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AN APPLICATION OF MATHEMATICAL PROGRAMMING IN PLANNING SURFACE WATER STORAGE[1]

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ABSTRACT: Designing a surface reservoir involves the concept of reservoir yield. This concept embodies three basic information items: hydrologic regime, active storage volume, and reservoir release policy. In the actual case presented below, the magnitude of the active storage was prescribed by a legal procedure, so that the planning issue became that of determining the reservoir yield given the hydrological information. A stochastic dynamic programming model was formulated to derive a schedule of seasonal optimal reservoir releases and their respective probabilities of occurrence. This schedule is the reservoir yield. The yearly cycle was divided into three seasons representing the actual climatic conditions, and conditional probabilities linking streamflows in consecutive seasons were estimated. An operating policy was postulated, based on the same set of legal decisions that prescribed the active storage volume, and target reservoir releases were assumed. Similarly, target storages at the end of each season were set up. The optimizing/minimizing criterion in the dynamic programming formulation was the sum of squares of deviations of actual releases and final storage volumes from their respective targets.
(KEY TERMS: dynamic programming; reservoir yields; surface storage.)

INTRODUCTION

The systems engineering approach was adapted to the planning of regional water resources more than 20 years ago (Maas, *et al.*, 1962), and since then considerable progress was made in this discipline, primarily due to advances in operations research and mathematical programming and to the spectacular improvements in the electronic computing equipment. Yet the engineers, planners, economists, and other professionals involved in the planning, design implementation, operation and monitoring of water resources systems were rather slow in making use of these powerful and sophisticated conceptual tools, so that documented examples of their real life application are still relatively rare. This paper offers an addition to this rather restricted list.

One of the major river basins on the Indian sub-continent, still largely undeveloped and which recently attracted some attention (Chaturvedi and Srivastava, 1981), is the Narmada. This river basin, with an estimated mean annual flow of 28 million acre-feet (Maf) – over 34 billion cubic meters (Bcm) – at a reliability of 0.75, has more than 30 potential reservoir sites on the main stem and tributaries. The last downstream reservoir site is Navagam, which is the subject of this paper.

THE PROBLEM

The Narmada river basin (see Figure 1) is shared by several states of the Union of India, as shown in Figure 2. This situation gave rise to an interstate dispute over the river waters, which was settled by the Narmada Water Disputes Tribunal. The Tribunal not only allocated the Narmada waters among several states, but also established a number of design criteria for the water resources system to be constructed (Narmada Water Disputes Tribunal, 1978). The Tribunal specified that the active storage capacity of the projected reservoir at Navagam should be 4.72 Maf (5.823 Bcm), a volume which is relatively small for effective regulation of the highly variable Narmada flow. Even after the construction of the other dams, and when the river basin upstream from Navagam will be fully developed (an event which is estimated to take place sometime in the 21st century), substantial flows of considerable variability are expected to reach the Navagam site. It appears important, therefore, to construct an analytical instrument which will enable planners to determine the reservoir yield at Navagam, under current conditions of quasi-virgin flow. Later, the model could be modified to represent conditions of full development of the river basin, and those at one or more intermediate stages.

A RESERVOIR OPERATION MODEL

System Configuration

1. The Hydrologic Regime. The fundamental information for the analysis of the reservoir yield at Navagam, in addition to its active capacity, K_a = 4.72 Maf, is the random unregulated flow, Q_t, in various within-year seasons, t. There does not seem to be a universally agreed definition of seasons in India.

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For example, according to one source (Vedula and Rogers, 1981), the monsoon season is considered to begin in June. The definition of seasons t (t = 1, 2, 3), given below, follows that of the Indian Meteorological Services.

t = 1, kharif (monsoon)	– July, August, September October;
t = 2, rabi	– November, December, January, February;
t = 3, hot weather	– March, April, May, June.

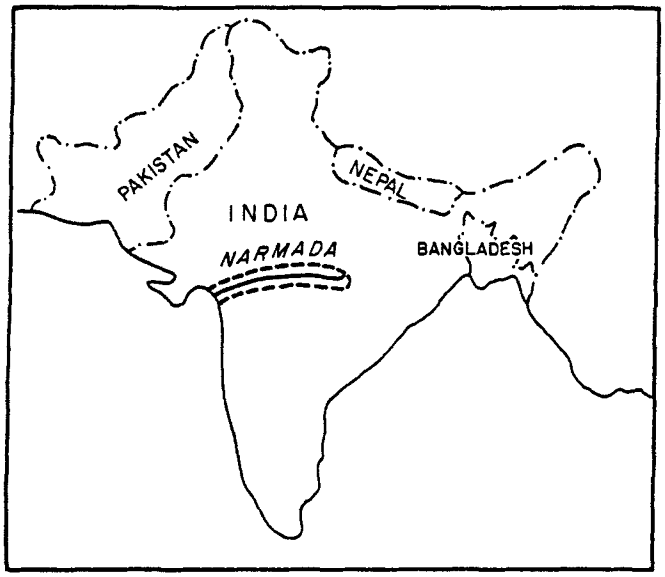

Figure 1. Map of India Showing Location of Narmada Basin.

The available streamflow data were collected during a 31-year period (1948-1970) at Garudeshwar, a place sufficiently close to the proposed reservoir site to be considered as representing the hydrologic regime at Navagam (Government of Gujarat, 1980). These data and the derived statistical parameters are shown in Table 1.

For the purpose of this analysis, it is convenient to represent the possible inflows in each period, Q_t, by a number of discrete values, each denoted by the index i, Q_{it}. Here i = 1, 2, . . . , 10. The discretization of streamflows is an important issue in itself. In this case, the values appearing in Table 2 were selected heuristically from the hydrological record shown in Table 1.

An important characteristic describing a hydrologic regime is the serial correlation of seasonal flows. An example of the empirical estimate of this statistical correlation of the Rabi following the wet season is shown graphically in Figure 3, where the straight line was determined by linear regression. This statistical dependence is the basis of empirically estimated conditional probabilities P_{ij}^{t}, that the probability of occurrence of flow $Q_{j,t+1}$ of magnitude j in season t+1 depends on flow Q_{it} of magnitude i in the preceding season t. Table 3 shows estimated values of P_{ij}^{t}. A more detailed statistical analysis of the hydrological data would have presumably "smoothed" the conditional probabilities shown in this table.

2. The Navagam Reservoir. The other variables relevant to the reservoir yield analysis are S_t (initial storage in season t) and R_t (volume of water released from reservoir during season t). Since S_t and R_t are outcomes, not only of a specific reservoir operating policy but also of the random inflows Q_t, they too are random variables exhibiting probability distributions.

The Navagam reservoir will be a multi-purpose facility. In addition to flood control and some streamflow regulating functions, it will supply irrigation water via the Navagam main canal and it will generate hydroelectric power. Two power plants are envisaged in connection with the Navagam reservoir: a riverbed power plant below the dam (Power Plant B) and one at the head of the main canal (Power Plant C) (see Figure 4). The reservoir release, R_t, is thus defined as

$$R_t = D_t + O_t \qquad (1)$$

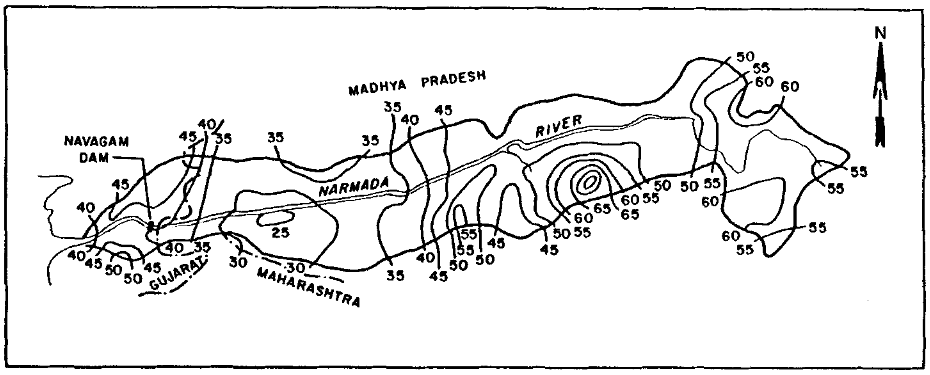

Figure 2. Annual Isohyetals, in Inches, in Narmada Basin, 1891-1968.

where D_t is the amount of water diverted into the Navagam main canal in season t, and O_t is the controlled flow through the river bed power plant in the same season, in Maf.

TABLE 1. Streamflows at Garudeshwar (seasonal flows, Q_t(Maf)).

No.	Year	t=1 Kharif	t=2 Rabi	t=3 Hot Weather	Total
1	1948	39.183	2.869	0.837	42.889
2	1949	31.095	2.379	0.591	34.065
3	1950	31.506	1.602	0.639	33.747
4	1951	14.935	0.990	0.608	16.533
5	1952	19.840	0.926	0.690	21.456
6	1953	21.735	1.002	0.315	23.052
7	1954	28.126	1.346	0.865	30.337
8	1955	36.827	2.938	1.347	41.112
9	1956	31.290	2.649	1.275	35.214
10	1957	18.016	1.191	0.638	19.845
11	1958	26.108	0.961	0.181	27.250
12	1959	47.890	4.005	1.406	53.301
13	1960	27.661	1.251	0.967	29.879
14	1961	36.766	2.550	0.490	59.806
15	1962	22.740	1.500	0.820	25.060
16	1963	20.485	1.236	0.640	22.361
17	1964	26.166	1.322	0.320	27.808
18	1965	9.454	0.443	0.255	10.152
19	1966	14.500	0.478	0.728	15.706
20	1967	28.367	1.579	0.427	30.373
21	1968	25.723	1.199	0.344	37.266
22	1969	38.372	1.349	1.948	43.669
23	1970	38.675	1.647	3.130	43.452
24	1971	31.107	1.834	0.545	33.486
25	1972	26.982	1.465	0.552	28.999
26	1973	60.563	2.303	0.620	63.486
27	1974	20.562	1.402	0.894	22.858
28	1975	36.046	1.729	2.167	39.942
29	1976	•	•	2.281	•
30	1977	37.728	2.483	1.029	41.240
31	1978	32.264	1.801	2.268	36.333

Statistical Parameters

Variable	Mean	Standard Deviation	Coefficient of Variability	Skewness
Kharif	30.024	11.537	0.384	0.835
Rabi	1.681	0.789	0.469	0.998
Hot Weather	1.026	0.873	0.851	1.956
Yearly Total	32.689	12.439	0.381	0.675

Source: Government of Gujarat, Irrigation Department, Sardar Sarovar Project, Identification Report, Gandhinagar, July 1980.

The range of possible initial storage volumes, S_t, is represented by discrete values, each denoted by the index k, k = 1, 2, . . . , 10. Values of S_{kt} appear in Table 4, which shows also volume-area relationships for the proposed reservoir. The discretization of S_t was made with 0.5 Maf increments, except for the last increment which was 44 percent larger.

TABLE 2. Discretization of Seasonal Streamflows at Navagam, Maf.

i	Kharif	Rabi	Hot Weather
1	9.45	0.46	0.22
2	15.10	0.97	0.35
3	19.73	1.22	0.53
4	22.24	1.38	0.64
5	27.00	1.58	0.85
6	31.45	1.79	1.00
7	37.81	2.34	1.34
8	47.89	2.56	2.24
9	56.77	2.90	3.13
10	60.56	4.01	3.95

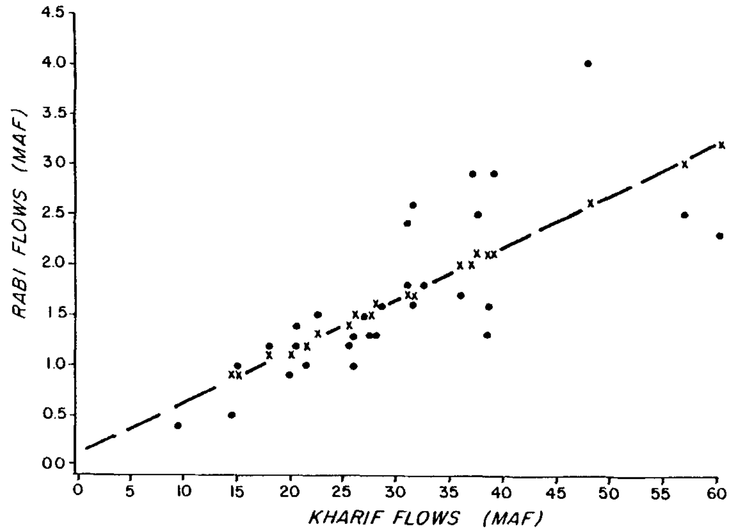

Figure 3. Statistical Dependence of Rabi Flows on Kharif Flows, Garudeshwar, 1948/9-1978/9.

Having defined the indices i and k in relation with inflows and storage volumes in season t, let indices j and ℓ denote corresponding inflows and storage volumes in season t+1. Thus, given an initial storage volume S_{kt} and an inflow Q_{it}, the final storage volume at the end of season t will be $S_{\ell,t+1}$, which is the same as the initial storage in season t+1. The storage $S_{\ell,t+1}$ is determined also by the release R which is related to the initial storage level (k), the final storage (ℓ), and the inflow (i) during the season t. The continuity condition for season t is

$$R_{ki\ell t} = S_{kt} + Q_{it} - E_{k\ell t} - S_{\ell,t+1}\,, \qquad (2)$$

where $E_{k\ell t}$ represents evaporation and seepage losses based on initial and final volumes stored in season t.

TABLE 3. Conditional Probabilities for the Rabi Season P^1_{ij}.

Kharif Flows Maf	Rabi Flows, Maf 0.46	0.97	1.22	1.38	1.58	1.79	2.34	2.56	2.90	4.01
9.45	1.00									
15.10	0.50	0.50								
19.73		0.25	0.50	0.25						
22.24		0.50			0.50					
27.00		0.14	0.29	0.43	0.14					
31.45					0.20	0.40	0.20	0.20		
37.81				0.17	0.17	0.17		0.17	0.33	
47.89										1.00
56.77								1.00		
60.56							1.00			

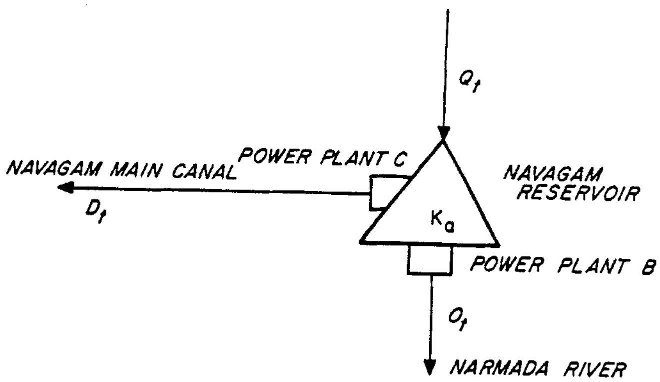

Figure 4. Schematic Representation of Navagam Reservoir.

TABLE 4. Elevation-Area-Volume Relations at Navagam.

Elevation ft.	k	Area, Million Acres	Capacity, Maf Gross	Active, S_{kt}
363	1	0.0282	2.98	0.00
380	2	0.0334	3.48	0.50
393	3	0.0388	3.98	1.00
406	4	0.0455	4.48	1.50
417	5	0.0534	4.98	2.00
426	6	0.0595	5.48	2.50
433	7	0.0651	5.98	3.00
400	8	0.0710	6.48	3.50
446	9	0.0793	6.98	4.00
455	10	0.0913	7.70	4.72

3. A Reservoir Release Policy. The continuity Equation (2) contains two interchangeable and equivalent decision variables: the reservoir release $R_{ki\ell t}$, and the final storage volume $S_{\ell,t+1}$. Regarding releases, the Tribunal specified that the net use of water abstracted from the Navagam reservoir (exclusive of evaporation losses), inclusive of an amount of 0.50 Maf/year to be delivered via the main canal to the state of Rajasthan, should vary in accordance with the degree of development of the Narmada river basin in the upstream state of Madhya Pradesh (Narmada Water Disputes Tribunal, 1978). Accordingly, the Tribunal defined three stages of development: I – practically no development in Madhya Pradesh; II – an intermediate state; III – full development and utilization of Narmada Waters in Madhya Pradesh. The Tribunal's specifications, emphasizing hydroelectric power generation, are shown in Table 5.

TABLE 5. Net Utilization of Narmada Waters at Navagam (Tribunal's Specification) (Maf/yr).

Stage	Navagam Canal	Riverbed Power Plant	Total
I	3.05	16.66	19.71
II	9.50	3.98	13.48
III	9.50	– – –	9.50

The Tribunal's decision for stage I was used for the derivation of the release targets, $R_{ki\ell t}$, required by the present analysis. The Navagam canal, which will supply the bulk of the water to the area to be irrigated by this project in the state of Gujarat, will presumably deliver 55 percent of its yearly allocation during the kharif season, 27 percent in rabi, and 18 percent in hot weather, in accordance with a proposed cropping pattern. The releases for the riverbed power plant were aimed to maximize power generation. Consequently, the assumed release targets are as shown in Table 6.

A Stochastic Dynamic Programming Formulation

In order to choose rationally from among the possible values of the decision variables $R_{ki\ell t}$ and $S_{\ell,t+1}$, a measure of system performance has to be specified. Let the measure of system performance be B, and a particular value of it, $B_{ki\ell t}$, be associated with an initial reservoir storage S_{kt}, an inflow Q_{it}, a release $R_{ki\ell t}$ and a final volume $S_{\ell,t+1}$. Since no information is available regarding net benefits potentially generated by the Narmada reservoir project, the measure of the system performance is expressed at this time only in physical terms (Maf), as the sum of squared deviations from a set of storage targets T_t^S and from a set of release targets T_t^R, specified for every season t. In this formulation, it is desired to minimize the measure of system performance $B_{ki\ell t}$ (Loucks, *et al.*, 1981).

TABLE 6. A Reservoir Release Policy at Navagam, Maf.

Season	Navagam Canal	Riverbed Power Plant	Total
Kharif	1.67	12.46	14.13
Rabi	0.83	2.55	3.38
Hot Weather	0.55	1.65	2.20
TOTAL	**3.05**	**16.66**	**19.71**

The targets T_t^S and T_t^R were given equal weights, both with respect to storage or release, and regarding the season t. At the time, no information was available to justify different weights to different targets. A detailed economic analysis would have led to an expression of system performance, $B_{ki\ell t}$, in monetary (rather than physical) terms, so that release targets and storage targets would be unnecessary. Data for such an economic analysis were not available.

Lacking an otherwise specified operating policy for the Navagam reservoir, storage targets T_t^S and release targets T_t^R will be assumed. Regarding storage, it is reasonable to assume that at the beginning of kharif (monsoon) season, the reservoir should be nearly empty in order to be capable of storing some of the very large flows anticipated during the season; thus $S_1 = 0.72$. At the end of kharif, the reservoir should be full – $S_2 = 4.72$ Maf. Assuming somewhat higher water utilization in rabi than in the hot weather season, it is postulated that $S_3 = 2.00$.

Regarding releases, the proposed targets are shown in the last column of Table 6.

A recursive backward-moving dynamic programming algorithm was developed assuming that the reservoir operation terminates at the end of season t = T, some year in the future. Let this terminal season be the hot weather (t=3). Define $f_t^n(k,i)$ as the total minimum expected value of the system performance n periods (seasons) to go in the operation of the reservoir, including the current season t, given that the initial storage volume and inflow in this season are S_{kt} and Q_{it}, respectively. Then, with only one season remaining,

$$f_3^1(k,i) = \min\{B_{ki\ell 3}\}\ \forall k,i;\ \ell \text{ feasible, given } k, i \text{ and } t. \quad (3)$$

With two periods remaining before the end of reservoir operation, the minimum value of the system performance criterion must reflect the operation of the reservoir during the last two seasons, rabi and hot weather. In both these seasons, the decisions will be affected by initial storages and inflows. However, the inflow during any one season is correlated statistically with the inflow in the immediately preceding season. The optimal operating policy for the last two seasons is then given by:

$$f_2^2(k,i) = \min_{\ell}\{B_{ki\ell 2} + \sum_{j=1}^{10} P_{ij}^2 \cdot f_3^1(\ell,j)\}, \forall k, i;$$

$$\ell \text{ feasible.} \quad (4)$$

In general,

$$f_t^n(k,i) = \min_{\ell}\{B_{ki\ell t} + \sum_{j=1}^{10} P_{ij}^t \cdot f_{t+1}^{n-1}(\ell,j)\}, \forall k,i;$$

$$\ell \text{ feasible}$$

$$n = 1, 2, \ldots,$$

$$t = 1, 2, 3. \quad (5)$$

Computer Results

A computer program was developed for the solution of the recursive equations (3) and (5) (Buras, 1981), and an optimal solution was reached in 12 iterations (n = 12). The results are shown in Table 7. They are valid only for the Stage I of the Narmada development plan.

Using the conditional probabilities P_{ij}^t, the computer results of the stochastic dynamic programming model can be used to estimate the joint probability of the initial storage volume S_{kt}, the seasonal inflow Q_{it}, and the optimal final storage volume $S_{\ell,t+1}$ which is specified for each k, i and t by the function $\ell(k,i,t)$. Denote this joint probability by PR_{kit}. Clearly, for each t,

$$\sum_k \sum_i PR_{kit} = 1 \quad (6)$$

The corresponding marginal probability distributions of initial storage volumes PS_{kt} and of seasonal inflows PQ_{it} are given by

$$PS_{kt} = \sum_i PR_{kit}, \qquad \forall k,t, \quad (7)$$

$$PQ_{it} = \sum_k PR_{kit}, \qquad \forall i,t. \quad (8)$$

Tables 8 and 9 list these marginal probabilities. Observe that the specified target storages $S_1 = 0.72$, $S_2 = 4.72$, and $S_3 = 2.00$ have very high probabilities of occurrence.

TABLE 7. Navagam Reservoir Optimal Release Policy.

Initial Level		Seasonal Flow		Initial Period	Release	Final Level	
k	Maf	i	Maf	t	R	ℓ	Maf
1	0.00	1	9.45	1	8.38	3	1.00
⋮		⋮					
1	0.00	10	60.56	1	55.72	10	4.72
2	0.50	1	9.45	1	8.37	4	1.50
⋮		⋮					
2	0.50	10	60.50	1	56.22	10	4.72
3	1.00	1	9.45	1	8.87	4	1.50
⋮		⋮					
4	1.50	10	60.56	1	57.21	10	4.72
5	2.00	1	9.45	1	9.35	5	2.00
⋮		⋮					
5	2.00	10	60.56	1	57.70	10	4.72
6	2.50	1	9.45	1	9.84	5	2.00
⋮		⋮					
6	2.50	10	60.56	1	58.19	10	4.72
7	3.00	1	9.45	1	9.83	6	2.50
⋮		⋮					
7	3.00	10	60.56	1	58.69	10	4.72
8	3.50	1	9.45	1	10.32	6	2.50
⋮		⋮					
8	3.50	10	60.56	1	59.18	10	4.72
9	4.00	1	9.45	1	10.31	7	3.00
⋮		⋮					
9	4.00	10	60.56	1	59.67	10	4.72
10	4.72	1	9.45	1	11.02	7	3.00
⋮		⋮					
10	4.72	10	60.56	1	60.38	10	4.72
1	0.00	1	0.46	2	0.42	1	0.00
⋮		⋮					
3	1.00	8	2.56	2	2.00	4	1.50
⋮		⋮					
10	4.72	10	4.01	2	6.62	5	2.00
1	0.00	1	0.22	3	0.14	1	0.00
⋮		⋮					
3	1.00	8	2.24	3	1.62	4	1.50
⋮		⋮			2.13	3	1.00
10	4.72	10	3.95	3	7.99	2	0.50

RELIABILITY OF SEASONAL RESERVOIR YIELDS

The maximum flow that can be made available at a specific site by the regulation of historic streamflows using a given size reservoir is referred to as the "firm yield" (Linsley and Franzini, 1979). This term implies an amount of water (Maf/season) which the reservoir will always be able to provide and larger amounts will be always available with less than 100 percent reliability. Hence, associated with any yield, there is a probability that it can be provided in any future year by a given size reservoir with a particular operating policy.

TABLE 8. Probabilities of Initial Storage at Navagam.

Period (Season)		Initial Volume, S_k		Probability
		k	Maf	PS_{kt}
Kharif	1	1	0.00	0.017
	1	2	0.50	0.623
	1	3	1.00	0.299
	1	4	1.50	0.061
Rabi	2	4	1.50	0.034
	2	8	3.50	0.076
	2	9	4.00	0.030
	2	10	4.72	0.860
Hot Weather	3	3	1.00	0.034
	3	4	1.50	0.038
	3	5	2.00	0.693
	3	6	2.50	0.235

TABLE 9. Probabilities of Seasonal Inflows Into the Navagam Reservoir.

Season	Kharif, t=1		Rabi, t=2		Hot Weather, t=3	
Index i	Q_{i1}	PQ_{i1}	Q_{i2}	PQ_{i2}	Q_{i3}	PQ_{i3}
1	9.45	0.034	0.46	0.087	0.22	0.082
2	15.10	0.107	0.97	0.154	0.35	0.136
3	19.73	0.134	1.22	0.135	0.53	0.093
4	22.24	0.066	1.38	0.161	0.64	0.282
5	27.00	0.237	1.58	0.125	0.85	0.122
6	31.45	0.162	1.79	0.091	1.00	0.064
7	37.81	0.157	2.34	0.063	1.34	0.097
8	47.89	0.041	2.56	0.090	2.24	0.061
9	56.77	0.032	2.90	0.052	3.13	0.031
10	60.56	0.031	4.01	0.041	3.95	0.032

The computer results of this analysis can be used to estimate the probabilities of the various seasonal releases. These (cumulative) probabilities are shown in Table 10. They are plotted in Figures 5, 6, and 7, which are the *reservoir yield functions* for Navagam for the Kharif, rabi, and hot weather, respectively.

Reservoir yields with reliabilities of 75 percent, 80 percent, and 90 percent are of interest. The 75 percent reliability is related to the level of risk accepted by the Tribunal ("three out of four years") regarding streamflow variability, on which its decisions were based. Reliabilities in excess of 90 percent are considered to have low confidence, since the accuracy of original data is probably less than 90 percent.

TABLE 10. Probabilities (Cumulative) of Seasonal Reservoir Releases.

Kharif		Rabi		Hot Weather	
Probability	Maf	Probability	Maf	Probability	Maf
0.031	56.218	0.041	6.624	0.032	5.325
0.063	52.428	0.094	5.514	0.064	4.505
0.086	44.042	0.184	5.174	0.097	2.866
0.104	43.548	0.247	4.954	0.195	2.715
0.134	34.456	0.338	4.404	0.255	2.598
0.168	33.962	0.463	4.194	0.285	2.375
0.261	33.468	0.624	3.994	0.407	2.225
0.276	27.602	0.759	3.330	0.536	2.015
0.421	27.108	0.859	3.080	0.654	1.998
0.423	26.613	0.874	2.873	0.746	1.905
0.535	23.152	0.913	2.379	0.805	1.708
0.653	22.658	0.951	2.375	0.830	1.578
0.660	22.163	0.966	2.363	0.847	1.544
0.674	18.393	1.000	0.898	0.866	1.526
0.724	17.898			0.943	1.217
0.726	17.403			0.962	1.106
0.755	15.882			0.983	1.087
0.855	15.388			1.000	0.616
0.859	14.893				
0.897	12.492				
0.927	12.478				
0.964	11.998				
0.966	11.503				
1.000	8.867				

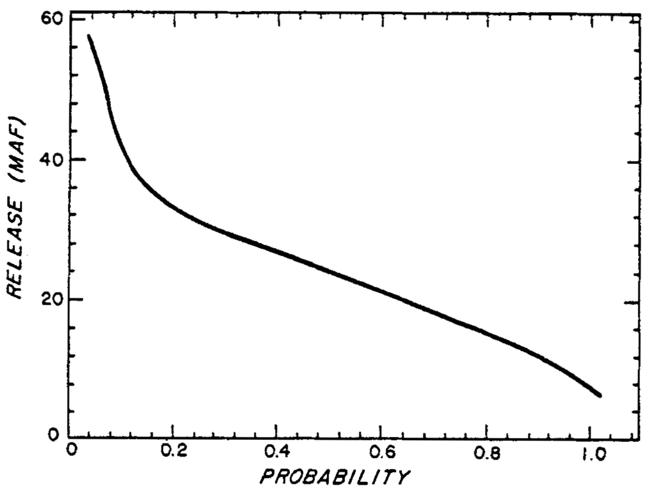

Figure 5. Kharif Reservoir Yield Function.

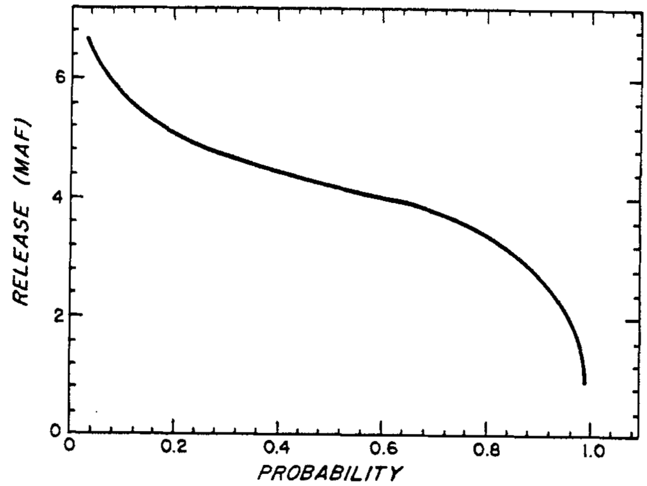

Figure 6. Rabi Reservoir Yield Function.

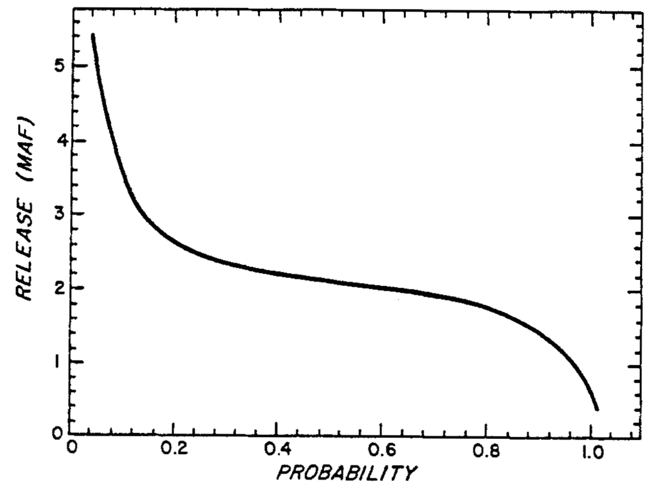

Figure 7. Hot Weather Reservoir Yield Function.

Now, the total releases, R_t are the sums of the flow diverted to the Navagam main canal, D_t, and the water passing through the riverbed power plant, Q_t (see Figure 4). Using the release policy shown in Table 7, the estimated reservoir yield at Navagam at three different levels of reliability (0.75, 0.80, 0.90) and its allocations between the main irrigation canal and the riverbed power plant in each of the three seasons is given in Table 11.

TABLE 11. Estimated Reservoir Releases at Navagam, Maf.

Reliability	Kharif			Rabi			Hot Weather			Total		
	D_1	O_1	R_1	D_2	O_2	R_2	D_3	O_3	R_3	ΣD	ΣO	ΣR
0.75	1.90	14.24	16.14	0.83	2.54	3.37	0.47	1.42	1.69	3.20	18.20	21.40
0.80	1.85	13.81	15.66	0.79	2.44	3.23	0.43	1.30	1.73	3.07	17.55	20.62
0.90	1.47	11.02	12.49	0.62	1.92	2.54	0.35	1.04	1.39	2.44	13.98	16.42

SUMMARY AND CONCLUSIONS

Planning of surface water storage is based on the concept of reservoir yield which is derived from the analysis of three basic items of information: the hydrologic regime, the active storage volume, and the release policy.

In many planning activities in the field of water resources, the hydrological regime is defined in terms of annual flows: means, variances, correlations, etc. This may be quite acceptable in temperature climatic zones where inter-annual and intra-annual variabilities have relatively small amplitudes. However, the high variability of the Narmada flows, as shown by the data in Table 1, makes the consideration of yearly flows useless for planning purposes. A more useful approach, taken in this study, is to consider seasonal flows.

Regarding active storage, the planning problem is usually stated so as to determine the volume which would yield a certain regulated flow, given a hydrological regime. In the case treated by this paper, the size of active storage was prescribed by legal procedures, so that the planning issue is inverted: for the given storage volume, determine the regulated flow which can be obtained from the hydrological regime, given a release policy.

As to release policies, the basic dilemma of operation is whether to release, in time of shortage, all the available water in order to meet best current demand or to keep part of it in storage in order to reduce future potential shortages (Major and Lenton, 1979). A commonly used rule is the "standard" operating policy (Fiering, 1967), which stresses target releases. The rule used in this analysis may be called the "final storage rule," since it stresses target final storage. This operating policy reflects a hedge against shortages caused by seasonal variations in streamflow.

The stochastic dynamic programming model formulated for the derivation of the yield functions of the reservoir used as optimizing (minimizing) criterion, the sum of squares of deviations of actual releases, and final storages from their respective targets. The algorithm produced a set of curves, one curve for each season, relating optimal total releases from the Navagam reservoir with their probabilities. In addition, the probabilities of initial storage volumes were estimated for each of the three seasons under steady-state conditions.

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