A PLANNING STUDY ON THE OPERATION OF THE COMPLETE MAHAWELI SCHEME IN SRI LANKA WITH SIMULATION TECHNIQUES

by

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Introduction

In 1960's, several local and foreign consultant agencies have conducted a number of feasibility studies on the development of Mahaweli Ganga basin in Sri Lanka. According to the interim report published by FAO/UNDP with the assistance of Irrigation Department of Sri Lanka in 1967, titled "Mahaweli Ganga Irrigation and Hydro-power Survey - Ceylon", the Figure 1 schematically represents the proposed complete scheme in a simplified form. The actual system is quite complicated and this figure shows only the most important components to be developed with future expansion works. The entire system consists of eleven reservoirs - both the existing and proposed, and few diversion structures inter-connected by a number of river reaches, canals and tunnels in various localities. Different reservoirs are planned for different purposes; some are dual-purpose meeting both the irrigation and hydro-power demands, and others are single-purpose meeting either irrigation demand or hydro-power releases. The feasibility studies have estimated the water demands from some of the reservoirs for their intended purposes.

The objectives of this study are twofold: First, it is to verify whether the expecting demands are feasible in an optimal operation pattern which accounts for the integral behaviour of the system; if not, then to estimate the most feasible and optimal monthly demand patterns. Second, to derive the operating rule curves for different reservoirs in order to meet those demands with acceptable shortages.

The SIMYLD - II model, developed by the Texas Water Development Board in U.S.A., is the basic tool used in the simulation process. This model was subject to necessary modifications before application, so that the reality of operation is maintained for the current system. Simulation is carried out on a monthly basis, by using records of 30-year monthly inflow data measured at various gauging stations in the region. Results are presented in the form of the most feasible water demands and reservoir operating policies by interpreting the model output. Also, some useful conclusions have been drawn based on the above results.

Model Description

The computer coded SIMYLD-II simulation model used in this study, consists of a main program and fifteen sub-programs. It can be used to analyse water storage and water transfer within a multi-reservoir system and is designed to simulate both the small scale systems and large scale systems. Model provides two primary uses to the planner. First, to simulate the operation of the system subject to specified sequences of demands and hydrology. In this respect, model simulates the movement of water within the system in order to meet the specified demands in a given order

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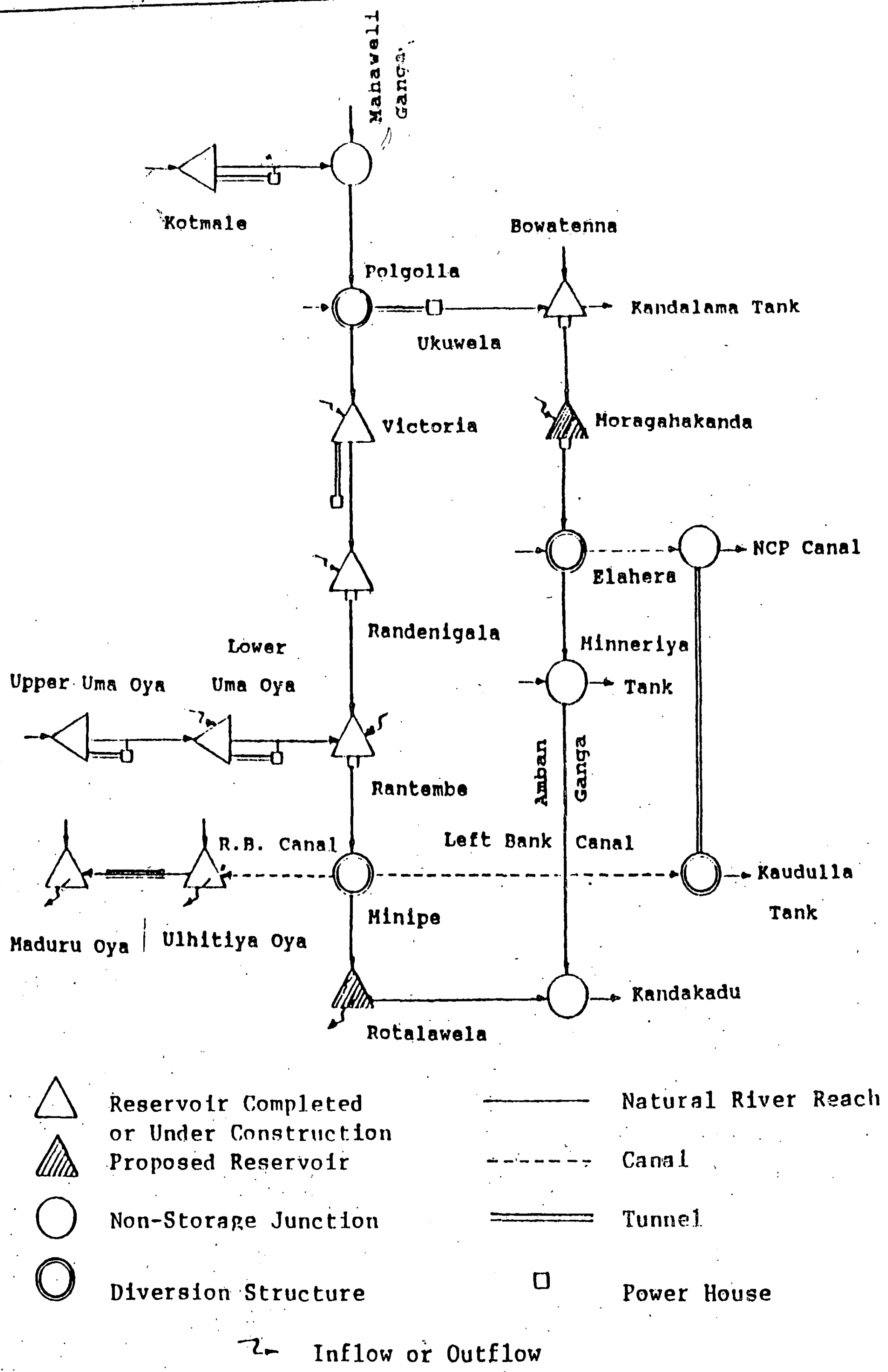

Figure 1: Network of Mahaweli Ganga Reservoir System Used in the Study

of priorities. The second use is to determine the Firm Yield of a given reservoir in the sytems. Here, the "Firm Yield" is defined as the maximum demand that can be met with acceptable shortages. For this purpose, an iterative procedure is used to converge on its firm yield at a given storage capacity.

The model is also designed to provide the user with flexibility in selecting operating rules for each reservoir. These rules are defined as the percentages of the reservoir capacity that are desired to be held at the end of each month. In addition, a priority ranking, used to determine the allocation of water between meeting demands and maintaining storage, is assigned to each reservoir.

The concept behind SIMYLD-II is that the physical water resource system can be transformed into a capacitated network flow problem. In making this transformation, the real system's physical elements are represented as a combination of two possible network components, namely nodes and links. A node analogues to a reservoir whereas a link represents a river reach, canal or a tunnel in the real system. The network is then converted into a closed circuit by introducing additional nodes and arcs so as to maintain the mass balance in any operational procedure. Moreover, the algorithm used in the model converts the pre-specified priority rankings into equivalent cost coefficients for various transfer elements in the network. Then it is solved as a cost minimization problem in transferring the moving material along various arcs. The Out-of-Kilter algorithm, which is considered to be a very efficient mathematical technique, is used as the optimization routine in solving this network flow problem. Also, some basic assumptions are made in the model development.

Mathematical Formulation

The mathematical formulation of the directed capacitated network flow problem is as follows:

Minimize:

$$Z = \sum_{ij} C_{ij} \cdot Q_{ij} \qquad (1)$$

Subject to:

$$\sum_{i} Q_{ij} - \sum_{i} Q_{ij} = 0 \; : \; J = 1,.N \qquad (2)$$

$$L_{ij} \leq Q_{ij} \leq U_{ij} \; ; \quad \text{for all } i,j \qquad (3)$$

where,

Q_{ij} = flow from node i to node j for time Δt,

C_{ij} = unit cost of flow from node i to node j for time Δt,

L_{ij} = lower bound of the arc from node i to node j,

U_{ij} = upper bound of the arc from node i to node j.

The set of constraints (2), satisfies the continuity of mass balance at all nodes in the network. Equation (3), describes the upper and lower limits on flows in all arcs in the network. The objective function to be minimized is expressed by equation (1). The "Out-of-Kilter" algorithm is used to solve this problem with optimal allocation of flows in different arcs.

System Behaviour in Operation

In the present study, the complete Mahaweli river system is assumed to be operated in the following manner.

The power plants at Kotmale, Ukuwela, Bowatenna, Victoria, Upper Uma Oya and Lower Uma Oya are supplied with water conveyed through their own tunnels. The other power plants at Moragahakanda, Randenigala and Rantembe are assumed to locate right below their dams. Therefore, during the operation of these reservoirs, water is regulated through the power plants allowing maximum usage for hydro-power generation. The irrigation demands are met by diversions made at Bowatenna reservoir and Minipe, Elahera anicuts. Water diverted by Bowatenna reservoir meets the Zone H irrigation requirement.

At Minipe anicut, part of the water is regulated along the left bank and the right bank canals. The right bank canal feeds both Ulhitiya and Maduru Oya reservoirs which supply the Zones C and B irrigation demands respectively. The possibility of meeting NCP (North Central Province) canal water requirement also is included, so that it is partly supplied by diversion made at Elahera anicut and the balance is pumped from the Minipe left bank canal through a tunnel as shown Figure 1. All water collected downstream of the system is diverted at Kandakadu anicut towards Zone A in meeting its irrigation demand and then allowing the excess water to flow into the sea at Trincomalle. The irrigation demands at various reservoirs and their estimated benefits are given in Table 1. Expected water releases for hydro-power generation have been estimated only for few reservoirs by the engineers of Ceylon Electricity Board (CEB) and they were used as initial values in this study. The most feasible and optimal releases are found and presented under the results of this paper.

Applications

Using the available record of 30-year streamflow data measured at various dam sites, monthly inflows to different reservoirs and other intermediate points were roughly estimated for that period. These data together with monthly precipitation, evaporation rates and expected demands are used as the input data to the model. In addition, following system parameters are identified and specified.

TABLE 1

Estimated Irrigation Demands and Benefits

Source	Annual Water Requirement ($10^6 m^3$)	Irrigable Area (ha) Existing	New
Bowatenna Reservoir	517.9	16950	23700
NCP Canal	3200.0	51160	107410
Elahera Canal	129.5	2000	2580
Ulhitiya Oya	442.7	1375	30660
Maduru Oya	693.0	2830	42950
Minipe L. B. Canal	924.8	28910	15540
Rotalawela Reservoir	200.0	4330	4160
Kandakadu	575.0	5830	30500

(1) Area/capacity relations, maximum and minimum capacities of reservoirs,
(2) Maximum and minimum transport capacities of canals and tunnels,
(3) Expected storage levels to be maintained in reservoirs,
(4) Desired reservoirs to be spilled in emergency situations,
(5) Sub-system reservoirs to be used to determine the hydrologic state of the simulation period, and
(6) Priorities of meeting demands and maintaining the storage levels.

A main disadvantage of SIMYLD-II model is that, it is unable to accommodate the non-consumable water demands such as hydro-power releases. Therefore, before application, some changes are made in the sub routines so that the tail water release at an upstream power plant would add to the immediate downstream reservoir after allowing for possible losses.

The model output is obtained in terms of,

(i) End-of-month reservoir levels to be maintained in different reservoirs,
(ii) Shortages in meeting demands,
(iii) Any excess volume of water to be spilled, on monthly basis.

With the given input data, first the model is run several times to obtain steady-state results by adjusting initial reservoir levels, so that the end-of-year reservoir contents are almost the same in different years. Then, attempts are made to find the most feasible demand patterns, wherever the expected demands are unable to meet. This is achieved in few trial simulations by adjusting the pre-specified demands propotionate to the shortages. In addition, the firm yields of the two reservoirs, Victoria and Randenigala are found by employing a special sub routine, so that the maximum shortage/demand ratio is less than 10%.

Rule Curve Derivation

In order to derive the rule curves of operation for different reservoirs, the end-of-month storage levels as given by the final model output over the entire simulation period are subject to a statistical analysis. The idea herein is to estimate the monthly reservoir levels to be maintained, so that the expected demands are met at an acceptable reliability. For this purpose, the Three-parameter Log Normal (LN3) distribution is selected to fit each set of monthly results. The principal advantage of this distribution is that it preserve the first three moments of a time series, hence makes forecasting at a sufficient reliability. Therefore, each set of end-of-month reservoir contents are fitted by LN3 distribution for each reservoir and distribution parameters are estimated.

Having computed the distribution parameters for all 12 months for a particular reservoir, few rule curves were estimated corresponding to different probability levels. The most appropriate rule curve is selected, so that it is much closer to the desired storage level pattern to be maintained in a year. Thus, rule curves are derived for every reservoir considering both the feasibility and the reliability.

Verification of Rule Curves

To confirm the derived rule curves and estimated demands, the model is re-run by reversing the priority allocations. In this case, the highest priority is given to maintain storage levels defined by the rule curves and low priorities are given to meet the demands. When analyzed the results, it is found that all the irrigation demands can be met without shortages, but some reservoirs indicate small shortages in meeting estimated hydro-power releases. Therefore, new demands are estimated for these reservoirs, so that the shortages would be minimal.

TABLE 2

Reservoir Contents to be Maintained at the End of Different Months

Reservoir	End-of-month Contents as Percentages of the Maximum Reservoir Capacity											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kotmale	59	53	30	23	35	56	62	66	66	74	71	71
Bowatenna	74	65	50	50	50	50	50	50	50	50	61	80
Moragahakanda	46	51	43	35	29	23	17	13	11	10	14	33
Victoria	82	81	70	60	59	67	73	70	63	66	74	81
Randenigala	72	74	73	68	59	53	50	48	49	57	74	76
Upper Uma Oya	68	75	29	24	24	24	24	24	24	24	31	44
Lower Uma Oya	58	75	26	23	17	17	17	17	17	23	35	47
Rantembe	83	67	21	21	21	21	21	21	21	21	38	80
Ulhitiya Oya	84	84	83	75	64	24	20	20	20	20	7	80
Maduru Oya	81	83	80	70	53	28	10	10	10	10	15	51
Rotalawela	75	73	63	45	28	13	12	12	12	12	24	51

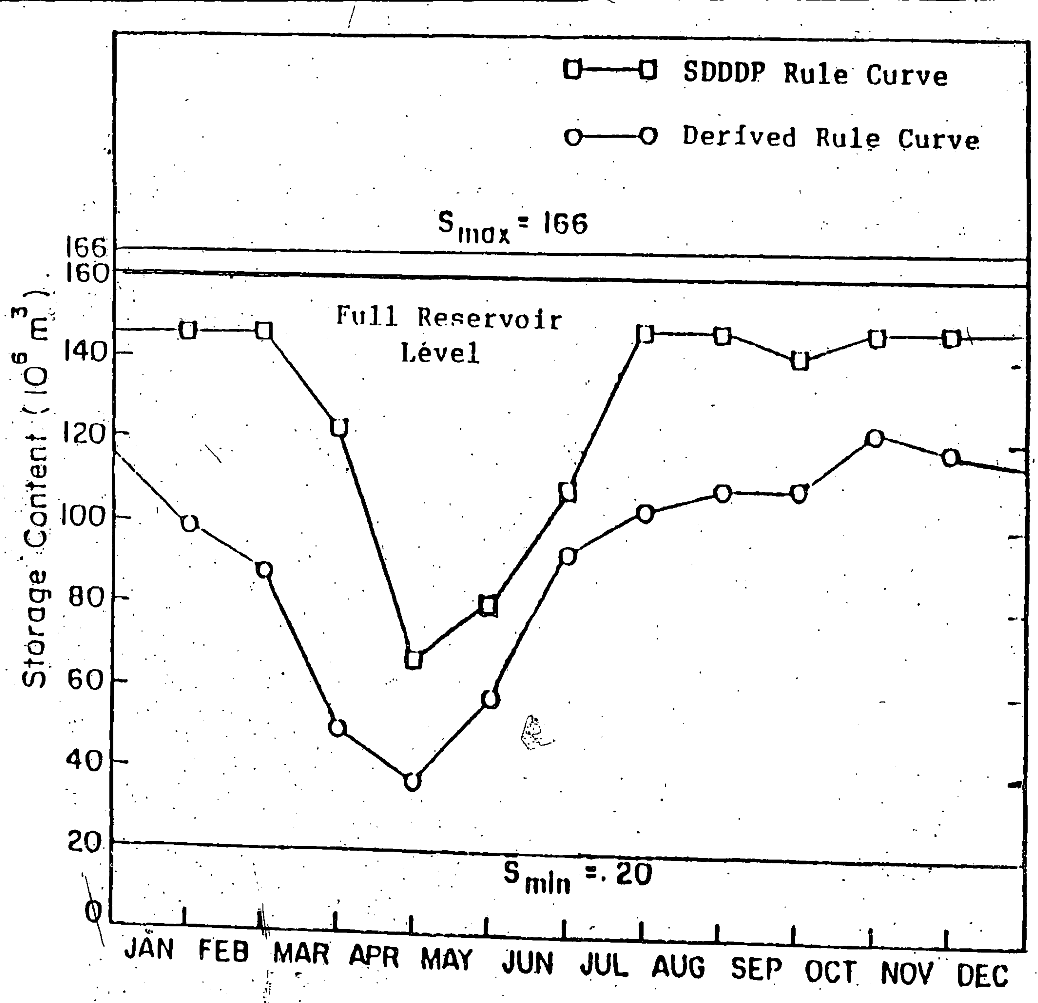

Fig. 2. Operating Rule Curves for KOTMALE Reservoir

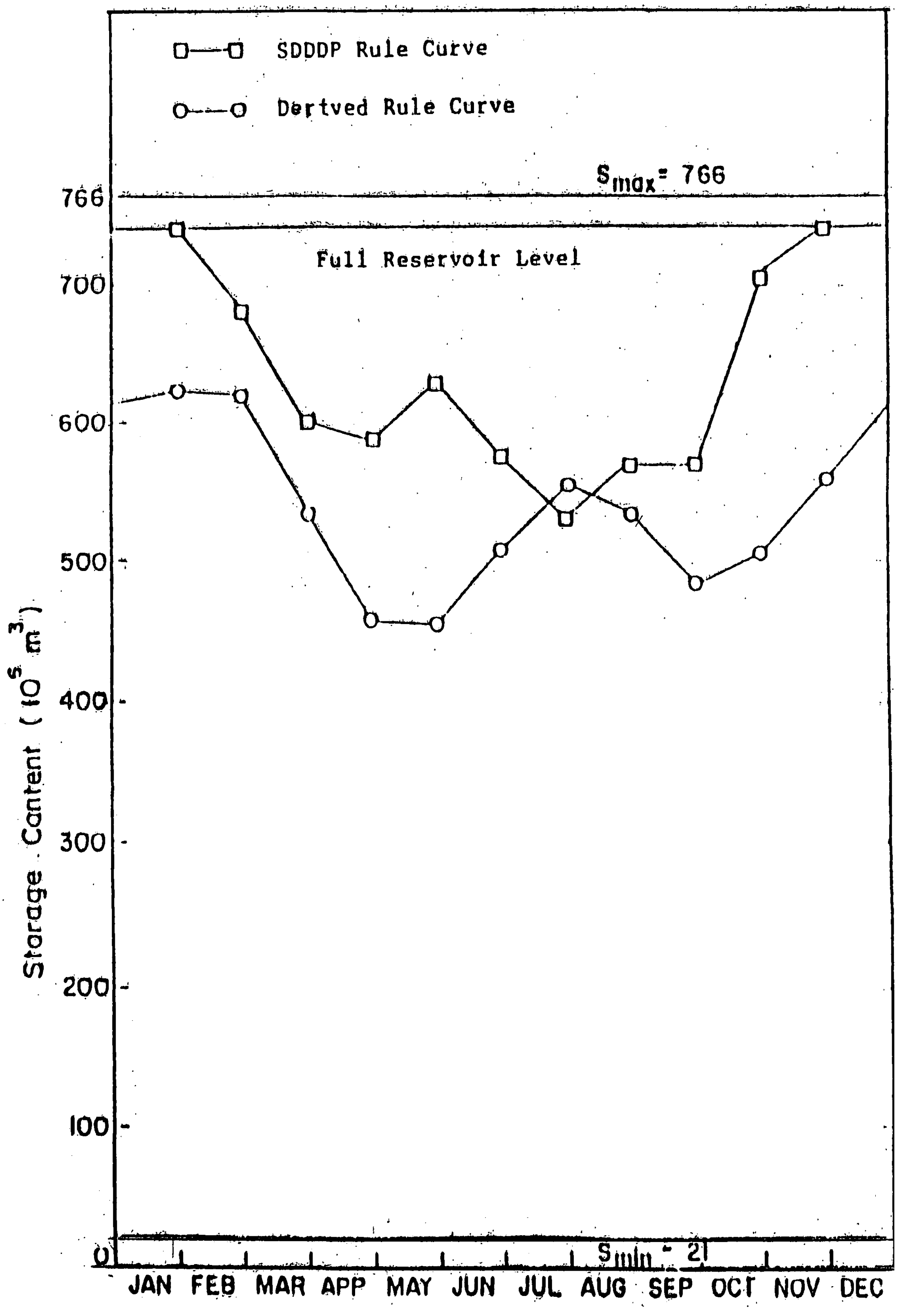

Fig. 3. Operating Rule Curves for VICTORIA Reservoir

Results and Discussions

The monthly rule curves for different reservoirs are expressed as percentages of the maximum reservoir capacity to be held at the end of each month and are listed in Table 2. According to these results, it is seen that the Moragahakanda reservoir has to be operated at low levels during most of the months in a year. Only about 50% of the potential capacity is utilized to store water except in a highly wet year. This is mainly due to the large downstream regulation maintained in meeting the NCP canal demand. Therefore, if NCP canal is to be implemented, the dam height of the Moragahakanda reservoir can be considerably cut down.

The reservoirs, Bowatenna, Upper Uma Oya, Lower Oma Oya and Rantembe have to be operated at very low levels during the period of April - October. This is due to the lack of inflows and necessity to maintain the high downstream flows.

The Figures 2 & 3 respectively represent the rule curves for Kotmale and Victoria reservoirs. For comparison, the rule curves derived in a previous study using Stochastic Discrete Differential Dynamic Programming (SDDDP), also are sketched in these diagrams. This approach considers the operation of an isolated reservoir, and therefore not applicable to a multi-reservoir system if integral behaviour is to be preserved. Eventhough, it provides some useful hints to the analyst in planning the multiple system through simulation techniques.

Corresponding to the above operating rules, the most feasible and optimal irrigation and hydro-power releases are estimated and given in Table 3. It is seen that all irrigation demands can be met without shortages. Some hydro-power demands are over-estimated and therefore unable to attain under the present hydrologic conditions.

The expected total firm energy production from power plants at Kotmale, Victoria, Randenigala, Upper Uma Oya, Lower Uma Oya and Rantembe is about 1,720 GWH. As estimated from this study, the most feasible firm energy production capacity from those power plants is about 1,520 GWH, which is almost 88% of the target.

The firm yields of the two reservoirs, Victoria and Randenigala (for hydro-power generation) also found and estimated to be 2,170 and 2,460 million cubic meters respectively.

Conclusions

Based on the results of this study following conclusions are drawn.

(1) Expected irrigation demands at various localities of the project area can be met without shortages through proper operation of the reservoirs and diversion structures.

(2) When the first priority is given to meet the irrigation demands, the expected water releases for hydro-power generation can not be fully met by the present hydrology. As estimated from the results of this study, only about 88% can be targeted.

(3) During operation of the system, the two reservoirs, Victoria and Randenigala are subject to less storage depletions and therefore can be used as storage reservoirs in a critical period.

(4) If NCP canal is implemented and its continuous demand is maintained, the Moragahakanda reservoir has to be operated at very low storage levels corresponding to a maximum retention of about 50-60% of the full storage capacity. Therefore, the proposed dam height can be considerably reduced.

(5) The derived operating rule curves correspond to the optimal benefits of water usage by minimizing the spills, the wastage of water.

In allocating the priorities for meeting demands, the first priority is given to irrigation demands and the second priority for water releases for hydro-power generation. Also, constant annual demands are assumed with fixed monthly variation patterns. Flexibility of the model was a great advantage in simulating the system behaviour under different operational conditions.

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REVIEWER'S COMMENT

The Mahaweli System configuration on which this study is based is given in the UNDP/FAO Report of 1968. Some of the component projects in this System may not be taken up for construction at all and even in some others already constructed or under active consideration, the design parameters have changed over the years. However, taken in the abstract, the study projects a methodology for the operation of a complex multipurpose water project.

TABLE 3

Possible Releases of Water for Irrigation and Hydro - power Production

Source (Reservoir or Canal)	Annual Volume of Release ($10^6 m^3$) Irrigation	Hydro-power Generation
Kotmale	-	718
Bowatenna	518	546
Moragahakanda	-	1000
Victoria	-	1446
Randenigala	-	1894
Upper Uma Oya	-	180
Lower Uma Oya	-	270
Rantembe	-	2730
Ulhitiya Oya	443	-
Maduru Oya	693	-
Rotalawela	160	-
Ukuwela Power Plant	-	950
NCP Canal	2880	-
Elahera Canal	130	-
Minipe Left Bank Canal	740	-
Kandakadu Diversion	778	-