indicated by the coefficient of variation, which is maximum for the month of March followed by May. The lowest value of coefficient of variation is for the month of July followed by August. High value of standard deviation indicates lack of reliability of flow, especially during the summer months.

About 96.8% of the annual river flow passes during the seven months of June to December. A long term hydrograph of the river flow for the site corresponding to the mean monthly flow is given in the Fig. 3. Mean annual flow is obtained as 2489.1Mm^3.

4. 1. 1 75% Chance Inflow

75% chance inflow for the 30 years of flow data has been worked out and presented in Table 9. Maximum discharge is recorded in the month of July followed by August. Minimum inflow is recorded during March followed by April. Total inflow during the 5 summer months of January to May is only 1.41 % of the total annual inflow. 75% chance inflow is low during February to May, whereas, the corresponding mean inflow rates are many times higher than the 75% chance inflows.

Table 9. Analysis of River flow data

Month	Mean river flow (Mm^3)	Standard deviation	Coefficient of variation (SD/ Mean)	75% chance River flow (Mm^3)
Jun	309.30	264.20	0.85	168
Jul	766.90	399.10	0.52	523
Aug	605.60	373.30	0.61	321
Sep	242.70	188.30	0.77	114
Oct	222.70	157.50	0.70	102
Nov	220.40	222.20	1.00	85.90
Dec	41.54	41.95	1.01	19.74
Jan	32.84	36.58	1.11	12
Feb	10.48	14.08	1.34	1.64
Mar	5.01	9.915	1.98	1.26
Apr	7.73	11.92	1.54	2.11
May	24.3	40.39	1.66	2.95

4. 2 Optimal monthly water allocation from the reservoir

The regulator-cum-bridge project at Thrithala, has been envisaged, by the Irrigation department to provide water for two purposes, viz. drinking and irrigation. The first hand information gained on the project suggested that there is further scope to increase the number of purposes and to enhance the water utilization efficiency and thereby to increase the economic viability of the project. Hence, two additional purposes such as downstream flow and fisheries has been incorporated making the water resources project a four purpose one. Incorporation

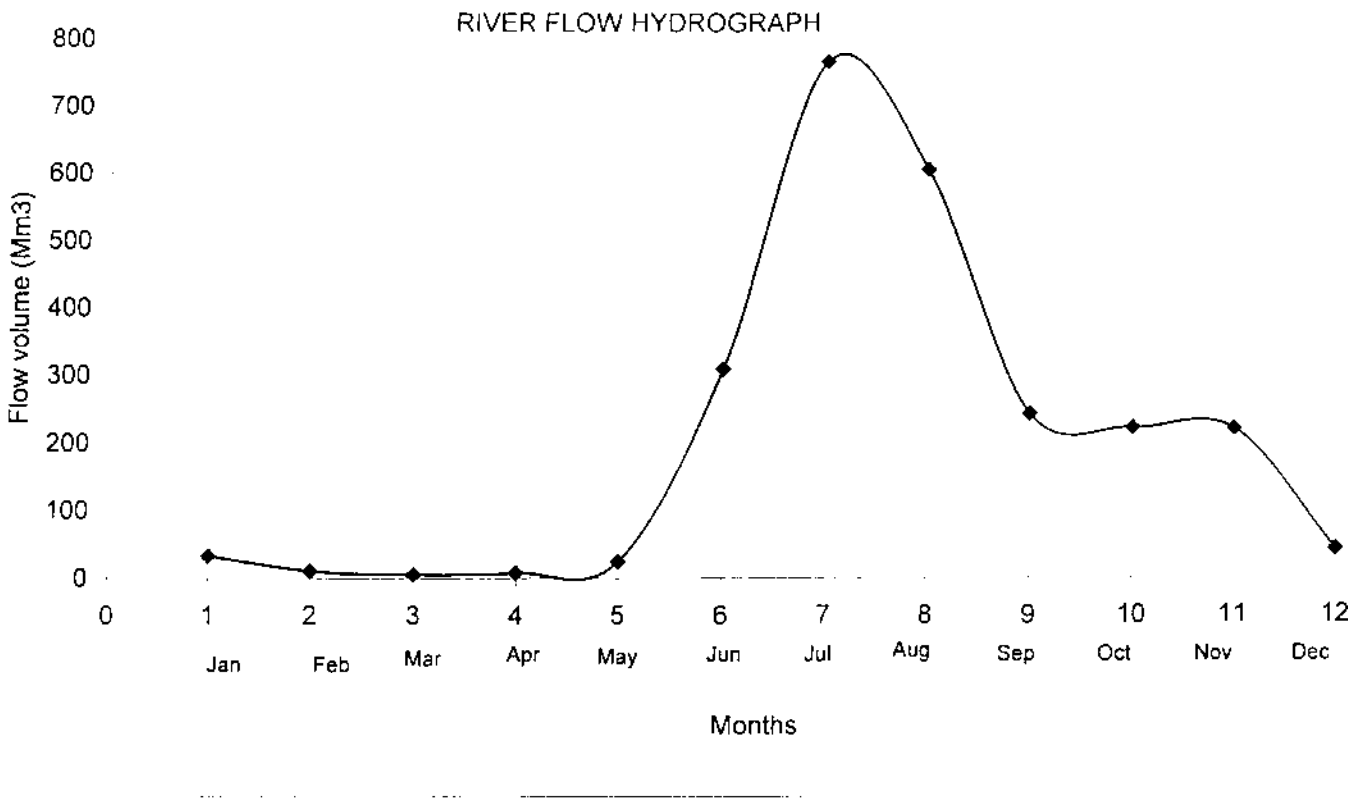

Fig 3. Annual River flow hydrograph

of downstream flow demand will make the project more socially acceptable. Because, dry weather flow at the river section of the project is very meagre and once the project is commissioned, practically there will be no water to the downstream of the regulator during summer.

Here, an attempt has been made to obtain the optimum water allocations for the four different purposes considered by formulating and solving a linear programming model. The 75% chance inflow has been taken as the input to the model, so that the output water allocations can also be expected with the same chance.

4 .2.1 Optimal releases with all the four demands

Optimal reservoir water allocations were determined using linear programming model in the first case, to meet all the four demands such as drinking water, irrigation, fisheries and downstream flow. Then some of the less important releases were eliminated and its effect on irrigation water availability, especially during summer was analysed. In the second case, downstream flow demand was eliminated and in the third case fisheries demand was eliminated. Results obtained corresponding to these cases are described below.

4.2.1.1 Optimal allocation when Irrigation Requirement calculated for the command area proposed by Irrigation Department was considered

The model was run by feeding the irrigation demand computed for the command area proposed by the ID. Optimal allocations as given by the model for the four purposes are given in Table 11. Inflow and reservoir storage can very well meet the drinking water demand of 1.6 Mm^3/ month throughout the year. This much quantity of water is expected to cater to a population of about 10 lakhs residing in 18 nearby panchayaths and 3 municipal towns.

Table 10. Monthly Irrigation Demand (Mm^3) calculated for the command area proposed by Irrigation Department

Month	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
IR(Mm^3)	0.798	0	1.979	2.832	4.272	5.246	6.561	2.484	4.355	5.248	2.444	0.208

Table 11. Optimal monthly allocation from the reservoir (Mm^3) when Irrigation Requirement calculated for the command area proposed by Irrigation Department was considered

Month	Optimal monthly water allocation				Storage	Surplus down stream flow
	Drinking water	Irrigation	Fisheries	Down flow		
Jun	1.6	0.798	1	0.5	13.3	151.702
Jul	1.6	0	1	0.5	13.3	520.95
Aug	1.6	1.979	1	0.5	13.3	316.721
Sep	1.6	2.832	1	0.5	13.3	108.668
Oct	1.6	4.272	1	0.5	13.3	95.393
Nov	1.6	5.246	1	0.5	13.3	78.559
Dec	1.6	6.561	1	0.5	13.3	10.474
Jan	1.6	2.484	1	0.5	13.3	6.795
Feb	1.6	3.455*	1	0.375*	8.947	0
Mar	1.6	4.679*	1	0.375*	2.994	0
Apr	1.6	1.944*	0.75*	0.375*	0.75	0
May	1.6	0.208	1	0.5	1	0.05

- indicates a deficit (shortage from the demand)

Releases for irrigation shows shortfall during the months from February to April. Targetted demands for irrigation during each month was estimated using modified Penman method for the command area proposed by the Irrigation department. Comparison between the demand and availability of irrigation water shows that the deficiency of irrigation water during the months of February, March and April were 20.67%, 10.84% and 20.46% respectively.

Fisheries storage indicates that the desirable level of 1 Mm^3 of storage was maintained almost all the months except during April. Even in that month, the deficit is only 25%. Water spread area of the reservoir corresponding to a 1 Mm^3 storage is 130 ha as indicated by the area- volume curve given in Appendix V. Assuming a conservative value of productivity of 2.5 t/ ha, a total annual fish production of 325 tonnes can be expected. It can boost the economic viability of the regulator to a great extent. Also, this increase may contribute to employment generation.

A nominal downstream release is highly desirable as the river becomes almost dry during summer. Impounding of water by the regulator make the downstream flow further worse. A downstream flow of 0.5 Mm^3 has been targeted, so that it will provide an assured flow of 16,667 m^3/ day. Though nominal, an assured downstream flow will be of great relief to the people living in the lower reaches of the regulator site on both banks, who depend heavily on river water for meeting many of their water needs. And certainly, the plan to release water to the downstream will have a positive impact on the social acceptability of the project.

River flow analysis reveals that downstream release is essential during the four months from February to May. The optimal allocation shows targetted release in May and deficit to the level of 25% during the other 3 months.

4.2.1.2 Optimal allocations corresponding to maximum possible increase in irrigation demand

When the water requirement for the command area proposed by the Irrigation Department was taken, the result shows that the storage space is full and there is significant surplus down flow during the months from June to January. This indicates

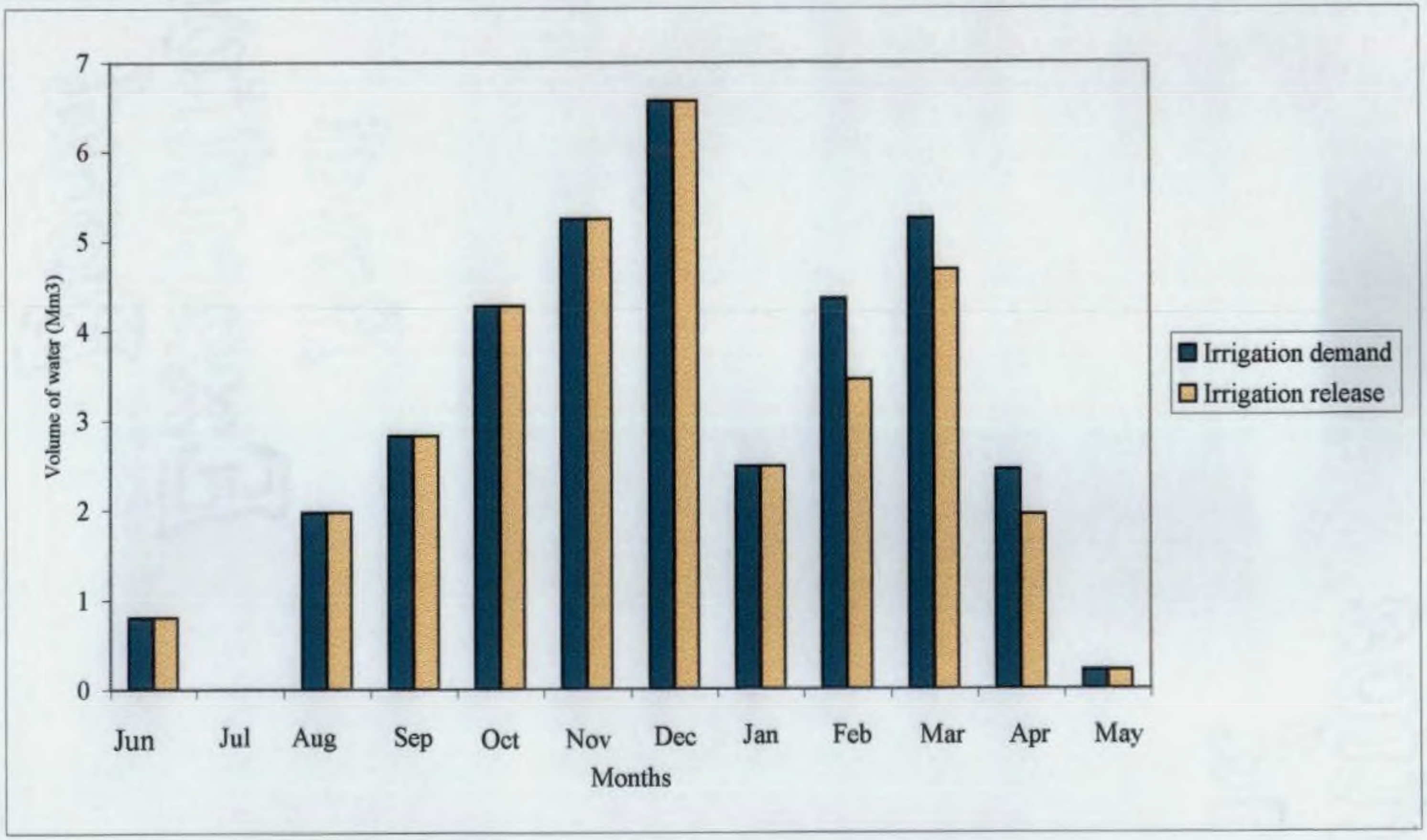

Fig. 4 Comparison of Irrigation demand(by Irrigation Department) and Irrigation release

that there is ample scope for increasing the water drawal for irrigation from the reservoir and thereby increasing the area that can be irrigated.

Table 12. Irrigation Demand(Mm^3) when maximum possible increase was given to the Irrigation Requirement

Month	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
IR(Mm^3)	2.79	0	6.93	9.91	14.95	18.36	22.96	8.69	4.79	5.77	2.69	0.26

Table 13. Optimal monthly allocations (Mm^3) corresponding to the maximum possible increase in Irrigation Demand

Month	Optimal monthly water allocation				Total Storage	Surplus down stream flow
	Drinking water	Irrigation	Fisheries	Down flow		
Jun	1.6	2.79	1	0.5	13.3	149.71
Jul	1.6	0	1	0.5	13.3	520.95
Aug	1.6	6.93	1	0.5	13.3	311.77
Sep	1.6	9.91	1	0.5	13.3	101.59
Oct	1.6	14.95	1	0.5	13.3	84.71
Nov	1.6	18.36	1	0.5	13.3	65.44
Dec	1.6	17.41*	0.75*	0.375*	13.3	0
Jan	1.6	8.69	1	0.5	13.3	0.34
Feb	1.6	3.59*	1	0.375*	8.809	0
Mar	1.6	4.33*	1	0.375*	3.206	0
Apr	1.6	2.15*	0.752*	0.375*	0.752*	0
May	1.6	0.26	1	0.5	1	0

- indicates a deficit

So, to study the possibility of higher irrigation demand gradual increase to irrigation demand was given and different trials were carried out with the model. It

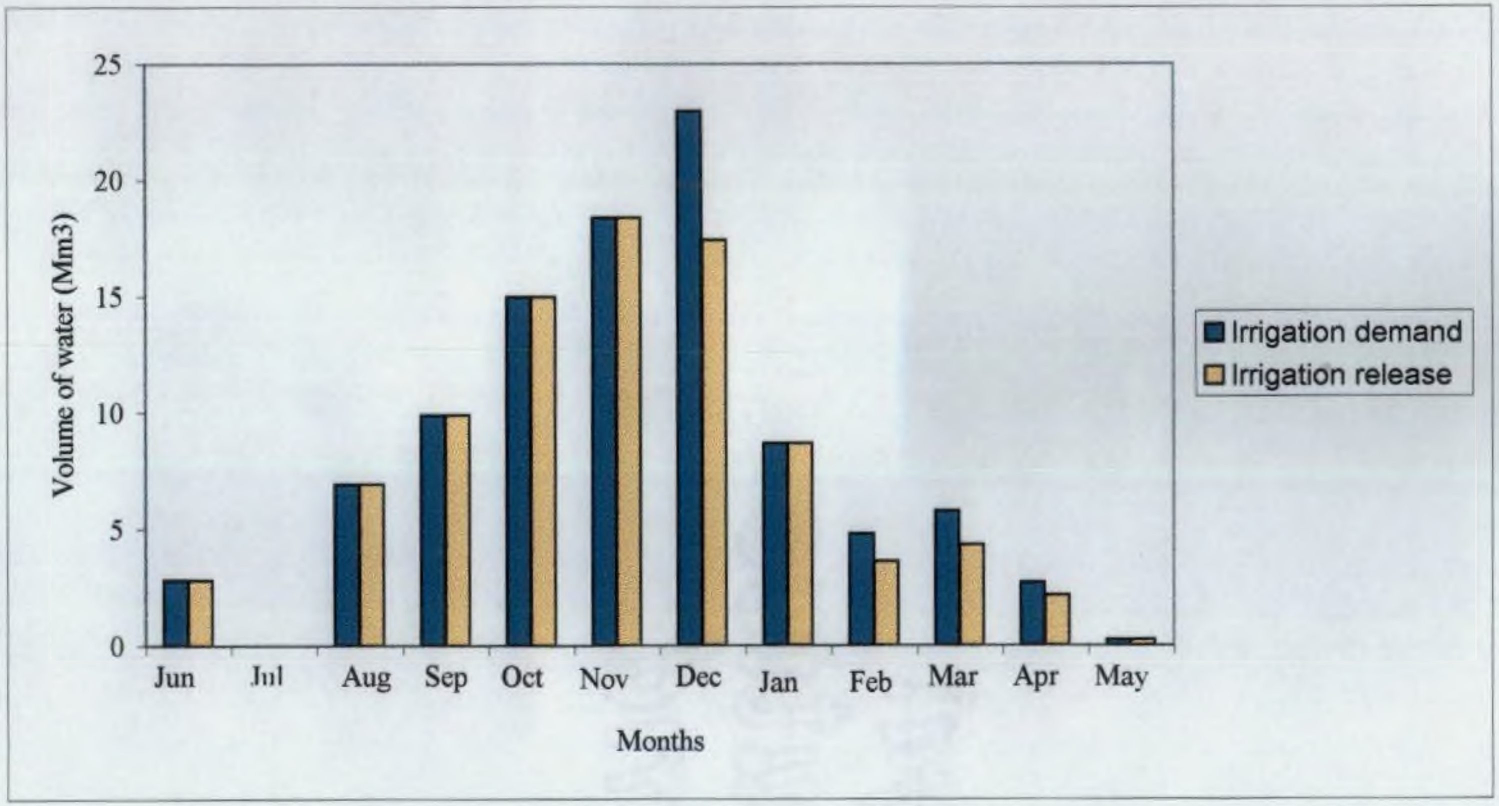

Fig. 5 Comparison of Irrgn demand and Irrgn release when Maximum Possible increaase in Irrigation demand was given

was observed that 350 % increase during 8 months from June to January, 10 % increase during 3 months of February to April and 25 % increase during month of May can easily be obtained from the available inflow and storage without affecting the other demands much. Optimal water allocation corresponding to this case is shown in Table 13. Maximum irrigation demand that can be adopted and fed to the model is given in Table 12. This irrigation demand was considered for further studies. Fig. 5 shows the comparison between the irrigation demand and irrigation release in this case.

4.2.2 Optimal allocations without downstream flow demand

The analysis was persued by eliminating the downstream flow demand from the set of demands. It was done so to study the effect of downstream flow

Table 14. Optimal monthly releases from the reservoir (Mm^3) when the downstream flow demand was eliminated

Month	Optimal monthly water allocation			Total Storage	Surplus down stream flow
	Drinking water	Irrigation	Fisheries		
Jun	1.6	2.79	1	13.3	150.21
Jul	1.6	0	1	13.3	521.45
Aug	1.6	6.93	1	13.3	312.27
Sep	1.6	9.91	1	13.3	102.09
Oct	1.6	14.95	1	13.3	85.21
Nov	1.6	18.36	1	13.3	65.94
Dec	1.6	17.79*	0.75*	13.3	0
Jan	1.6	8.69	1	13.3	0.835
Feb	1.6	3.59*	1	9.184	0
Mar	1.6	4.92*	1	3.3634	0
Apr	1.6	2.69	0.75*	0.75	0
May	1.6	0.26	1	1.498	0

* indicates a deficit

demand on irrigation releases during the summer months. When the down flow requirement was not considered, there was a considerable increase in the irrigation water allocation during the months of March and April. As the increase in water availability is limited to only two months, utilizing this water for irrigation may not be practically feasible. Hence, it is highly desirable to incorporate a targeted downstream flow demand to the set of demands of the reservoir, which will enhance its economic viability and social acceptability. The optimal releases corresponding to this case are given in Table 14. It do not make any impact on the fisheries storage.

Table 15. Optimal monthly releases from the reservoir (Mm^3) when fisheries demand was eliminated

Month	Optimal monthly water allocation			Total Storage	Surplus down stream flow
	Drinking water	Irrigation	Down flow		
Jun	1.6	2.79	0.5	13.3	149.71
Jul	1.6	0	0.5	13.3	520.95
Aug	1.6	6.93	0.5	13.3	311.77
Sep	1.6	9.91	0.5	13.3	101.59
Oct	1.6	14.95	0.5	13.3	84.71
Nov	1.6	18.36	0.5	13.3	65.44
Dec	1.6	17.22*	0.375	13.3	0
Jan	1.6	8.69	0.5	13.3	0.585
Feb	1.6	3.59*	0.375*	8.809	0
Mar	1.6	5.22*	0.375*	2.316	0
Apr	1.6	2.02*	0.375*	0	0
May	1.6	0.26	0.5	0248	0

* indicates a deficit

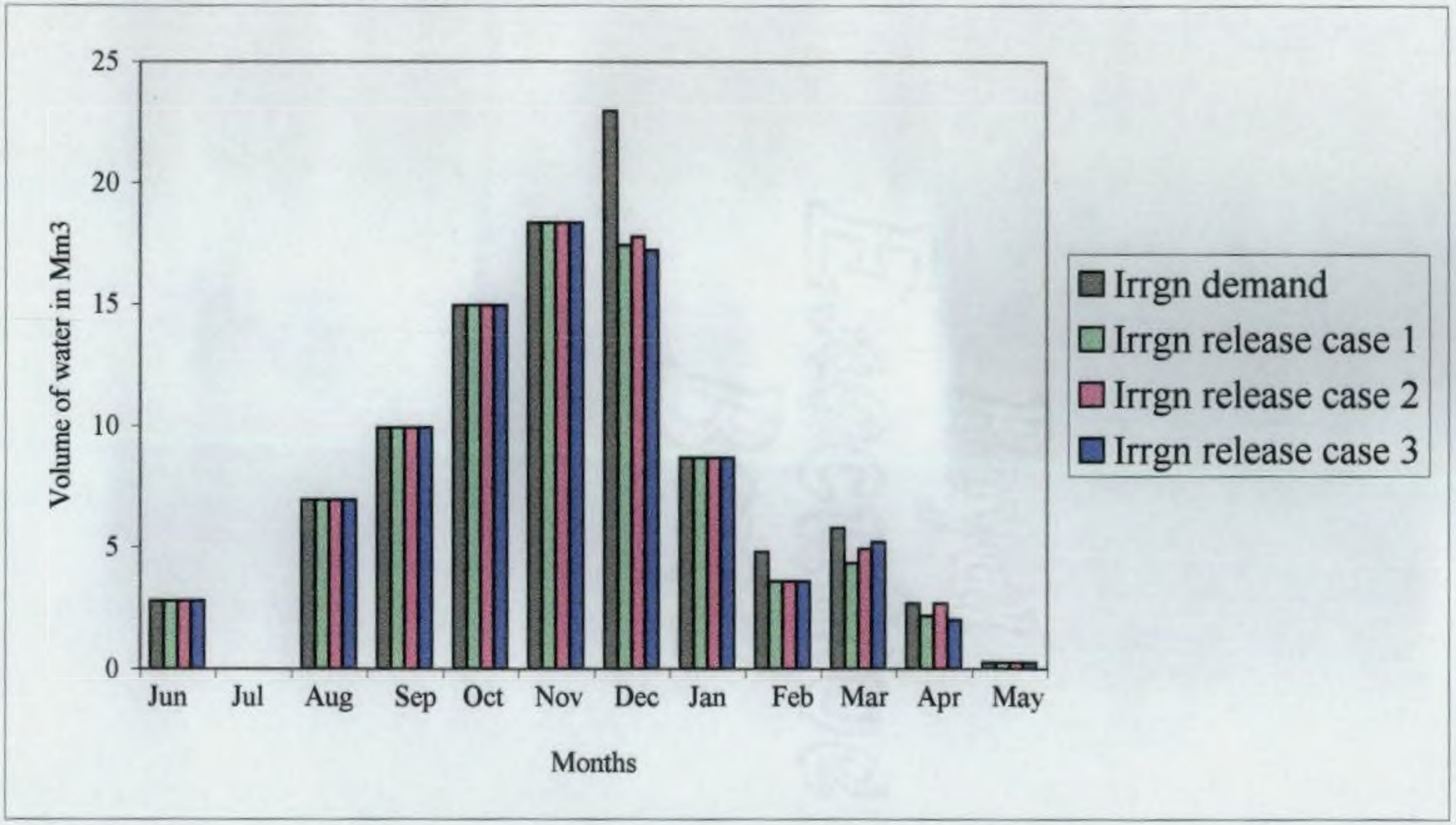

Fig. 6 Comparison of Irrgn demand and irrgn releases in 3 different cases, i.e when all the four demands are there,when no downstream flow demand and when no fisheries demand respectively

4. 2. 3 Optimal releases without fisheries demand

Water allocation without fisheries demand and maintaining status quo for all other demands is given in Table 15. When no fisheries activity was assumed, it does not contribute much to the summer water allocations for irrigation, barring the exception for the month of March. Elimination of fisheries storage has shown no impact on downstream flow. Hence, it reveals that a fisheries storage of 1 Mm^3 does not compete significantly with other water needs. So, an assured fisheries storage of 1 Mm^3 can safely be incorporated to the set of demands of the reservoir.

4. 3 Modelling for selection of optimal cropping pattern

Monthly optimal water releases for irrigation given by the reservoir allocation model as shown in Table 13 were used for obtaining the optimum cropping pattern for the command area of the project. Two different approaches were used to arrive at the optimal cropping pattern. The objectives set by the two approaches were

1. To obtain maximum annual net returns from the command area.
2. To obtain the maximum area of cultivation per year.

For each of the objectives, 6 trials were conducted with different constraint sets as described in section 3. 6. The solution to the linear programming model was obtained using Excel Solver software package.

4.3.1 Optimal cropping pattern for net benefit maximization

All the 6 cases stated in section 3.6 were tried with the model to get the optimal allocation of area for each crop with the objective of achieving maximum net benefit from the command area for a year. Optimal area allocation for the crops considered in all the six trials is given in Table 16. Cropping pattern described under case no. 4 was found to give better net profit compared with the other cases.

Table 16. Cropping pattern under net benefit maximization (ha)

Case no. / Crops	1	2	3	4	5	6
Coconut	88	200	150	150	100	88
Paddy(kharif)	1712.95	1270.56	1468.05	1468.05	1665.55	1712.95
Paddy(rabi)	3541.23	3510.36	3525.30	3529.71	3543.17	3544.18
Paddy(summer)	400	200	250	100	200	300
Pulses	100	300	250	462.37	300	150
Vegetables	222.13	338.44	310.47	500	450.10	251.69
Sesamum	500	600	600	600	600	700
Net benefit in Million Rs.	68.38	72.95	71.94	77.34	74.67	70.31

Higher water availability during all the four months of Rabi season results in higher area allocated for irrigation. The increase in area is more than double of that proposed by ID. In the case of Kharif season, the increase in area is not as significant as that during Rabi. The reason being that, Kharif season starts from the month of May during which the water availability is very scarce. The area allocated for summer paddy is only 100 ha, as it is higher water demanding and lesser remunerative. Allocation of areas for pulses, vegetables and sesamum has been increased considerably compared to that proposed by ID. Area that can be irrigated for the upland crops, which are perennial has also shown remarkable increase from 88 ha to 150 ha.

4.3.2 Optimal cropping pattern for Area Maximization

The above stated 6 cases were also solved with the objective to maximize the net sown area per year with the available water and the results are shown in Table 17. Case no.4 gave the best result. It can be seen that case no.4 gave maximum value for both benefit maximization and area maximization. The maximum profit obtained in benefit maximization was Rs. 77.34 million and maximum area allocated in area maximization was 6817.19 ha.

Table 17. Cropping pattern under area maximization (ha)

Crops \ Case no.	1	2	3	4	5	6
Coconut	88	200	150	150	100	88
Paddy(kharif)	1712.95	1270.56	1468.06	1468.05	1665.55	1712.95
Paddy(rabi)	3541.23	3510.36	3525.30	3529.71	3543.17	3544.18
Paddy(summer)	400	200	250	100	200	300
Pulses	100	300	250	569.43	300	150
Vegetables	100	300	250	300	300	150
Sesamum	630	640.98	664.47	700	759.99	808.38
Net area sown(ha)	6572.18	6421.90	6557.82	6817.19	6598.71	6753.51

Area allocation for both Kharif and Rabi does not show any difference between the net benefit and area maximization approach, for the optimum solution because, only paddy has been proposed for these two seasons. Raising of paddy for two seasons is essential to meet the food requirement. Also, introducing other crops in these seasons is not practically possible due to water logging during heavy rainfall periods. Maximizing the area approach has increased the allocation for pulses and sesamum and decreased the allocation for vegetables.

4.4 Cropping pattern with changes in multiple demand set of the reservoir release

4.4.1 Cropping Pattern when no downstream flow was provided

When the irrigation allocation without considering the downstream flow demand was considered, the total optimal cropping area under area maximization was 7163.02 ha, which results in a 5.07% increase in the cropping area. The net benefit obtained under benefit maximization was Rs. 82559040 (6.75% increase) as given in Table 18. Benefit maximization approach gives higher allocation for pulses and rabi season paddy without any influence on other crops. In the area maximization objective also, the increase in allocation is seen only for Rabi (paddy) and pulses.

Table 18. Optimal cropping pattern with the irrgn release when the down stream flow demand was eliminated

Crops	Area allocated (ha)	
	Net benefit maximisation	Area maximisation
Coconut mixed crop	150	150
Paddy (kharif)	1468.05	1468.05
Paddy (rabi)	3606.87	3606.87
Paddy (summer)	100	100
Pulses	731.04	838.10
Vegetables	500	300
Sesamum	600	700
	Net benefit is **Rs. 82559040**	Net area sown is **7163.02 ha**

Table 19. Optimal cropping pattern with the irrgn release when the fisheries demand was eliminated

Crops	Area allocated (ha)	
	Net benefit maximisation	Area maximisation
Coconut mixed crop	150	150
Paddy (kharif)	1468.053	1468.05
Paddy (rabi)	3491.16	3491.16
Paddy (summer)	100	100
Pulses	980.50	993.66
Vegetables	313.12	300
Sesamum	600	600
	Net benefit is **Rs. 81795504**	Net area sown is **7102.87 ha**

4.4. 2 Cropping Pattern when no fisheries storage was provided

When the available irrigation water without considering the fisheries demand was considered, the optimal cropping area under area maximization was 7102.87 ha (4.19 % increase in the cropping area). The net benefit under benefit maximization was Rs. 81795504 (5.76% increase) as is given in Table 19.

4.5. Sensitivity analysis

Sensitivity analysis was carried out to study the effect of changes in the returns from each crop on the optimal solution. Four trials were conducted with various returns from the summer crops. The returns considered for the four trials are shown in Table 20. The results given in Table 21 shows that, the optimal allocation of the area for each crop is changing according to the respective changes in net return from each crop. When the return from a crop is reduced to certain level, the model gave zero values of area allocation for that crop.

Table 20. Returns considered for different crops

Summer crops	Returns from crops in Rs/ha			
	Trial 1	Trial 2	Trial 3	Trial 4
Rice	13000	14000	10000	12000
Pulses	16000	22000	15000	20000
Vegetables	20000	18000	8000	22000
Sesamum	9000	10000	3000	5000

Table 21. Area allocated for different crops when return from the crops vary

Crops	Trial 1	Trial 2	Trial 3	Trial 4
Coconut mixed crop	150	150	150	150
Paddy(kharif)	1468.05	1468.05	1468.05	1468.05
Paddy(rabi)	3529.71	3529.71	3529.71	3529.71
Paddy(summer)	100	100	100	100
Pulses	462.37	664.01	664.01	462.36
Vegetables	500	300	300	500
Sesamum	600	600	600	600
Net benefit in Million Rs.	77.14	80.45	68.20	77.49

4.6 Optimal Cropping Pattern Vs the Cropping Pattern proposed by Irrigation Department

A comparison between the cropping pattern suggested by the ID and that obtained using the optimization model is presented in Table 22. In the case of net benefit maximization model, the total area that can be irrigated has increased from 3397 ha to 6810 ha, i.e., an increase of about 100%. Area that can be brought under irrigation during the summer season increase from 1303 ha to 1662 ha (an increase of 27%). The major difference between the optimal proposal and that by the ID lies in the allocation for paddy during Rabi season. An increase of 170% area has been registered in this case. Irrigated area in Kharif season has increased from 1303 ha to 1468 ha. Lower increase in area during kharif season is due to the water scarcity faced during May. If the starting of the crop season is delayed from may to June, area that can be irrigated during season can be increased considerably.

Table 22. Comparison of the Optimal cropping pattern with the proposal of Irrigation Department

	Proposal of ID	Net Benefit Maximization	Area Maximization
Area allocation (ha)			
Coconut mixed crop	88	150	150
Paddy (kharif)	1303	1468.05	1468.05
Paddy (Rabi)	1303	3529.71	3529.71
Paddy (summer)	600	100	100
Pulses	100	462.37	569.43
Vegetables	103	500	300
Sesamum	500	600	700
Net area cultivated(ha)	3397	6810.13	6817.19
Net Benefit (Lakhs)	429.29	773.38	760.01

Another major difference observed between the proposals was in the allocation of area for paddy during summer. Optimal allocation permits only 100 ha of paddy as it is of high water demanding and low net benefit yielding. In the cases of pulses and vegetables, the increase is to the tune of 4.5 to 5 times. For the upland crops, the irrigated area increased from 88 ha to 150 ha (70% increase). This increase in area assume more significance for the upland crops as they are perennial. In the case of area maximization; the trend of increase shown was comparable with benefit maximization. *Total area that can be irrigated is 6817 ha and the net benefit is* 760 lakhs.

Table 23. Merits of Optimal operational policies

	Proposal of the Irrigation Department	Optimal operational policies
a. objectives met		
1. Drinking water	1.6Mm^3/ month	1.6Mm^3/ month
2. Irrigation	3397 ha/ year	6817.19 ha/ year
3. Fisheries	Nil	0.75 Mm^3
4. Downstream flow	Nil	0.4 Mm^3
b. economic aspects		
1. Drinking water	No economical values assigned	No economical values assigned
2. Irrigation (Rs.)	429.29 lakhs	773.38 lakhs
3. *Fisheries (Rs.)*	0	60 lakhs
4. Downstream flow (Rs.)	0	32 lakhs
5. Total annual benefit (Rs.)	429.3 lakhs	865.38 lakhs
6. Net Present Value (NPV) Factor	4.98	4.98
7. Net Present Value of benefit (Rs.)	2 136 lakhs	4 308 lakhs
8. *Cost of the project (Rs.)*	1 900 lakhs	1 900 lakhs
9. B/C Ratio	1.124	2.267

4.7 Merits of optimum operational policies

A comprehensive comparison between the proposal by the ID and the optimal operational policies of the regulator-cum-bridge derived from the model is presented in Table 23. The major attraction of the optimal plan is the addition of two more objectives, namely fisheries and downstream flow. Among these, addition of downstream flow to the objective set assumes great significance, as the river becomes dry during summer and commissioning of the project makes the downstream flow practically nil. Hence, if the downstream flow demands are not addressed, it may endanger the social acceptability of the project.

There is no significant difference between the proposals with regard to the drinking water availability. In the case of irrigation, the optimal plan gives a 200% increase of the area that can be irrigated. The benefits out of irrigated area can be increased from the level of Rs. 429 lakhs to 773 lakhs (80% increase). The entire benefits derived out of fisheries is additional incase of optimal plan, as this objective was not envisaged in the existing proposal. The economic benefits from fisheries has been worked out considering a conservative productivity value of 2.5 t/ ha/ annum and a market price of Rs. 30/ Kg. Similarly, the benefits derived from the downstream water release is wholly attributed to the new operational policies. A benefit of Rs. 32 lakhs has been derived by assuming a price of Rs. 2/ m^3 of water released.

The annual net benefits have shown an increase from Rs. 429 lakhs to Rs. 865 lakhs. Net Present Value factor for the Year 2000 with a project life of 25 years and with a market interest rate of 12% by assuming that the project will be commissioned in the year of 2004 has been worked out to be 4.98. NPV has been obtained as Rs. 2136 lakhs and Rs. 4308 lakhs for the existing proposal and new proposed operational plan respectively. For a project cost of Rs. 1900 lakhs, the benefit-cost ratio has been worked out to be 1.124 for the existing plan and 2.267 for the optimal plan proposed (an increase of 100%). Hence, the optimal operational policies improve the economic viability and social acceptability of the water resources project significantly.

SUMMARY

SUMMARY

Water resources projects involving reservoirs are very expensive and inter linked with many social issues. Hence, they must be subjected to thorough analysis to see that each drop of water impounded is utilized in the best possible manner and in a socially acceptable way. For this, formulations of operational policies incorporating maximum objectives considering social acceptance aspects is a must. Keeping this idea in mind, a study has been conducted for a regulator-cum-bridge under construction at Thrithala in Palakkad district of Kerala state in Indian peninsular with the specific objectives of determining the optimum water allocation of the reservoir for meeting various demands on it and obtaining the optimum cropping pattern for the command area.

The project selected is a multi-purpose one and the multi-objectives of the reservoir system, including the additional objectives incorporated in the order of priority were; 1. Drinking water demand, 2. Irrigation demand, 3. Pisciculture demand and 4. Downstream flow demand. Linear programming technique was used to optimize the water allocation from the reservoir for different purposes. The problem was formulated as a monthly operational model and the operating horizon was taken as 12 months from June to May. The water requirement for each of the purposes was taken as the targets to be achieved by the model. The mathematical model was formulated with all the known quantities on the right hand side of the constraint equations. The deviations from each target were then incorporated with a penalty coefficient. In each of the objectives the target was again divided into 25%, 50%, 75% and 100% level, in order to minimize the deviations from the monthly target of each of the objectives and the penalty coefficients were obtained from their priority levels. The slopes of the lines drawn to each level of target from the priority levels were taken as the penalty coefficients. The objective of the model was to minimize the sum of the deviations of the allocations from the targets of each objective. The constraints considered for the model were; 1) Continuity equation constraints, 2) Storage constraint, 3) Release constraints and 4) Target constraints.

The LP model was solved using Excel Solver software package. The effect of elimination of some of the least important demands (i.e., downstream flow demand and fisheries demand) was studied by eliminating theses demands separately form the multiple demand set of the reservoir operation. The 75% chance inflow was considered for the study and the solution gave the optimal release for each month for the entire operating horizon of one year.

With the irrigation allocation from the first model, another linear programming model was used to obtain an optimal cropping pattern for the command area of the project with the objectives of maximising the net profit from the command area for the year and maximising the net area put under cultivation in an year. Maximizing the net profit from the command area consisted of the maximization of the net returns from the command area in economic terms with the available water and area bounds for different crops and seasons. The objective of the area maximization was to maximize the area, which can be put under irrigation with the same available water and with the same constraints. This model was also solved with the Excel Solver software package. Six sets of constraints were considered. The cropping pattern which gave maximum net profit in the case of net profit maximization and the cropping pattern which gave maximum area under area maximization, were selected. These cropping patterns were compared with the cropping pattern proposed by the Irrigation department for the same project both in economical terms and in terms of the number of objectives met.

The following conclusions have been drawn out of the study.

1. River flow analysis with 30 years data reveals that monthly mean maximum flow of 767 Mm^3 occurs in the month of July and monthly mean minimum flow of 5.01 Mm^3 during March. About 97% of the annual river flow takes place during the seven months from June to December.

2. Summer river flow is very meager and will get further worsened to the downstream side after the commissioning of the project. Hence, an assured downstream release is essential.

3. First hand information suggested that, there is scope to increase the water utilization efficiency and effectiveness of the reservoir by incorporating additional objectives and formulating optimal operational policies.

4. When the irrigation demand for the command area proposed by Irrigation department was considered, the result shows that the storage space is full and there is significant surplus downstream flow during the months from June to January. This indicates that there is ample scope for increasing the water drawal for irrigation from the reservoir.

5. Optimal monthly water allocation corresponding to maximum possible increase in irrigation demand showed a deficit, less than 25% during the months of February, March and May.

6. Optimal allocation showed a deficit from the targetted downstream flow during the months from February to April. When the downstream flow demand was eliminated, the increase in water availability was limited to only two months. Utilizing this water for irrigation is practically not possible. Hence, the downstream flow demand is not in competition with irrigation release from the practical point of view.

7. Allocation for fisheries is met with a shortfall in the month of April. When fisheries allocation was deleted, it did not contribute significantly to irrigation water. Hence, this demand is also compatible with the irrigation demand.

8. Optimal cropping pattern with net benefit maximization objective gave a net benefit of 773 lakhs, which is 80% higher than that of the proposal by Irrigation Department. The area that can be irrigated got doubled. The

increase in area during Rabi season was more significant (170% increase) and increase in irrigated area for upland crops was 70%.

9. Summer paddy allocation was restricted to a small area as it is less remunerative and high water demanding.

10. Optimal cropping pattern with area maximization objective gave a total annual irrigated area of 6817 ha, an increase of 100% from the existing proposal by the Irrigation Department.

11. Sensitivity analysis showed that the model is sensitive to the changes in the returns from each crop. When return from a crop is reduced to a certain level, the model gave zero value of area for that crop.

12. Total annual benefits from the optimal plan was Rs. 865 lakhs against Rs. 429 lakhs from the existing proposal (100% increase). Benefit-Cost ratio was found to be 2.27 for the new proposal and 1.12 for the existing proposal.

13. The study summarises that optimal operational policies, even for a small water resources project increases its economical viability to a great extent and make the project more socially acceptable. Hence, all reservoirs must be planned based on optimal operational policies incorporating maximum number of objectives to improve their utility value and better social acceptance.

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* Originals not seen

APPENDICES

APPENDIX-I

HISTORICAL MONTHLY RIVER FLOW DATA (Mm^3)

Mon / Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1968	**12.43**	4.25	2.29	4.94	17.02	205.9	1973	1117	315.5	168.2	78.23	3.59
1969	5.01	0.97	0	0	11.52	185.4	1368	361	280.6	193	48.94	28.08
1970	13.11	6.84	7.64	9.16	18.31	482.9	774	1135	173.1	312.3	162.9	31.62
1971	21.6	9.77	1.88	0	20.15	1006	934.1	470.3	175.5	541.4	52.03	164.8
1972	42.97	16.31	1.91	5.66	206.8	163.3	1186	253.4	80.2	220.6	86.2	137
1973	23.57	5.54	0	3.26	9.34	416.5	824.8	491.7	90.51	223.2	66.19	37.06
1974	20.57	5	1.78	2.49	6.07	30.54	1110	1214	416.6	198.4	96.48	13.72
1975	21.03	12.01	24.54	2.38	60.67	995.3	682.7	1526	769.1	582.9	331	38.47
1976	34.86	23.37	3.06	30.04	28.33	22.5	314.1	321.8	172.2	242.9	281.7	46.17
1977	25.16	3.67	NA	2.45	24.23	248.8	842.4	340.1	293.7	573.6	1014	19.12
1978	0.62	0.01	1.77	0	0.03	403.9	740.4	789.7	169.7	89.59	297.3	1.94
1979	3.72	0.07	1.81	9.68	14.06	269.1	862.1	1064	123.9	63.97	690.1	24.79

APPENDIX-I (contd.)

1980	162.5	34.99	1.9	3.19	21.33	651.9	1340	668	146.3	477.5	165.6	7.76
1981	6.01	4.85	4.82	9.62	29.88	780	604.9	934.8	524.4	190.6	125.7	19.22
1982	28.6	22.7	12.39	7.77	12.81	417.8	561.9	833.3	479.7	129.7	189.4	20.26
1983	0.66	0	0	2.21	0	39.1	848.8	868.3	480.4	251.7	255.3	106.7
1984	11.65	2.31	1.87	2.4	0.79	233.8	484.2	128.3	35.86	93.03	19.53	5.59
1985	96.2	18.43	3.34	44.72	2.91	274.2	381	200.8	50.53	73.19	20.64	20.5
1986	47.87	11.06	1.62	0	7.03	153	186.2	305.6	93.23	95.93	92.16	35.79
1987	19.09	3.75	0	0.68	0	65.84	253.4	173.6	120	107.6	206.9	77.42
1988	37.87	4.15	9.16	36.68	43.34	132.3	243.9	231.2	251.9	40.56	24.18	24.15
1989	18.76	0.48	2.74	2.37	2.99	223.7	403.9	260.4	181.4	219	85.61	24.53
1990	42.16	0.67	0	2.22	30.29	271.5	473.8	319.8	54.72	84.43	171.8	41.98
1991	38.27	5.06	0	2.97	0	274	747.9	604.1	73.97	135.6	160.6	22.62
1992	7.44	0	1.32	2.01	0	312.9	688.6	710.9	431.5	356.1	407.6	0

APPENDIX-I (contd.)

1993	79.34	59.47	47.42	28.3	39.75	172.5	618.2	481.9	107.2	332.1	260.7	120
1994	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1995	98.5	37.62	1.2	0	72.76	198.3	839.3	329.2	568.2	73.37	226.6	39.75
1996	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1997	0	0	0.8	1.32	0	28.12	1185	823.2	135.6	164	555.2	50.6

*Source: Dept. of Field Studies, Irrigation Complex, Thrissur

APPENDIX-II

HISTORICAL MONTHLY RAINFALL DATA (*mm*)

Month / Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1967	15.5	0	7.3	8.4	149.4	414.4	0	591	158.7	113.1	298.3	78.5
1968	0	3.3	82.6	126.8	135.6	671	1136	482.9	308.8	86.8	98.2	0
1969	0	0	5	28.6	166.6	624.4	636.1	152.4	194.5	233.9	80.6	0
1970	0	0	0	151.7	287.2	464.8	623.2	537.5	193.4	215.4	27.5	0.2
1971	8	0	0	59	340.9	823.5	651.6	400.8	253	233.2	0	122.2
1972	0	0	0	29.4	397.4	442.8	703.3	348.3	112.7	485.5	187.1	116.8
1973	0	0	0	93.7	115.3	693	485.6	393.2	49.2	237	151.1	10.1
1974	0	0	0	152.4	115.9	345.5	1159	476.5	346.3	85.8	100.3	0
1975	1.2	0.2	71.5	61.4	186.1	899.3	350.7	611.4	417.1	224.5	145.7	0
1976	0	0	29.3	124	39.9	166.9	568.6	197.9	74.9	178.1	231.5	0.5
1977	0	0	25	128.4	222.8	517.8	521.9	189	141.2	476.1	304.5	0

APPENDIX-II (contd.)

1978	0	10.8	0	34.4	357.3	780.8	540.1	458	67.7	183.9	437.2	11.1
1979	0	16.4	0	64.5	78.4	646.7	801.8	423	184.6	234.7	278.1	1.8
1980	0	0	14.8	99.9	50.5	760.4	875.1	343.8	178.6	230.4	103.1	58.2
1981	0	0	8	59.3	171.7	1085	443	561.7	376.3	242	168.6	0
1982	0	0	0	45.8	198.8	775.9	526.9	609.4	71.6	153.1	146.4	0.1
1983	0	0	0	0	94.3	235.1	592.6	644.8	527.1	176.7	63.8	17
1984	8.2	56.8	103.6	74.8	54.9	809.6	619.7	234.1	134.8	321.7	41	23.2
1985	28.8	0	0	29.6	147.1	854.4	464.2	282.2	77.8	177.6	115.4	41.6
1986	11.2	1.2	2.8	47.8	45.1	740.8	270.3	342.6	234.3	176.1	210.4	0
1987	0	0	0	6.4	66	535.4	337.6	301.4	136.7	127.9	242.4	46.4.
1988	0	22.8	12.4	93.9	181.8	477.9	410.8	250.6	398	42.6	28.8	0.4
1989	0	0	8.6	61.2	60.1	745.3	450.3	215.3	237.5	247.9	61	0
1990	0	0	6.4	327	467	567	211	26	332	82	0	0
1991	9.6	0	9.7	127.6	66.7	787.3	939.5	554.2	31.5	251.9	133.6	0

APPENDIX-II (contd.)

1992	0	0	0	4.6	77.7	694.4	680.4	395.1	268.4	173	247.4	0
1993	0	35.8	1.2	28.8	162.1	772.8	662.7	261.2	34.4	409.3	93.8	13.8
1994	6.2	0	27.8	131.4	64	856.8	1015	363.2	172.3	354.5	94.4	0
1995	0	0	0	83.6	265.5	558.8	724	363	258.8	97	154.4	0
1996	0	0	48.8	102.2	45.4	348	537.4	217	318.4	307.8	16.2	13.7
1997	0	0	10.4	43.75	105.2	489	990.3	411.8	245.7	265.3	315.8	23.7
Mean	**2.96**	**4.91**	**15.84**	**80.03**	**150.64**	**638.05**	**628.46**	**376.37**	**217**	**202.73**	**148.32**	**15.42**

*Source: Dept. of Field Studies, Irrigation Complex, Thrissur

APPENDIX-III

EFFECTIVE RAINFALL FOR DIFFERENT CROPS FOR DIFFERENT MONTHS (mm)

Month	Paddy	Coconut	Sesamum	Pulses	Vegetables
Jan	0	0	0	0	0
Feb	0	0	0	0	0
Mar	0	12.992	12.923	12.923	12.672
Apr	29.31	59.92	55.2	55.2	38.81
May	49.76	98	---	---	---
Jun	377.55	100	---	---	---
Jul	342.94	100	---	---	---
Aug	191.93	100	---	---	---
Sep	101.8	100	---	---	---
Oct	105.38	100	---	---	---
Nov	54.15	94	---	---	---
Dec	0	11.34	---	---	---

APPENDIX-IV

CALCULATION OF IRRIGATION REQUIREMENTS

IRRIGATION REQUIREMENT OF PADDY (NURSERY) (m^3 / ha)

	Kharif May 17th to June 10th		Rabi Sept 6th to Sept 30th	Summer Dec 27th to Jan 20th	
	May (15 days)	June (10 days)	Sept (25 days)	Dec (5 days)	Jan (20 days)
K_c	1.1	1.1	1.1	1.1	1.1
ET_0 (mm/ day)	3.7	2.3	3.1	3	3.88
ET_c (mm/ day)	4.07	2.53	3.41	3.3	4.268
Percolation (mm/ day)	0	6	6	6	6
TWR (mm/ day)	4.07	8.53	9.41	9.3	10.268
TWR (mm/month)	61.05	85.3	235.25	46.5	205.36
ER (mm/ month)	24.08	125.85	84.83	0	0
IR (mm)	36.92	0	150.42	46.5	205.36
IR (m^3/ha)	369.23	0	1507.69	465	2053.33

APPENDIX-IV (contd.)

WATER REQUIREMENT FOR PUDDLING (m^3/ha)

	Kharif		Rabi			Summer	
	Nursery	Main field	Nursery		Main field	Nursery	Main field
Month	May	June	Aug	Sep	Sep	Dec	Jan
WR (m^3/ha)	0.035	0.035	0.0175	0.0175	0.035	0.035	0.035

APPENDIX-IV (contd.)

WATER REQUIREMENT OF PULSES(Mm^3)

Month	Jan 10 days	Feb 28 days	March 31 days	April 26 days
K_c	0.5	0.7	0.99	0.93
ET_0 (mm/day)	3.88	4.15	4.5	4.4
ET_c(mm/day)	1.94	2.905	4.455	4.092
TWR/ Month(mm)	19.4	81.34	138.105	106.392
ER(mm)	0	0	12.923	55.2
IR(mm)	19.4	81.34	125.182	51.192
IR (m^3/ha)	194	813.4	1251.82	511.92
GrossIR/ ha (m^3/ ha)	340.35	1426.32	2196.49	898.25

APPENDIX-IV (contd.)

IRRIGATION REQUIREMENT OF VEGETABLES (Mm^3)

Month	Jan 10 days	Feb 28 days	March 31 days	April 26 days
K_c	0.5	0.7	0.99	0.93
ET_0 (mm/day)	3.88	4.15	4.5	4.4
ET_c(mm/day)	1.94	2.905	4.455	4.092
TWR/ Month(mm)	19.4	81.34	138.105	106.392
ER(mm)	0	0	12.672	38.81
IR(mm)	19.4	81.34	125.433	67.582
IR (m^3/ha)	194	813.4	1254.33	675.82
GrossIR/ ha (m^3/ ha)	340.67	1427.35	2214.28	1192.3

APPENDIX-IV (contd.)

IRRIGATION REQUIREMENT OF SESAMUM(Mm^3)

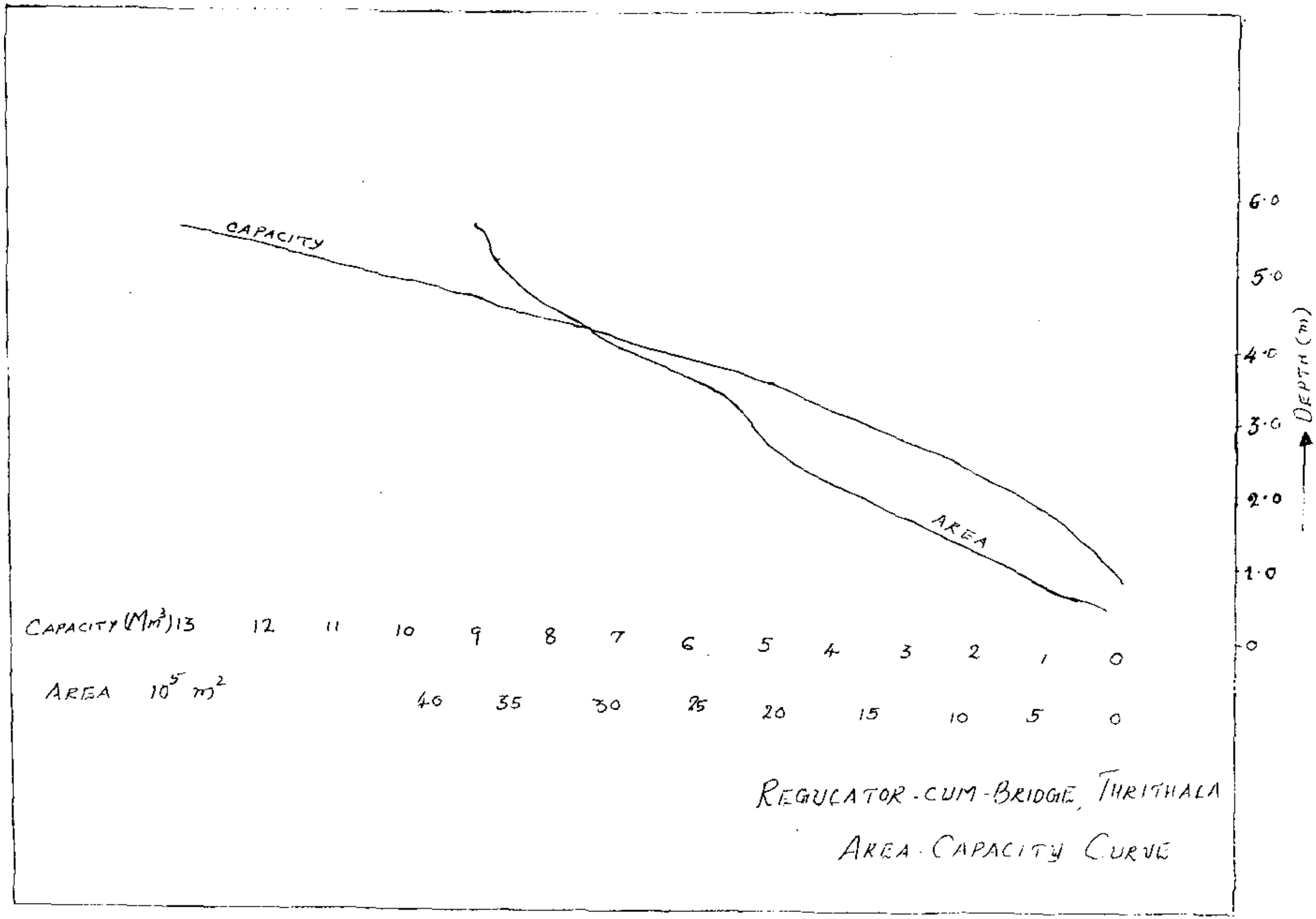
Month	Jan 10 days	Feb 28 days	March 31 days	April 21 days
K_c	0.5	0.73	0.94	0.63
ET_0 (mm/day)	3.88	4.15	4.5	4.4
ET_c(mm/day)	1.94	3.03	4.23	2.772
TWR/ Month(mm)	19.4	84.34	131.13	58.212
ER(mm)	0	0	12.672	38.81
IR(mm)	19.4	84.34	118.46	19.402
IR (m^3/ha)	194	843.4	1184.6	194.02
GrossIR/ ha (m^3/ ha)	340.35	1488.42	2077.19	340.35

APPENDIX-IV (contd.)

IRRIGATION REQUIREMENT OF COCONUT WITH MISCELLANEOUS TREES AND PEPPER

Month	K_c	ET_0 mm/day	ET_c mm/day	WR mm/ month	ER mm	IR mm/ month	IR (m^3/ha)	Gross IR m^3/ ha
Jan	1.1	3.88	4.268	132.308	0	132.308	1323.08	2320.58
Feb	1.1	4.15	4.565	127.82	0	127.82	1278.2	2252.79
Mar	1.1	4.5	4.95	153.45	12.99	140.46	1404.6	2472.09
Apr	1.1	4.4	4.84	145.45	59.92	85.28	852.8	1495.21
May	1.1	3.7	4.07	126.17	98	28.17	281.7	498.404
Jun	1.1	2.3	2.53	75.9	100	0	0	0
Jul	1.1	2.2	2.42	75.02	100	0	0	0
Aug	1.1	2.9	3.19	98.89	100	0	0	0
Sep	1.1	3.1	3.41	102.3	100	0	0	0
Oct	1.1	3.1	3.41	105.71	100	5.7	57	65.308
Nov	1.1	3.2	3.52	105.6	94	11.6	116	203.351
Dec	1.1	3.0	3.3	102.3	13.34	90.96	909.96	1594.89

APPENDIX-V



CAPACITY
AREA
6·0
5·0
4·0
3·0
2·0
1·0
0
DEPTH (m)
CAPACITY (Mm³) 13 12 11 10 9 8 7 6 5 4 3 2 1 0
AREA 10⁵ m² 40 35 30 25 20 15 10 5 0
REGULATOR-CUM-BRIDGE, THRITHALA
AREA-CAPACITY CURVE

OPTIMAL WATER USE AND CROPPING PATTERN FOR THRITHALA REGULATOR - CUM - BRIDGE PROJECT

By

SARITHA, E. K.

ABSTRACT OF THE THESIS

Submitted in partial fulfilment of the requirement for the degree

MASTER OF TECHNOLOGY IN AGRICULTURAL ENGINEERING

Faculty of Agricultural Engineering and Technology

Kerala Agricultural University

Department of Land and Water Resources & Conservation Engineering

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ABSTRACT

Reservoir projects involve huge financial investment and hence, every drop of water stored in the reservoir must be utilised very judiciously. Allocation of water in the case of multi-purpose projects among various competing needs such as drinking water, irrigation, pisciculture, downstream flow, etc. is a matter of great concern. Hence, formulation of optimal operational policies for reservoirs has become highly essential to improve their financial viability, social acceptability and overall performance. So a study has been undertaken for a regulator-cum-bridge under construction at Thrithala in Palakkad district of Kerala state in Indian peninsular with the specific objectives of determining the optimum water allocation of the reservoir for meeting various demands on it and obtaining the optimum cropping pattern for the command area.

A linear programming model was formulated to optimize the reservoir operation of the multipurpose project with the objectives of Drinking water demand, Irrigation demand, Pisciculture demand, and Downstream flow demand, in the order of priority. The deviations of the allocations from the targets to be achieved were minimized by introducing penalty coefficients to each deviation according to their order of priority. Using the irrigation allocation from this model, another Linear Programming model was formulated to obtain the optimal cropping pattern for the command area. Both models were solved using Excel Solver software package. The optimal operational plan and the optimal cropping pattern obtained were compared with the operating plan and cropping pattern proposed by the irrigation department. The optimal operation plan with the incorporation of additional objectives was found to be more socially acceptable and economically viable. The optimal cropping pattern showed that there is more than 100% increase both in the net benefit as well as in the net area irrigated.