WATER RESOURCES BULLETIN
VOL. 13, NO. 5 AMERICAN WATER RESOURCES ASSOCIATION OCTOBER 1977

RESERVOIR YIELD: AN IMPORTANT ENVIRONMENTAL PARAMETER[1]

Leo M. Eisel[2]

ABSTRACT: Analysis of the storage-yield relationship can be used to help resolve conflicts between environmental values and water resources development. New Melones Reservoir in northern California presents a classic example of such a conflict between preservation of white water for recreational purposes and development of the site for a major multi-purpose reservoir. Analysis of the storage yield relationship for the proposed New Melones project indicates potential trade-offs between white water preservation and reservoir yield.
(KEY TERMS: environmental quality; water resources planning; reservoirs.)

INTRODUCTION

Reservoir yield has always been an important parameter in the design of water resource projects. Reservoirs have been designed and operated to ensure that specific releases could be made with particular frequencies. Developments in chance-constrained programming, and in other forms of stochastic programming, have permitted analysis of the relationship involving reservoir capacity, magnitude of release, operating policy, and release frequency (Loucks and Dorfman, 1975; Revelle, *et al.*, 1969; Eisel, 1972; and others). Detailed analysis of this relationship, however, has often been neglected in the design of water resource systems.

In recent years, opposition to some proposed reservoirs has developed because of the anticipated environmental degradation caused by inundation of land and water areas and because reservoir construction is incompatible with other uses of the site. Detailed analysis of the relationship involving storage capacity, magnitude of release, and frequency of release could be an important step in resolving conflicts which may arise between environmental values and construction of water resources development projects.

As an example, analyses have been performed concerning the New Melones Reservoir on the Stanislaus River in California. Currently under construction, this U.S. Army Corps of Engineers reservoir presents a typical example of conflicts between water resources development and environmental values.

[1]Paper No. 77041 of the *Water Resources Bulletin.* Discussions are open until June 1, 1978.
[2]Director, Illinois Environmental Protection Agency, Springfield, Illinois 62706.

THE PROBLEM

The New Melones Reservoir site on the Stanislaus River is approximately 35 miles northeast of Modesto, California, and will be operated by the Bureau of Reclamation as part of the Central Valley Project (see Figure 1). The 2,400,000 acft reservoir is currently under construction and when completed will provide: (1) irrigation water for the Central Valley Project; (2) flood protection for urban and agricultural areas; (3) low-flow releases for maintenance and enhancement of water quality and fish and wildlife; and (4) reservoir recreation. Two 150-megawatt generators may also be installed as part of the project. The New Melones Reservoir will replace the existing Melones Reservoir and inundate approximately 13 miles of the Stanislaus River including nine miles which are now used intensively for white water recreation. Potential inundation of this white water reach generated significant opposition to the project and created a classic conflict between pro-dam forces and environmentalists.

Table 1 indicates the miles of white water river that would be inundated by reservoirs of various capacities at the New Melones site as well as a site immediately downstream near the existing Tulloch Reservoir. A new reservoir at the Tulloch site would replace the existing Tulloch Reservoir with a larger reservoir which would have been an alternative to the New Melones project. This table illustrates the trade-offs between reservoir capacity and preservation of white water in terms of reduced reservoir capacity, but does not indicate the trade-offs between reservoir yield and preservation of white water. Investigation of this latter relationship could be important to objective resolution of the conflict between preservation and development. A relatively simple model can be employed to investigate the trade-offs between reservoir yield and preservation of white water.

TABLE 1. Inundation of White Water by Alternative Projects.

(The "New Melones" site is at the site of the project now under construction. The "Tulloch" site is an alternative site downstream near the existing Tulloch Dam.)

Site	Capacity (1000 acft.)	Miles of White Water Remaining
No Project	0	9.0
New Melones	450	7.5
New Melones	560	6.0
New Melones	1000	2.5
New Melones	1500	1.5
New Melones	2400	0
Tulloch	630	9.0
Tulloch	1000	9.0
Tulloch	2480	7.5

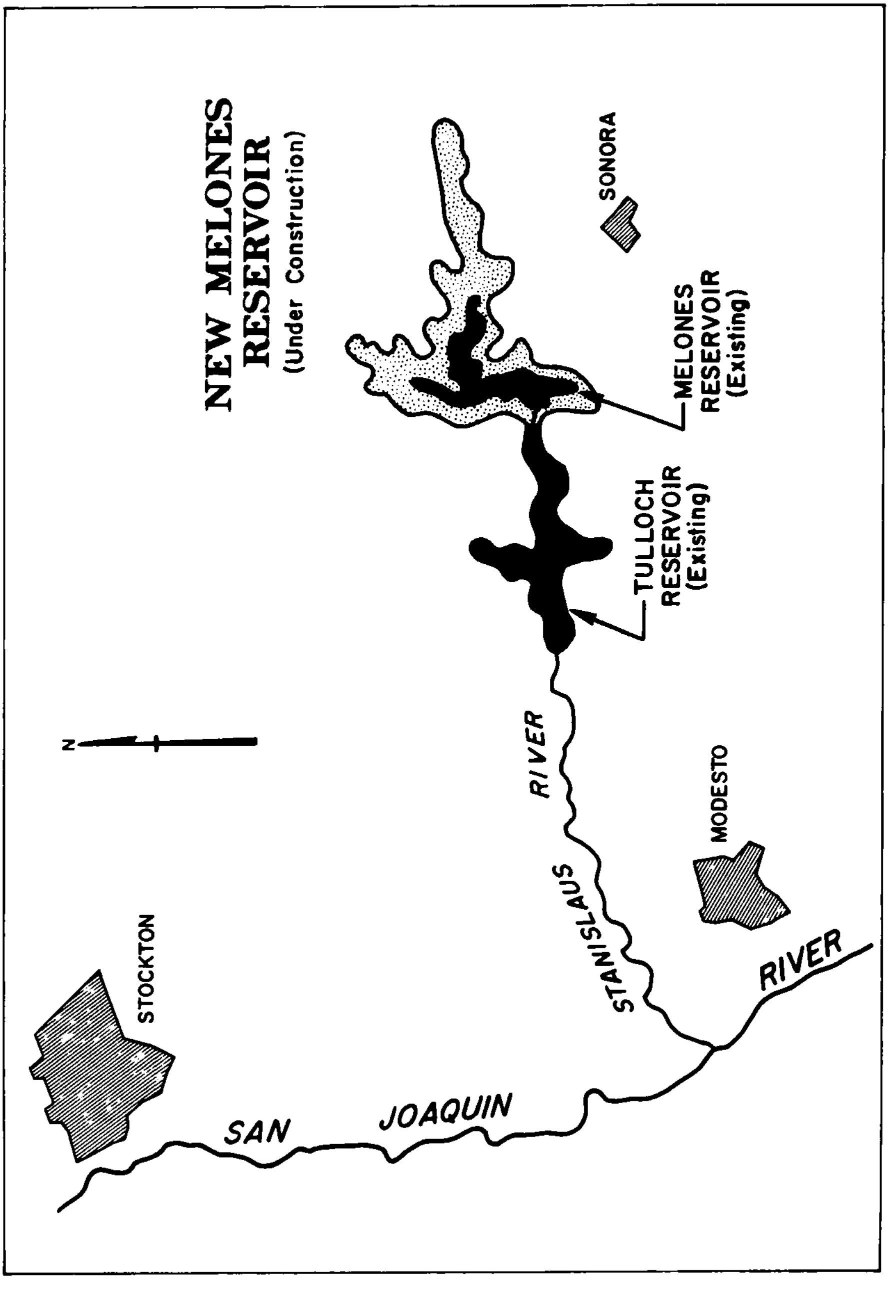

Figure 1. Location Map for New Melones Reservoir, California.

THE MODEL

A simulation model is developed to investigate the storage yield relationship. This model incorporates a lag-one Markovian flow generating model to produce annual flows which are, in turn, disaggregated into monthly flows by using a procedure developed by Valencia and Schaake (1973). The generated monthly flows are then routed through a simple reservoir model.

Data for estimating various parameters in the Markovian and disaggregation models were obtained from U.S. Bureau of Reclamation estimates for remaining monthly inflows to the New Melones Reservoir site after deducating all appropriated water (U.S. Bureau of Reclamation, 1972). Data were available for the 31-year period, 1923-1963. These data were suitable because only unappropriated inflows can be stored in New Melones Reservoir for irrigation or other purposes.

The generated monthly flows were routed through the reservoir according to proposed operating policies developed by the U.S. Army Corps of Engineers (1967). Flood control operation of the proposed reservoir requires that at least 450,000 acft of storage be reserved for flood control during winter and spring months. The vector of monthly flood storage reserves used in this model study is detailed in Table 2. For example, storage for irrigation, hydropower, recreation, water quality and fish and wildlife conservation could not exceed 2,400,000 – 450,000 = 1,950,000 acft in New Melones Reservoir during November; any excess must be dumped.

TABLE 2. Reservoir Storage Reserved for Flood Control, New Melones Reservoir. (U.S. Army Corps of Engineers, 1967)

(Thousand acft.)

Oct.	300
Nov.	450
Dec.	450
Jan.	450
Feb.	450
Mar.	450
Apr.	450
May	300
June	100
July	0
Aug.	0
Sept.	0

The irrigation operating policy for the proposed New Melones Reservoir has not been detailed by the Bureau of Reclamation or Corps of Engineers (California State Water Resources Control Board, 1973). However, a monthly distribution of expected irrigation water demand has been estimated by the Bureau of Reclamation for another California project comparable to the proposed New Melones Reservoir (Table 3). For purposes of model studies herein, the demand schedule detailed in Table 3 was used as a basis for developing a proposed irrigation operating policy for the New Melones Reservoir.

TABLE 3. Estimated Distribution of Monthly Demand for Irrigation Water, U. S. Bureau of Reclamation, Auburn, Folsom South Unit, California. (U.S. Bureau of Reclamation, 1974)

	Percent of Annual Total
Oct.	3.7
Nov.	0
Dec.	0
Jan.	0
Feb.	0
Mar.	0
Apr.	7.7
May	14.3
June	19.4
July	23.8
Aug.	19.4
Sept.	11.7
	100.0

The proposed project would also provide releases for water quality control and fish and wildlife preservation and enhancement in the Stanislaus River and lower San Joaquin River. A proposed release schedule was developed by the Corps of Engineers for fish and wildlife conservation (Table 4).

TABLE 4. Fish and Wildlife Releases Proposed New Melones Reservoir. (U.S. Army Corps of Engineers, 1967)

(1000 acft.)

Oct.	9
Nov.	9
Dec.	9
Jan.	6
Feb.	6
Mar.	6
Apr.	6
May	6
June	3
July	3
Aug.	3
Sept.	3
	69

The Bureau of Reclamation, under its agreement with the California Regional Water Quality Control Board, would make releases necessary to maintain certain water quality standards in reaches of the Stanislaus and San Joaquin Rivers, in addition to the fish and wildlife releases. Considerable uncertainty and disagreement have existed, however, concerning the release volumes required to maintain these standards (California State Water Resources Control Board, 1973). Disagreement has also existed concerning proper water quality standards (California State Water Resources Control Board, 1973).

An operating policy for hydropower generation was not developed in the course of the planning process for the proposed New Melones project (Corps of Engineers, 1967). Considerable uncertainty also exists concerning the hydropower function of the reservoir.

Because of the uncertainty and disagreement over operation of the reservoir for hydropower and water quality releases, these requirements were not incorporated into the simulation study.

The flood control, irrigation, and fish and wildlife conservation objectives were incorporated into four operating policies developed for model study purposes. For example, assume that the objective of the New Melones project is to provide an annual irrigation release of 60 percent of the mean annual unappropriated inflow of the Stanislaus at the reservoir site (approximately 335,000 acft), plus maintain the proposed fish and wildlife releases. This would represent an annual target release of about 201,000 acft for irrigation, plus 69,000 acft for fish and wildlife, for a total annual release of about 270,000 acft. This 270,000 acft release is denoted as operating policy A in Table 5. The 270,000 acft annual target would be released according to the monthly schedules detailed in Tables 3 and 4. Operating policies B, C and D in Table 5 were developed in a similar fashion for irrigation targets of 70, 80 and 90 percent of mean annual unappropriated inflows at the New Melones site.

TABLE 5. Reservoir Operating Policies.

Operating Policy	Annual Irrigation Target (% of Mean Annual Unappropriated Inflow at the New Melones Reservoir Site)	Annual Irrigation Target (1000 acft)	Annual Fish and Wildlife Conservation Release (1000 acft)	Total Annual Target Release (1000 acft)
A	60	(0.60) (335)=201	69	270
B	70	234	69	303
C	80	268	69	337
D	90	302	69	371

RESULTS

Five thousand years of monthly streamflow data were generated and routed through the proposed reservoir. The results of these routing studies are presented in Figure 2. The family of curves in Figure 2 demonstrates the relationship between reservoir yield and reservoir capacity for the various operating policies.

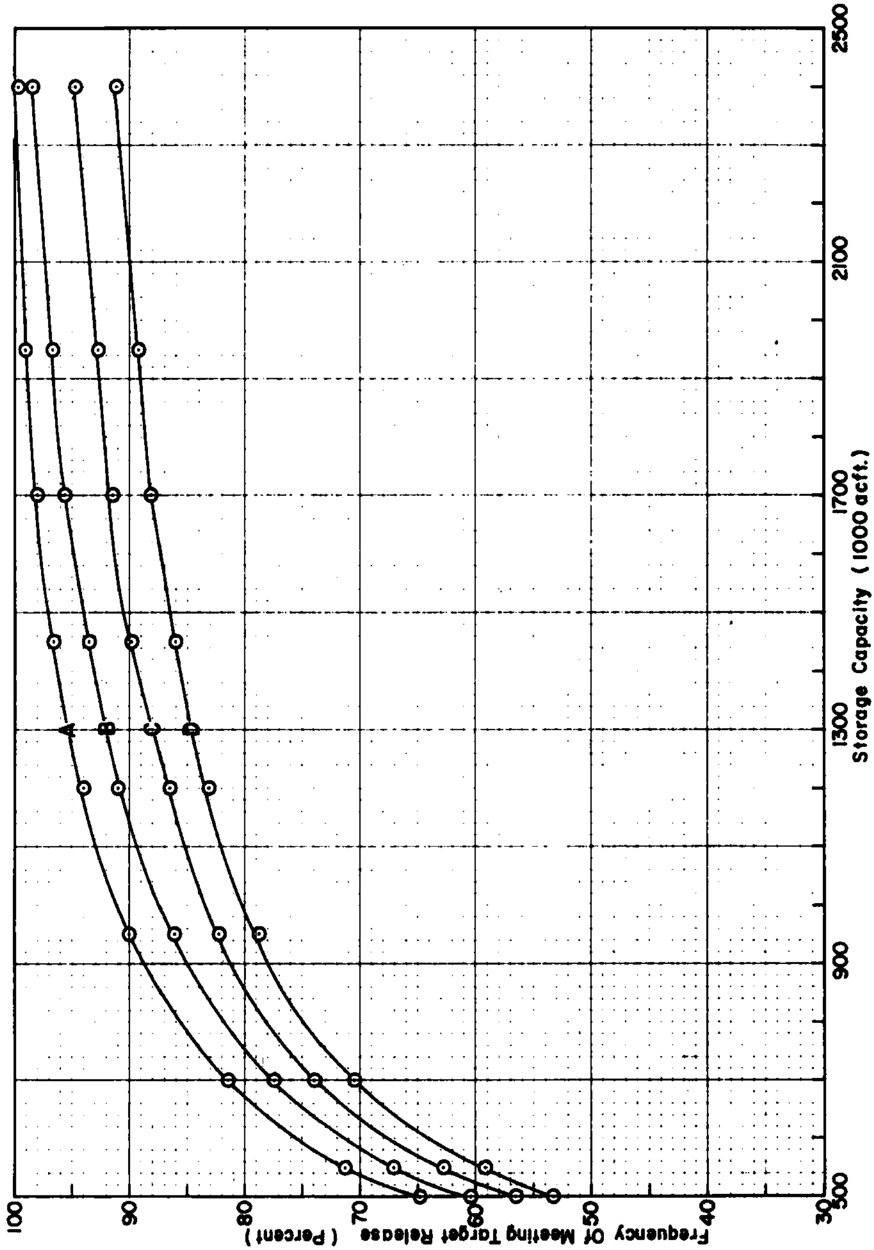

Figure 2. Family of Curves Indicating the Relationship Between Reservoir Capacity and Reliability of Making the Target Releases Required Under Operating Policies A, B, C and D. (See Table 5)

Curve D in Figure 2 indicates that with the 1,200,000 acft reservoir, it was possible to release the 90 percent mean annual inflow irrigation target, plus the fish and wildlife target release, with an 83 percent reliability over the 5000 years of monthly flows. Doubling reservoir capacity from 1,200,000 acft to 2,400,000 acft increased the reliability of making this same release to about 91 percent. Therefore, increasing capacity from 1,200,000 to 2,400,000 acft could be expected to increase reliability by 8 percent. Similar results for other target releases are demonstrated in Figure 2. In the case of an irrigation target release of 60 percent of mean annual streamflow (curve A), increasing reservoir capacity from 1,200,000 acft to 2,400,000 acft will increase reliability from about 94 percent to 99.6 percent for this target release.

Table 3 indicates that the largest irrigation water deliveries from the New Melones project might be required during the period June through September. The reliability of irrigation water releases from the New Melones Reservoir during these months would be of interest to potential irrigators using New Melones water. Table 6 presents a summary of the 5000 years of monthly simulation results for the June to September period. For example, with operating policy D, the total August target release could only be made in about 35 percent of all Augusts over the 5000 year period with the 500,000 acft reservoir. The reliability of meeting this target release could be expected to increase to 77 percent and 88 percent respectively with the 1,200,000 and 2,400,000 acft capacity reservoirs. Therefore, doubling capacity from 1,200,000 to 2,400,000 acft would increase reliability by about 11 percent in the case of operating policy D. Similar results for operating policies A, B and C are included in Table 6.

TABLE 6. Frequency of Making Monthly Target Releases From June to September with Various Reservoir Capacities and Release Policies.

Storage Capacity (1000 acft)	Release Policy	Frequency of Making Monthly Target Releases (percent)			
		June	July	Aug	Sept
500	A	73	64	54	48
	B	71	58	47	41
	C	68	53	41	33
	D	66	48	35	28
1200	A	95	94	92	91
	B	90	90	88	87
	C	90	86	82	80
	D	86	81	77	74
2400	A	100	100	100	100
	B	99	98	98	98
	C	96	95	93	92
	D	93	90	88	86

Figure 3 further demonstrates that the New Melones Reservoir release deficiencies may not be substantially decreased with the larger reservoir capacities. This figure indicates that for operating policy D, irrigators could expect to receive, in the average August, about 79 percent of that month's target release with the 1,200,000 acft reservoir and about 89 percent with the 2,400,000 acft reservoir. In other words, during the average August over the 5000 year period, about 79 percent (or 57,000 acft) of the 72,000 acft August target release could be expected with the 1,200,000 acft storage and 89 percent (64,000 acft) with the 2,400,000 acft reservoir. Table 7 provides similar results for the June to September period.

TABLE 7. Average Percent of Monthly Target that was Actually Released From June to September with Various Reservoir Capacities and Operating Policies.

Storage Capacity (1000 acft)	Operating Policy	Average Percent of Monthly Target that was Actually Released			
		June	July	Aug	Sept
500	A	76	69	59	51
	B	75	65	53	44
	C	74	61	47	37
	D	72	57	42	31
1200	A	96	94	93	92
	B	93	91	89	87
	C	91	88	84	81
	D	89	84	79	76
2400	A	100	100	100	100
	B	99	99	98	98
	C	97	95	94	92
	D	94	91	89	87

These estimates of reservoir yield for irrigation purposes would be decreased if reservoir operating policies for hydropower and water quality releases had been incorporated in the simulation model. Analysis of the simulation results, however, indicates that varying the monthly distribution of releases has relatively little effect on annual reliability in comparison to varying the total annual target release. This results because, for New Melones Reservoir, annual carry-over storage from wet years to dry years is of considerably more importance than carry-over storage from season to season. Therefore, the results presented for annual reliability (e.g., the probability of making a release equivalent to 90 percent of mean annual inflow at the New Melones site) should not change significantly if the monthly release pattern included water quality and hydropower releases as well as irrigation releases. The total water available for irrigation, however, would be reduced.

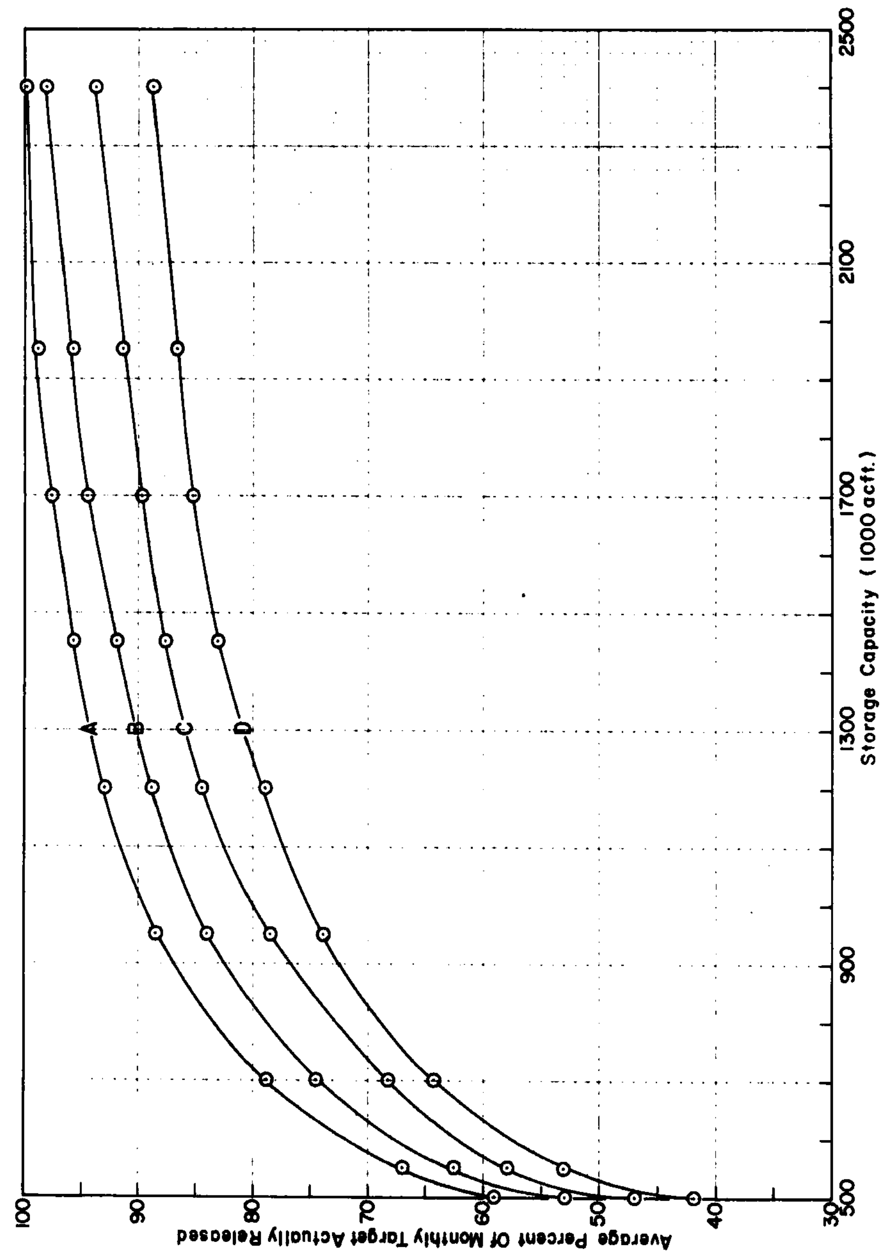

Figure 3. Family of Curves Demonstrating the Relationship Between Reservoir Capacity and Release Deficiencies in August for Operating Policies A, B, C and D. (See Table 5)

DISCUSSION

The results of the simulation analysis demonstrate that substantial increase in capacity of the New Melones Reservoir may produce generally modest gains in reliability. These results are not unexpected and confirm the general fact that the last few percent of certainty of yield require a large amount of storage. The objective of this analysis however, has not been to reconfirm this relationship but rather to demonstate, using the New Melones project as an example, how relatively simple analysis could assist in quantifying trade-offs among environmental values and the products of traditional water resources development. It is realized that New Melones Reservoir was originally authorized by Congress in 1944 and, consequently, was largely planned and designed before the recent development of public concern over environmental quality. Consequently, this analysis is not intended as criticism of past planning practices of the U.S. Bureau of Reclamation or the Army Corps of Engineers, but rather to highlight the potential of relatively simple analysis in resolving real world environmental conflicts in water resources development.

The results suggest that a smaller reservoir constructed a few miles downstream at the alternative site near the existing Tulloch Reservoir would have a yield nearly equivalent to the proposed project and would have preserved the nine-mile white water area as well. For example, the 1,200,000 acft reservoir at the alternative Tulloch site probably would have preserved all of the nine-mile white water reach. With this reservoir, the target release of 90 percent of mean annual streamflow plus the fish and wildlife releases would have been made with 83 percent reliability as compared to 91 percent reliability with the proposed 2,400,000 acft New Melones Dam; a decrease in reliability of eight percent. With the smaller release targets (operating policies A, B and C) the decrease in reliability with the smaller reservoir would have been even less.

The results provide some quantification of the trade-offs that exist between preservation of white water and reservoir yield. However, the desirability of increasing reliability from 83 to 91 percent must be expressed in dollars if it is to be considered adequately in the planning process. Development of agricultural production functions for areas receiving irrigation water from the project would be necessary to quantify the losses caused by achieving less than 100 percent reliability. These agricultural production functions would have facilitated comparison of the incremental economic benefits received from increased reliability with the cost of various alternatives achieving this increased reliability (a larger reservoir, conjunctive use of groundwater, etc.). However, in the case of the New Melones Reservoir, such analysis was not possible because the Bureau of Reclamation failed to present evidence of a specific plan for use of the water and did not indicate where the water conserved by the New Melones Reservoir would be used (California State Water Resources Control Board, 1973). Because of this lack of basic information, the analysis herein could not be developed further to investigate the economic trade-offs between increased reservoir capacity and certainty of yield.

LITERATURE CITED

California State Water Resources Control Board, New Melones Project Water Rights Decision, 1973. Decision 1422, Sacramento, pp. 14-15.

Eisel, L. M., 1972. Chance Constrained Reservoir Model. Water Resour. Res., 8(2), pp. 339-347.

Loucks, Daniel P. and Philip J. Dorfman, 1975. An Evaluation of Some Linear Decision Rules in Chance Constrained Models for Reservoir Planning and Operation. Water Resour. Res., 11(6), pp. 777-782.

ReVelle, C., E. Joeres, and W. Kirby, 1969. The Linear Decision Rule in Resource Management and Design. 1, Development of the Stochastic Model. Water Resour. Res., 5(4), pp. 767-777.

U. S. Army Corps of Engineers, 1967. Design Memorandum No. 10, New Melones Reservoir, Stanislaus River, California. Sacramento.

United States Bureau of Reclamation, 1972. Exhibit No. 28 in the Matter of Applications 14858, 14859, 19303, and 19304, to the California State Water Resources Control Board. Sacramento.

United States Bureau of Reclamation, 1974. Amendment to the Final Environmental Impact Statement and Supplement on Auburn-Folsom South Unit. Sacramento, p. 58.

Valencia, Dario and John C. Schaake, Jr., 1973. Disaggregation Processes in Stochastic Hydrology. Water Resour. Res., 9(3), pp. 580-585.