THE ASSESSMENT OF LONG-TERM OPERATION OF MULTI-UNIT RESERVOIR SYSTEMS

by

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Abstract

The derivation of optimal operation policies for a multiple-reservoir system is very complex due to the dimensionality constraints. The paper presents a methodology devised to overcome this difficulty during the determination and assessment of long-term optimal operation policies for a multiple-reservoir system. To overcome dimensionality constraints the determination of the overall operational scheme is based upon the decomposition of the system into single-reservoir subsystems. Subsequently, each subsystem's operation is individually optimized and simulated. The methodology combines a stochastic dynamic programming (SDP) based optimization model with a reservoir operation simulation model. The applicability of the approach is presented on the complex Mahaweli Development Scheme in Sri Lanka.

1.0 Introduction

There are large spatial and temporal discrepancies between the availability of and the demand for water. Multi-unit reservoir systems coupled with interbasin water transfer and conveyance structures play a very important role in redistribution of available water in both space and time. Planning the optimal operation of such a multi-purpose multi-unit reservoir system is a very important but rather complicated task. During the last several decades many attempts have been made towards solving this problem by various mathematical means.

Dynamic programming (DP) has been broadly used in water resources management, particularly in reservoir operation. State-of-the-art reviews with extensive lists of references on DP and its applications are found in the work by Yakowitz (1982) for several water resources problems and Yeh (1985) for optimal reservoir operation. The popularity of DP in water resources management is due to its inherent flexibility to accommodate the most important features of water resources systems, such as: their dynamic nature, nonlinear interrelationships and stochasticity of processes involved. Yet, the discrete nature of DP causes the computational effort to become prohibitive by increasing the number of elements of the system. This increases the number of state and decision variables needed to describe the system. Many DP-based algorithms have been developed aiming to overcome this so called "curse of dimensionality" problem.

The method presented in this paper combines physical decomposition of a system with DP-based optimization, for the derivation of a long-term operational policy for a multiple-reservoir system.

To illustrate the applicability of the proposed algorithm, the multi-purpose Mahaweli Development Scheme in Sri Lanka is selected. It comprises of several reservoirs, diversion structures, interbasin water transfers and hydro-power generation facilities etc.,. The derivation of optimum operation policies for the reservoirs in this complex system is undoubtedly important to maximize the benefits from the system.

2.0 Methodology

Consider a multiple-reservoir system consisting of a number of reservoirs situated in several neighbouring and/or distant river basins. The reservoirs interact by means of serial and parallel interconnections allowing also water to be transferred from one basin to another. The optimal operation of these reservoirs is of paramount importance to obtain the maximum benefit from the system.

Due to high dimensionality of the problem the derivation of the optimal operational strategy for such a system is confronted with prohibitive computational requirements imposed by any straightforward optimization application. The proposed algorithm is based on a physical decomposition of a system into a group of single-reservoir subsystems. Thus, a multidimensional decision problem is reduced to a sequence of one-dimensional optimization tasks. Consequently, a

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combined optimization/simulation procedure is applied to each reservoir. The sequence in which reservoirs are introduced into analysis is mainly determined by their position in the system.

The algorithm is essentially an iterative procedure. One iteration cycle comprises optimization and simulation of operation of each reservoir within the system. These iterations are repeated until the solution converges to an acceptably stable optimal solution. The procedure starts by optimizing the performance of the uppermost reservoir of the system. The operation policy derived for that reservoir is then used to simulate its performance over the period, for which hydrological data are available. The sequence of free downstream releases from the reservoir is one of the results from this simulation. These releases represent the volume of water left after supplying all the demands. These nonconsumptive volumes of water (free downstream releases) are added to the incremental inflows to estimate the total inflows to the next downstream reservoir.

Then the optimization and simulation of the next reservoir is carried out similarly to the previous one. These optimization/simulation cycles are continued further downstream until the operation policy of the last reservoir is assessed, which concludes one iteration. Data transfer between two consecutive iterations consists of sets of reservoir water shortages obtained by simulation in the preceding computational step. The methodology is presented as a flowchart in Figure 1.

2.1 Optimization

The core of the method is the SDP-based optimization algorithm. The applied SDP algorithm is a variation of the one given by Loucks et al. (1981). The SDP-based optimization procedure derives the optimal, expectation oriented, long-term operational strategy for a single reservoir. Due to the nature of DP all state and decision variables are represented in their respective discrete domains. A month is considered as one stage in the present study. The state of the system (reservoir) is the volume of water stored at the beginning of a time stage. Uncertainty is explicitly incorporated into the optimization procedure with inflow to a reservoir being represented by different classes with their respective independent or transitional probabilities being considered as an additional state variable in the SDP-based optimization procedure. Thus, whether the inflows are considered to be random or Markovian, the system's state is described by two state variables: (a) reservoir storage at the beginning of the month, and (b) the inflow to the reservoir during the month.

The decision to be taken at each stage within one annual cycle is the storage volume of the reservoir at the end of the time interval. Thus, the operating policy is defined for each month and is expressed in terms of the optimal decision to be taken as a function of system states.

The operational policies were derived and the performances of the system were obtained based on the following two objective functions.

Objective Function 1

To minimize the expected value of annual sum of squared shortages of supply water (single sided deviation of the releases from the respective monthly irrigation demands).

where, $DEF_j = (QD_{,j} - R_j)^2$

$\mathscr{E}$ = expectation operator,

N = number of stages (months) in one year, i.e., N = 12,

$Q_{D,j}$ = water demand (target release) from the reservoir during period j,

Rj = the total release from the reservoir during period j.

Objective Function 2

To maximize the expected value of annual sum of total energy generation. The satisfaction of the irrigation demands is not considered during the optimization.

where,

$TEPj = 9.81 \eta Q_j H_j t_j$ =energy produced,

$\mathscr{E}$ = expectation operator,

N = number of stages (months) in one year, i.e., N = 12,

Q_j = total release from the reservoir during period j,

$Qj \leq R_{max}$

R_{max} = allowable release through the power generators,

$H_j = EL_j - TW_j$ = the head,

EL_j = elevation of water level in reservoir during period j,

TW_j = tail water level of power station during period j,

t_j = time in hours in period j, and

η = overall efficiency of turbines, generators and transmission taken as 0.75.

The optimizations are subjected to constraints in reservoir storage volume and release. State transformation equation is based on the principle continuity of the reservoir.

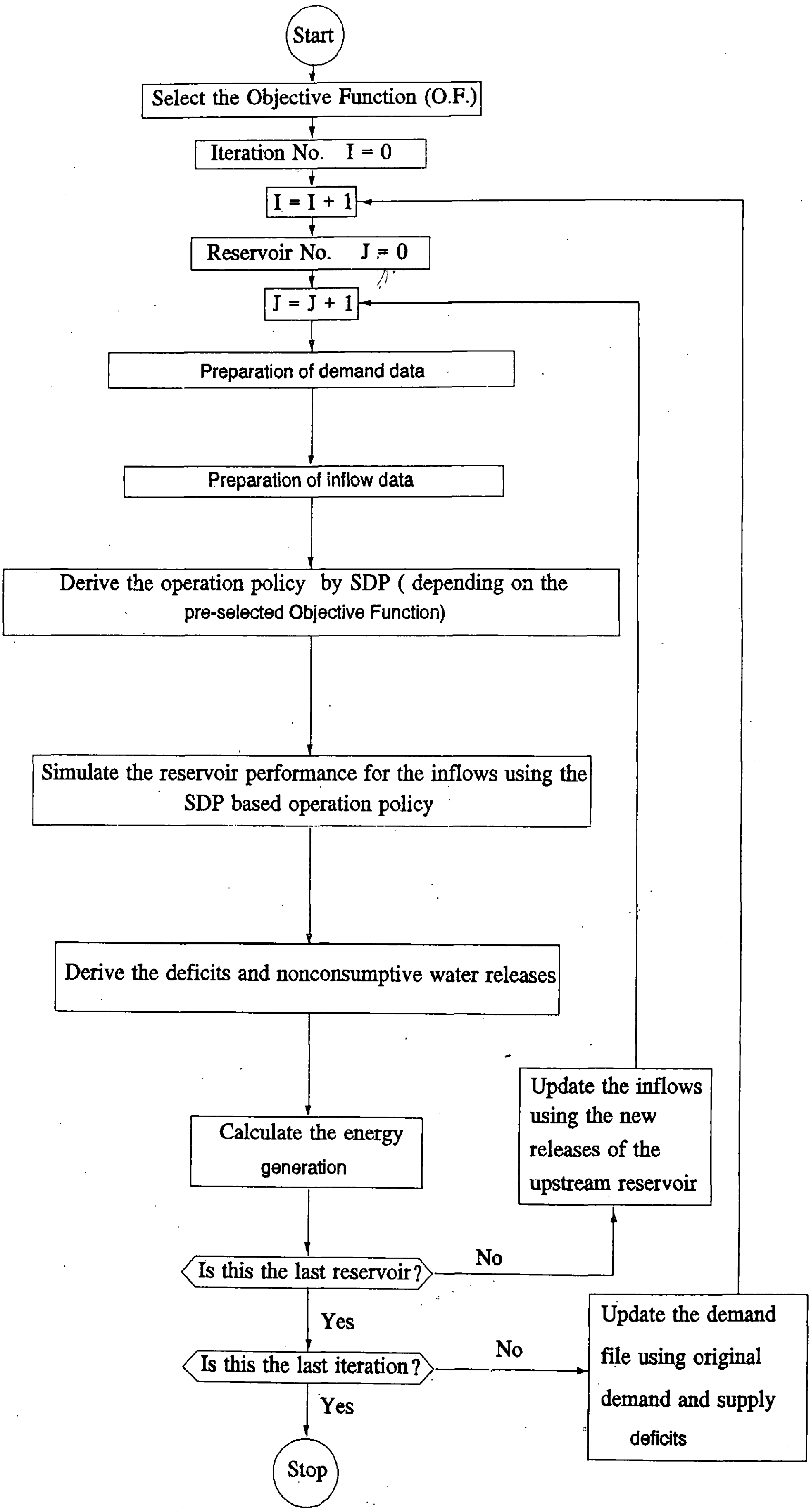

Figure 1 Flowchart of the sequential approach

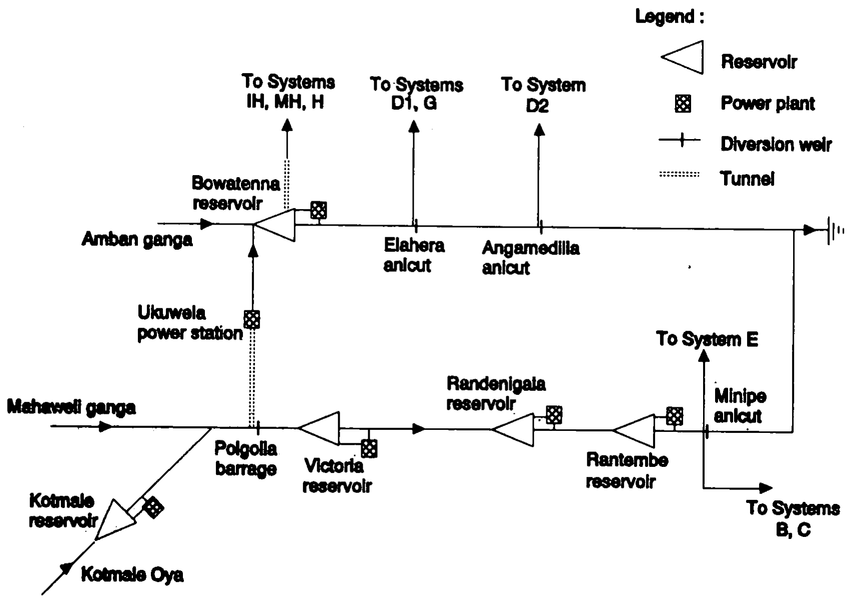

Figure 2 Schematic diagram of the Mahaweli Development Scheme

2.2 Simulation

Once an operational strategy is defined, simulation is carried out to assess and to incorporate the effects of the reservoir's performance into the operation of the system as a whole. The simulation is carried out over the total historical record of inflow. The role of simulation in the presented approach is twofold:

- It is used to evaluate the effectiveness of a reservoir's operating policy.
- In conjunction with release allocation algorithm, simulation provides necessary information on the interaction among reservoirs (i.e., expected levels of each individual demand fulfilment and deficit, additional flows available to reservoirs situated downstream on the river course, shortages in supply that a reservoir is going to encounter by following the derived operating policy and energy generated at each reservoir).

3.0 The Mahaweli Development Scheme

The Mahaweli Development Scheme plays a major role in the irrigation development and the hydropower generation in Sri Lanka. This multipurpose water resources development scheme has been designed to harness the irrigation and hydroelectric potential of the Mahaweli river, the largest river in the country.

Figure 2 shows the system configuration considered in this study. There are three reservoirs in the main stem of the Mahaweli river: Victoria, Randenigala and Rantembe, each with a power plant. These reservoirs regulate the flow for irrigation demands to systems B, C, and E at Minipe anicut. The Kotmale reservoir with a power plant is situated on the Kotmale Oya (creek), a tributary of the Mahaweli river.

Downstream of the Kotmale reservoir is Polgolla diversion structure. Polgolla barrage plays an important

Table 1
Salient features of the reservoirs in the system

Reservoir	Storage Capacity (MCM)		Rated Head of Turbines (m)	Max. allowable discharge through Turbines (m3/s)
	Normal Maximum WL	Minimum operating WL		
Kotmale	172.9	22.2	201	3x38
Victoria	720.0	34.0	190	3x46.7
Randenigala	875.0	295.0	78	2x90
Rantembe	22.0	4.4	31	2x90
Polgolla	4.1	2.0	78	2x28.3
Bowatenna	52.0	17.1	53	94.9

role in the Mahaweli water resources system. It is used to divert water from the Mahaweli river to the Amban Ganga basin through a diversion tunnel. The diverted water is used to generate hydropower at Ukuwela power station before it reaches the Bowatenna reservoir. The main purpose of the Bowatenna reservoir is to regulate the diverted water for the irrigation systems H, IH and MH. Downstream discharge from Bowatenna reservoir is used to generate hydropower. The irrigation demands of systems D1 and G are diverted from Elahera anicut. The Angamedilla anicut diverts water demands of irrigation system D2. (Table 1)

Due to the small storage capacity of the Rantembe reservoir it is considered as a run-of-the-river power plant in this study. Due to the importance of the Polgolla diversion structure it is considered as a separate reservoir, despite its small storage capacity. The Ulhitiya reservoir and the Maduru Oya reservoir, which are situated downstream of the Minipe anicut regulate Mahaweli water for the irrigation systems B and C. The present study does not consider the operational aspects of this sub-system explicitly.

4.0 Analysis and Results

The presented algorithm was employed to develop long-term operational policies for the reservoirs of the complex Mahaweli Development Scheme, viz., Kotmale reservoir, Polgolla barrage, Bowatenna reservoir, Victoria reservoir and Randenigala reservoir and to assess the performance of the system based on the derived operation policies. Incremental inflows for 37 years (1957 - 1993) were used in the study. The actual irrigation water deliveries made during the period from 1991 to 1995 from Bowatenna reservoir (System H) and at Elahera, Angamedilla and Minipe anicuts were available. The maximum values for each month from this record were used as the irrigation demands in the study. All these data, which were obtained from the Water Management Secretariat of MASL were not checked for accuracy and consistency by the author.

The operation policy designated for a reservoir by the model is a set of rules specifying the storage level at the beginning of the next month for each combination of storage levels at the beginning of the current month and the inflow during the current month. The simula-

Table 2
Average annual energy generations

	Average Annual Energy (GWh)					
	Objective Function 1			Objective Function 2		
Polgolla Capacity (MCM/month)	146.7	100.0	85.0	146.7	100.0	85.0
Kotmale	382.6	382.6	382.6	382.6	382.6	382.6
Polgolla/Ukuwela	214.7	163.0	143.3	214.7	163.0	143.3
Bowatenna	101.4	64.6	50.7	102.2	65.4	51.6
Victoria	571.9	690.7	735.9	575.2	698.8	745.4
Randenigala	266.1	318.6	337.6	295.6	347.7	368.0
Rantembe	164.3	184.4	192.1	166.6	189.1	197.6
Total	1701.0	1803.9	1842.2	1736.9	1846.6	1888.5

Table 3
Average annual irrigation supply deficits

	Average Annual Irrigation Supply Deficit (MCM)					
	Objective Function 1			Objective Function 2		
Polgolla Capacity (MCM/month)	146.7	100.0	85.0	146.7	100.0	85.0
Bowatenna/ System H	10.4	10.3	10.3	17.3	16.9	17.9
Elahera	131.6	289.5	373.5	128.7	285.0	367.5
Angamedilla	127.9	184.2	189.2	126.9	184.0	189.1
Minipe	204.8	148.7	123.0	328.6	251.7	211.3
Total	474.7	632.7	696.0	601.5	737.6	785.8

tion process is used to assess the derived operation policy and evaluate the system operation.

Table 2 compares the average annual energy generations for the two objective functions. The first objective function considers the satisfaction of irrigation demand while the second maximizes the total energy generation from the whole system. As Table 2 reveals the energy generation has increased with the second objective function. The energy generation at the Kotmale power plant remains the same for all the cases. The energy generations at the Ukuwela and Bowatenna power plants reduce with the reduction in the Polgolla diversion capacity. When the diversion capacity at Polgolla is reduced the flow towards downstream Victoria reservoir increases. Along with that the energy generations at the Victoria, Randenigala and Rantembe power plants increase. By sending more water towards the Victoria reservoir from the Polgolla barrage, more energy could be generated from the whole system.

The variation of average annual irrigation supply deficits for the two objective functions is shown in Table 3. The total system irrigation deficit increases with the reduction in the Polgolla diversion capacity. This table shows the impact of the Polgolla diversion capacity on the supply of irrigation demands at various places of the system. These values are the averages of the deficits obtained by simulating the system operation for the total period of 37 years.

Figure3 compares the historical (actual) irrigation water supplies with the releases obtained from the proposed methodology during a period of 3 years. The releases obtained from the simulations are based on expectation oriented, long-term operational policies. The supply to the System H is always higher than the requirement. The diversions from the Elahera anicut and the Angamedilla anicut are comparable. However, the supply from the Minipe anicut show some deviations due to the expectation oriented nature of the operational policies. Note that the demands used in the SDP model are the maximum values for each month of the historical record (for one year). The SDP model derives operational policies targeting these high demands. Therefore, the simulations carried out based on SDP based operational policies show some discrepancies. As Figure 3(a) shows additional areas in the System H could be supplied with irrigation water.

Figure 4 shows releases for different diversion capacities at the Polgolla barrage. Irrigation water supply to the System H through the Bowatenna reservoir is not affected by the change in diversion capacity of the Polgolla barrage. More water could be supplied from the Elahera anicut, when the diversion capacity at the Polgolla barrage is increased. A similar behaviour is observed with the supply from the Angamedilla anicut also, but to a lesser degree. The irrigation supply from the Minipe anicut could be increased by decreasing the diversions to the Amban ganga basin at the Polgolla barrage.

By reducing the diversions at the Polgolla barrage the total energy generation could be increased marginally. Yet, the associated increase in the irrigation supply deficit is relatively high. Also, energy generation from the system could be increased by using operational policies derived based on an objective function for maximizing energy generation. However, as the results show the associated increase in the irrigation supply deficit is very high. These results demonstrate the applicability of the methodology in deriving operational policies and then assessing the performance for a multi-unit reservoir system.

5.0 Conclusions

The presented methodology could be applied successfully to derive and assess long-term operation of complex reservoir systems. The algorithm can easily accommodate changes in a system's parameters. Also, inclusion of new reservoirs or demand centres into the model, or exclusion of some elements from the model is possible without performing major programming tasks. These facilities enable the quick comparison of several alternative water resources development plans.

Although the results would reflect local optimum performances of different systems the advantage of a fairly simple implementation of the procedure to a number of alternatives provides easy and quick comparison of the corresponding outcomes. In addition, it should be noted that, by reducing a task to a single reservoir optimization, the method allows fine state space discretization and the maximum exploitation of the advantages of dynamic programming.

6.0 Acknowledgement

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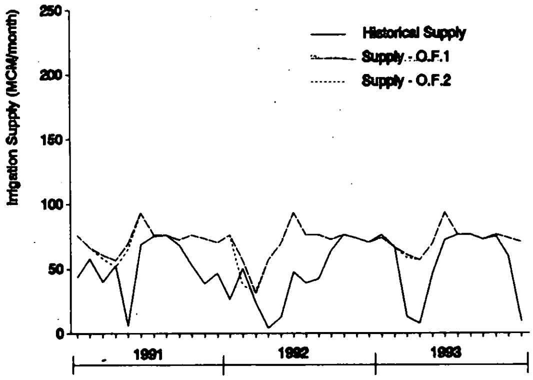
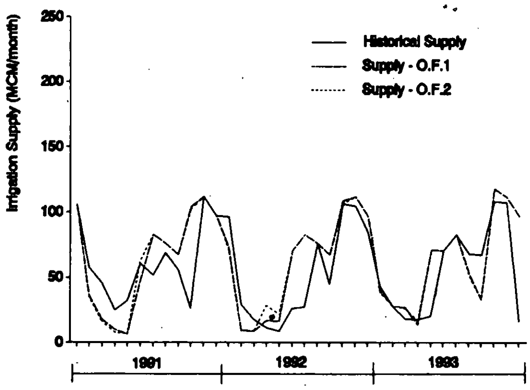
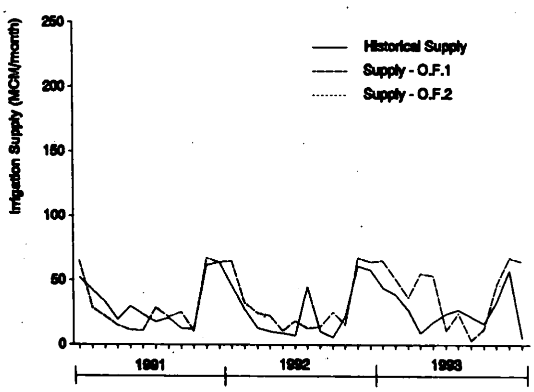
Figure 3
Comparison of irrigation water supplies obtained from the model with the historical supplies



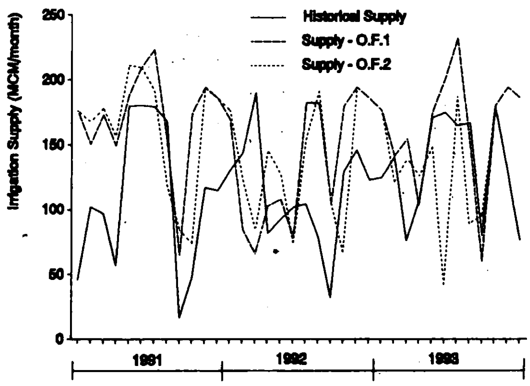
(a) Irrigation Water Supply to System H



(b) Irrigation Water Supply from Elahera anicut

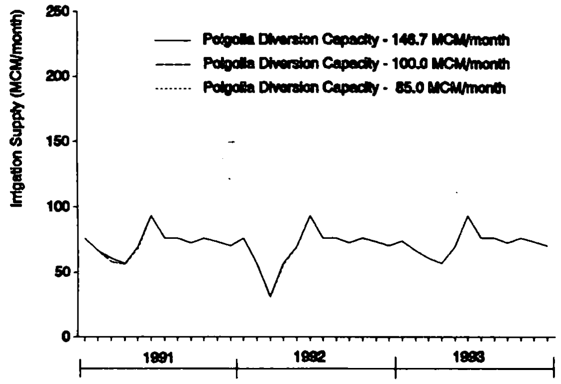


(c) Irrigation Water Supply from Angamedilla anicut

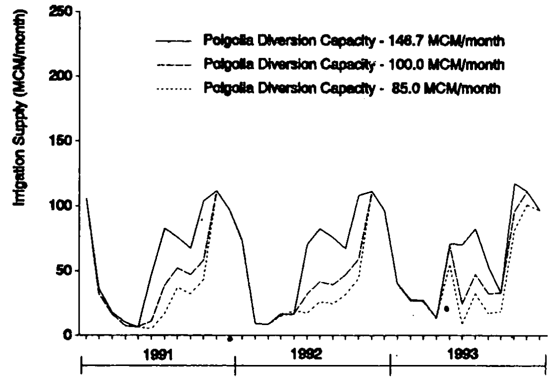


(d) Irrigation Water Supply from Minipe anicut

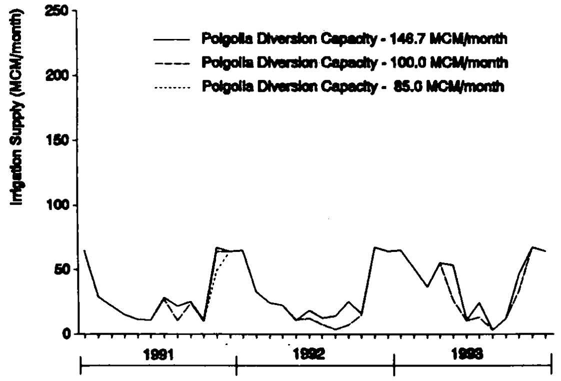
Figure 4
Comparison of diversion capacity of the Polgolla barrage



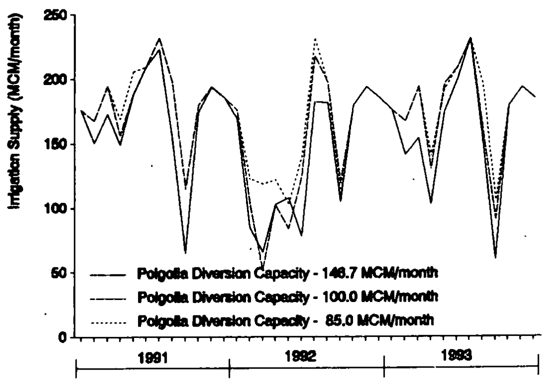
(a) Irrigation Water Supply to System H



(b) Irrigation Water Supply from Elahera anicut



(c) Irrigation Water Supply from Angamedilla anicut



(d) Irrigation Water Supply from Minipe anicut

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