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14. ABSTRACT
Droughts have occurred in the Potomac and Delaware River basins, 1962-67 and in California, 1975-77. Selected reservoirs in these basins are examined to identify their operation during the drought period. Different ways of responding to drought are also analyzed in this report.

15. SUBJECT TERMS
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FOREWORD

This research document is a Master's Thesis prepared by the author as partial fulfillment of the requirements for a Master of Science Degree, Department of Civil Engineering, University of California, Davis. The thesis is entitled "Historic and Current Reservoir Operation of the Delaware and Potomac River Basins and the State of California During Drought". This subject should be of interest to Corps of Engineers planners and operations managers. It contains information on a variety of methods used for operating and managing multiple-purpose reservoirs during drought conditions and the effectiveness of such methods. The Hydrologic Engineering Center is grateful to the author for granting permission to reproduce this thesis as a research document.

ACKNOWLEDGEMENT

I would like to thank the United States Army Corps of Engineers, Institute of Water Resources (IWR) for funding my research trip to the Delaware and Potomac river basins. I would also like to thank the people who took time to meet with me, during that trip and in California, to discuss their region's drought experience, identify pertinent drought operation issues, and provide copies of unpublished studies, legal and informal agreements, annual operation summaries, and other written material. The information I obtained from them forms the core of this report. These people are: John E. McSparran and William Gast of Pennsylvania's Department of Environmental Resources; Daniel P. Sheer of the Interstate Commission of the Potomac River Basin; Jim Dalton and Jim Crews of IWR; Robert Fish, Deputy Delaware River Master (Retired); William Link, Michael Cowan, and Chester Bowling of the Central Valley Project; and Larry Gage of California's Department of Water Resources.

A special thanks to Kyle Schilling of IWR for guiding me through my visit to the East Coast, making published material available, and allowing me access to his personal files.

A grateful thanks to William Johnson, my graduate studies advisor, for his support, guidance, and criticism throughout this undertaking.

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I INTRODUCTION

During the past 25 years, the United States has experienced two of its most severe droughts. One occurred in the Northeast during 1962-1967. The other happened from 1975 through 1977 in the Great Plains and the states along the West Coast. Many of the water supply systems in these areas are based upon surface reservoir storage. This report discusses the drought response of three regional reservoir systems within these drought impacted areas. Both single reservoir and multiple reservoir operations are examined. The study areas are the Potomac River Basin, the Delaware River Basin (both on the East Coast) and the state of California.

The reservoir systems of these regions are chosen for study for several reasons. First, they are hydrologically diverse. California is an arid region. The Delaware and Potomac basins are humid. Secondly, all three are technically, institutionally, and politically complex. Studying complex reservoir systems is more beneficial than studying simpler reservoir because issues involved in drought operation of a large reservoir system are broader in scope and can be narrowed to apply to smaller systems. Thirdly, the droughts in these areas were severe and the impacts of their water supply management were widely felt. Finally, drought operation plans have been developed for almost all of the reservoir systems studied as a result of their drought experience.

Although drought is welcomed by no one, once it has occurred, it provides a water resources manager or planner with very valuable information. Actions which were taken in desperation during a drought exemplify a reservoir system's flexibility; its strengths and weaknesses. It is important to learn from past experiences and the experience of others. Therefore, the primary purposes of this report are to investigate management responses which occurred during drought and to investigate and assess current reservoir drought operation plans. In addition, conclusions and observations regarding reservoir drought operations are made.

The analysis is not restricted to one aspect of water resources management. It addresses whatever aspect, whether institutional, legal, technical, or social, that pertains to the operation discussed. It attempts, through a series of case studies, to merge the academic and the actual realms of reservoir operation to produce accurrate conclusions and realistic recommendations for operations studies and institutional responses. Methods of investigation included interviews, published reports and articles, unpublished reports, inter-agency correspondence and historical data. A research trip was taken to Washington D.C., Ft. Belvoir, Virginia, and Harrisburg and Milford, Pennsylvania which, in addition to providing access to much of the printed material referenced in this report, allowed the author to meet with the water system managers or analysts directly involved with past or current drought operations of the Delaware and Potomac river basins. These interviews greatly helped the author to understand the historic and current water system management issues of the basins and the key components to their drought management plans.

I.A. THE STATE OF CALIFORNIA

I.A.1. The 1976-1977 Drought

Precipitation in California's major river basins during the 1976-1977 water year (October 1-September 30) averaged 35% of normal. The low precipitation combined with the dry conditions of the previous year to produce runoff during 1976-77 which was 24% of normal and the lowest recorded value for the Sacramento River Basin. About 75% of

California's available water supply originates within this Basin, which lies north of the city of Sacramento, while 75% of its water requirements occur south of this point (see Figure 1). The 1976-1977 extremely low runoff produced critical water shortages in the Sacramento and San Joaquin river basins plus two-thirds of California's coastal area. Essentially, only its southern-most quarter did not experience significant water shortages. In all, 47 of California's 58 counties were declared disaster areas (U.S. Bureau of Reclamation, 1977a).

I.A.2. Water Supply Systems

Two major water supply systems; the Central Valley Project, operated by the Federal government, and the state-operated State Water Project, store water in reservoirs in the Sacramento River Basin and transport this supply via natural channels, canals, and an aqueduct to users in the San Joaquin Valley and further south. Figure 1 includes the basic components of these systems plus the specific case studies which are investigated in this report. The Orland Project serves irrigation needs and is discussed in this report as an example of an operation which consolidates reservoir storage to decrease evaporation losses. Success Lake, on the Tule River in the southern San Joaquin Basin, is an example of an operation which releases storage from a normally unused pool. It is one of several reservoirs providing water supply and flood control on streams which empty into a land-locked lake bed (the Tulare Lake Bed). Finally, San Luis Reservoir is part of the Central Valley Project and the State Water Project and is cited as a critical component for illustrating water supply loans.

I.B. THE EASTERN RIVER BASINS

I.B.1. The 1962-67 Drought

FIGURE 1: Selected Water Supply Systems in California

The 1962-67 drought effected the entire northeastern arm of the Nation, from the Atlantic Ocean west to the Great Lakes and from Maine south through Virginia. In 1965, New York City's water supply system was stressed to the point where the city refused to abide by a Federal Supreme Court decree regarding flow maintanence in the Delaware River. In other words, legal and institutional arrangements were unraveling and water resources management chaos was approaching.

Communities along the Potomac River also experienced grave shortages during 1965 and 1966. Based upon the worst drought of record for that time, the minimum flow in the Potomac River was believed to be 500 million gallons per day (mgd). For one week in September of 1966 the flow was below this value, dropping to a minimum of 388 mgd (Sheer, 1983). Water supply reservoirs in the area were also nearing depletion. A hurricane reprieved the supply.

This drought prompted water supply system studies at many institutional levels. Local, state, and Federal agencies began seeking remedies to their water supply situation. Two current reservoir operation schemes which evolved from some of these initial studies are presented in this report. They are the drought operation plans for water supply in the Potomac River Basin and the Delaware River Basin.

I.B.2. Reservoir System Purposes and Operations

The Delaware River Basin's water resources system is technically, institutionally and legally complex. The basin includes parts of the states of New Jersey, New York, Pennsylvania, and Delaware. The water resources system supports an out-of-basin diversion providing half of the water supply for New York City, recreation within the basin, an out-of-basin diversion to New Jersey, and required Delaware Estuary outflow. The current reservoir operation plan for drought evolved directly from the 1965 drought experience. Both the plan and the historic drought experience are presented in this report.

The Potomac River reservoir system operates primarily to serve three water supply agencies located near the mouth of the river and to maintain required Potomac Estuary outflow. Until recently, these three agencies operated independently. Each water sypply district was severely stressed during the 1960's drought and, to a lesser degree, by a local drought which occurred in the mid-1970's. The experience of one of these districts, the Fairfax County Water Authority, during 1977 illustrates how drought risk analysis can alter water supply operations and is presented in Section II.B.3. The current operations plan for the Potomac River Basin, which coordinates the operation of the three districts, is presented in Section III.C. It demonstrates how coordinated system operation can increase water supply.

The location of the Delaware River and the Potomac River basins are shown in Figure 2. Location of specific reservoirs and other water supply system components are shown in later, more appropriate, sections.

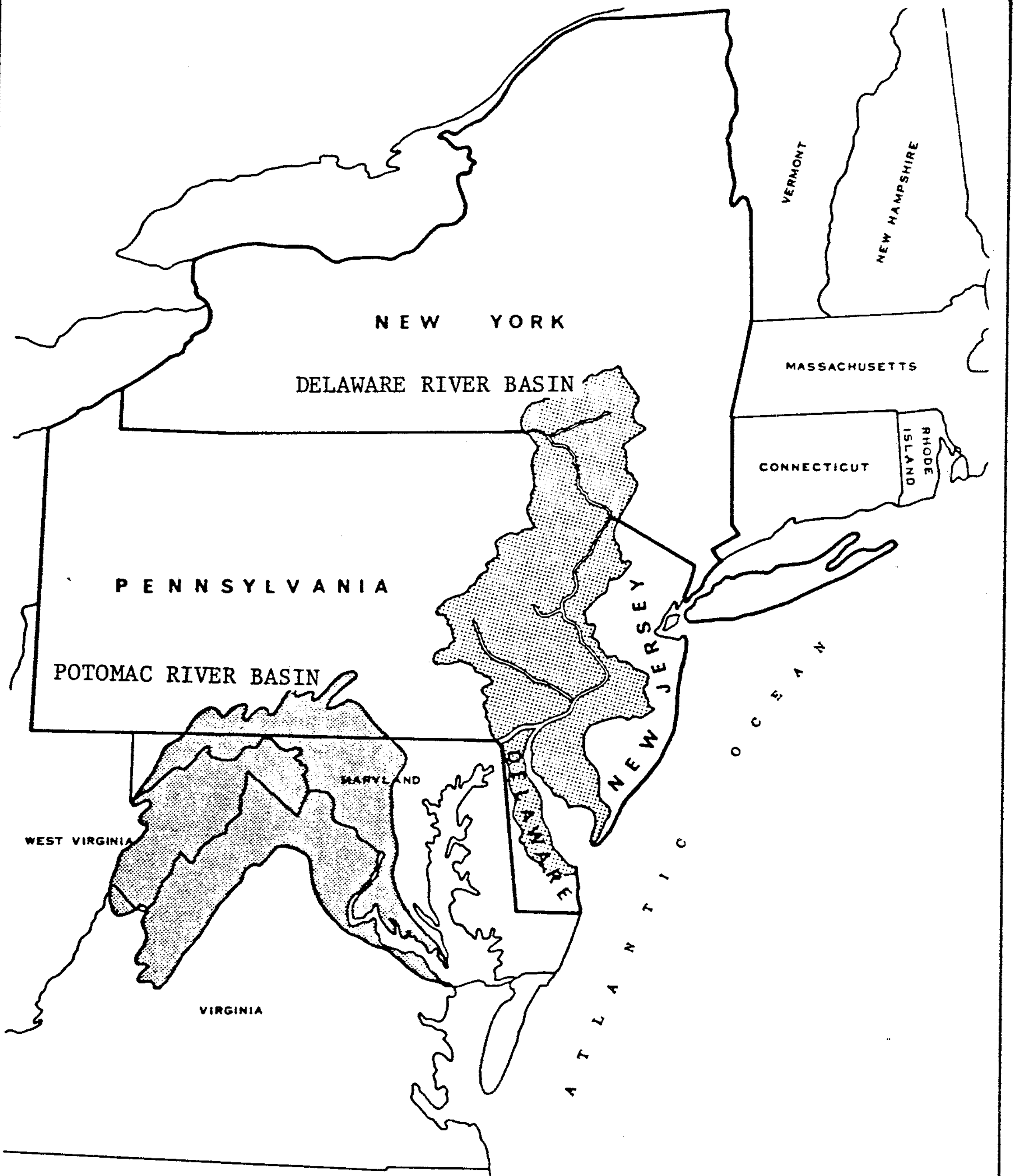


FIGURE 2: The Delaware and Potomac River Basins
(Adapted from Hogarty, 1970)

II. DROUGHT OPERATIONS

This section documents reservoir operations during actual droughts. Four of these operations had as their purpose to increase municipal and industrial (M and I) or agricultural water supply during drought. They are analyzed for constraints to implementation, time of implementation, and the public and institutional interaction required for implementation. In addition, the increased water supply provided by the operation is quantified.

Three other case studies are presented which address diverse issues of reservoir operation during drought. Operation of the Shasta/Trinity System in California illustrates multipurpose reservoir operation during drought. This study discusses the extent to which each purpose was met and emphasizes physical, legal, and other constraints to operations. Drought operations for Lake Oroville, near Oroville, California discusses the economic impacts upon hydropower revenue and the advantage provided by coordinated reservoir system operation. Finally, reservoir operation in the lower Potomac River Basin is presented to show how drought risk analysis alters water supply operation objectives and to provide background information to a discussion on the current water supply operation. Table 1 contains a list of the case studies presented in this section.

II.A. OPERATIONS WHICH INCREASE SUPPLY

Study of reservoir operation during the droughts in California and the Delaware River Basin identified four methods of reservoir management which can produce additional supply in the midst of a drought. These methods are 1) Water Supply Loans, 2) Consolidation of Storage, 3) Minimum Pool Release, and 4) Project Purpose Change. Each method is described in the following four sections. An estimation of the quantities of water supply which could be made available by each

TABLE 1: DROUGHT OPERATION CASE STUDIES

METHOD	FACILITY
Water Supply Loans	San Luis Reservoir, CVP, California
Consolidation of Storage	Orland Project, CVP, California
Minimum Pool Release	Success Lake, Tule River, California
Project Purpose Change	Francis E. Walter and Prompton Reservoirs, Lake Wallenpaupack and the Mongaup system, Delaware River Basin
Multi-Purpose Operation	Shasta/Trinity System, CVP, California
Hydropower Revenue Impacts	Lake Oroville, SWP, California
Drought Risk Analysis	Occoquan Reservoir, Fairfax County, VA

operation is given as a final section (Section II.A.5).

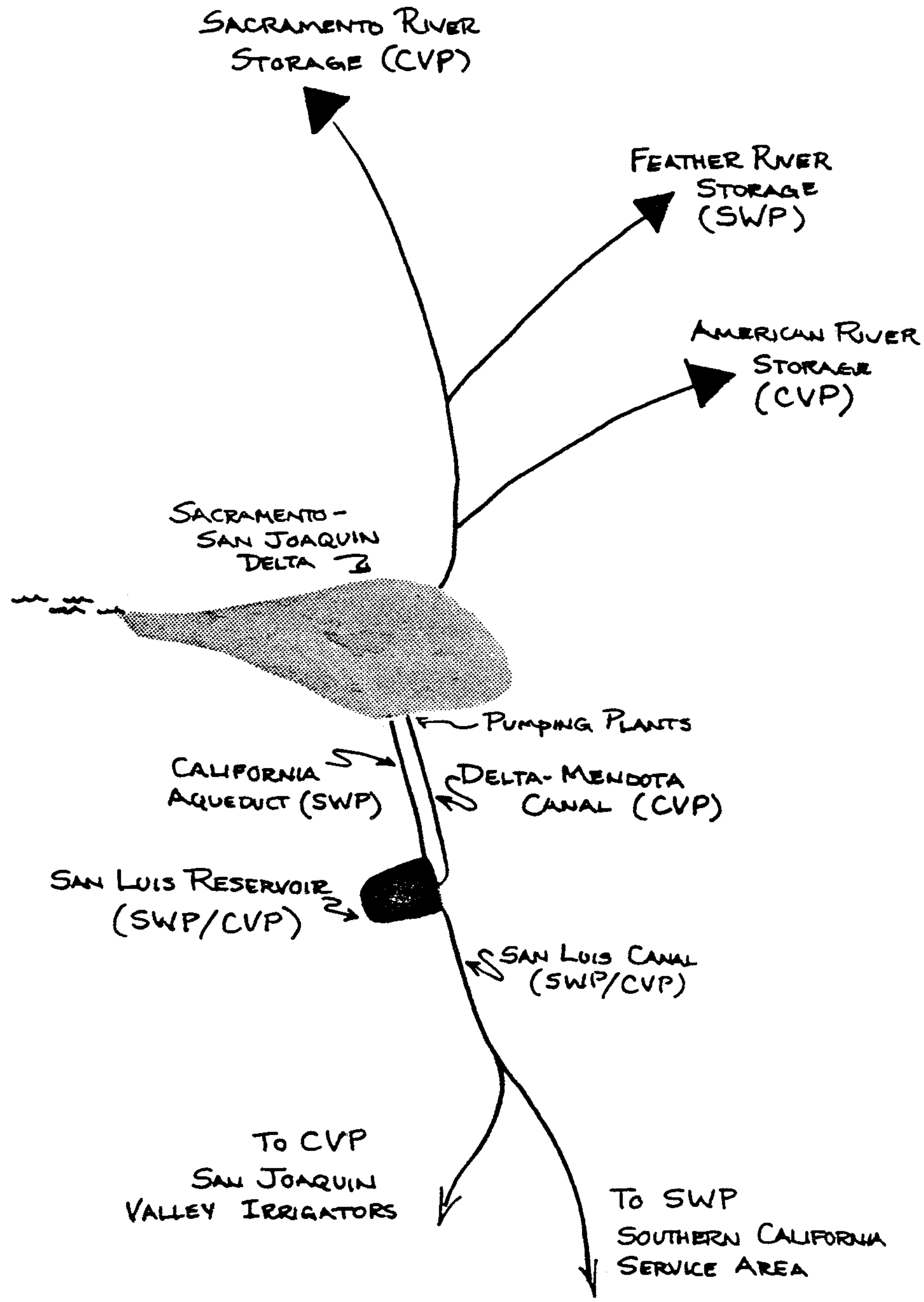
II.A.1. Water Supply Loans

Water supply conditions for a drought strickened area can be greatly improved by a water supply loan from another less water-short system. The primary limitation to this operation is the existence of physical connections between the systems. If the systems store water within the same reservoir, the loan may be accomplished easily. Loans are technically feasible for reasons specific to the water supply systems involved in the transaction. For example, one system may have an excess of supply or may be able to reduce its reservoir demands by using other sources, or the timing of supplies and demands of the two systems allow for a temporary transfer.

Two major water supply systems in California store water in a common reservoir. This shared facility enables them to temporarily transfer substantial quantities of water between them. In August of 1977, 75,000 acre-feet (ac-ft) of water supply was loaned from one system, the California State Water Project, to the other, the Central Valley Project. Studying the conditions under which this loan was made will illustrate what components are required to facilitate temporary water storage transfers.

a. Project Description.

San Luis Reservoir is a shared facility of the Central Valley Project (CVP), a Federal water project managed by the U.S. Bureau of Reclamation (Bureau), and the State Water Project (SWP) which is owned by the State of California and managed by its Department of Water Resources (DWR). Figure 3 is a schematic of the water resources facilities and their operation. The primary purpose of these projects



SWP = California State Water Project

CVP = Central Valley Project

FIGURE 3 Water Transfer System Incorporating San Luis Reservoir is to transport water from storage on the water-rich rivers north of the Sacramento-San Joaquin Delta (Delta) to CVP and SWP water contractors in the San Joaquin Valley (Valley) and, further south, out of the Valley, to SWP's Southern California Service Area. Reservoir releases flow down the Sacramento, Feather, and American Rivers to the Delta. Quantities not required for Delta water quality are pumped from the Delta and transported via canals to storage in San Luis Reservoir. Releases from San Luis Reservoir flow south via another shared facility, the San Luis Canal, for distribution to the corresponding contractors.

CVP and SWP operations are related by a series of informal and legal agreements which recognize the value of coordinated operation. Coordinated operation is fairly limited in scope and has evolved from addressing only proportional decreases in water supply to the SWP and CVP during supply-short years to include the coordination of releases for specified Delta water quality objectives. Generally, the projects are independently operated to meet their individual water supply and power commitments. Water supply and power exchanges between the CVP and SWP do occur, but they are usually prompted by facility outages. In 1977 however, scarcity of supply prompted a loan of 75,000 ac-ft between the two systems.

b. The 1977 Loan.

SWP storage in San Luis Reservoir was much lower than normal during 1977. By August, SWP water supply contractors were approaching the end of their normal irrigation demand period and SWP storage in San Luis Reservoir was starting to level-off at 300,000 ac-ft (California Department of Water Resources, 1978b). The CVP, on the other hand, was running out of stored supply. Federal storage at San Luis Reservoir was being drawn below the level forecasted by the Bureau. In April, the Bureau forecasted a storage of 77,000 ac-ft to be in San Luis Reservoir by September 1, however, by August 14, storage was 43,500 ac-ft (U.S. Bureau of Reclamation, 1977a). All this storage was forecasted to be used by August 21 (Martin, 1977a). In order to avoid making larger releases from Lake Shasta, which would lead to the loss of its power generating capability, and to complete the irrigation season, the Bureau requested a loan of 75,000 ac-ft from SWP storage in San Luis Reservoir. The request was made on August 16 (Martin, 1977a). The loan was approved and completed four days later.

Figure 4 is from the DWR's Bulletin 132-78. The Bulletin summarizes 1977 water management activities in California. The figure contains a plot of total storage level and the State's storage in San Luis Reservoir during 1976 and 1977. The steep slope of the 1977 total storage line during June through August indicates how rapidly CVP storage was being depleted. The discontinuity in the State's storage on August 20, 1977 represents the 75,000 ac-ft loan to the CVP. As shown on the figure, the loan was repaid by the Bureau by November 30, 1977.

c. Components of the Loan.

The water supply loan appears simple and uncomplicated and, in a sense, it is. The actual transfer of supply occurred on paper. There were no special inter-connections built or complicated accounting of water supplies required to implement the loan. In addition to the physical arrangement being conducive to a loan, there are three other reasons for its simplicity. First, there are no recreational concerns involved with the loan. San Luis Reservoir does provide some incidental recreation (primarily boating and fishing) however, it does not effect

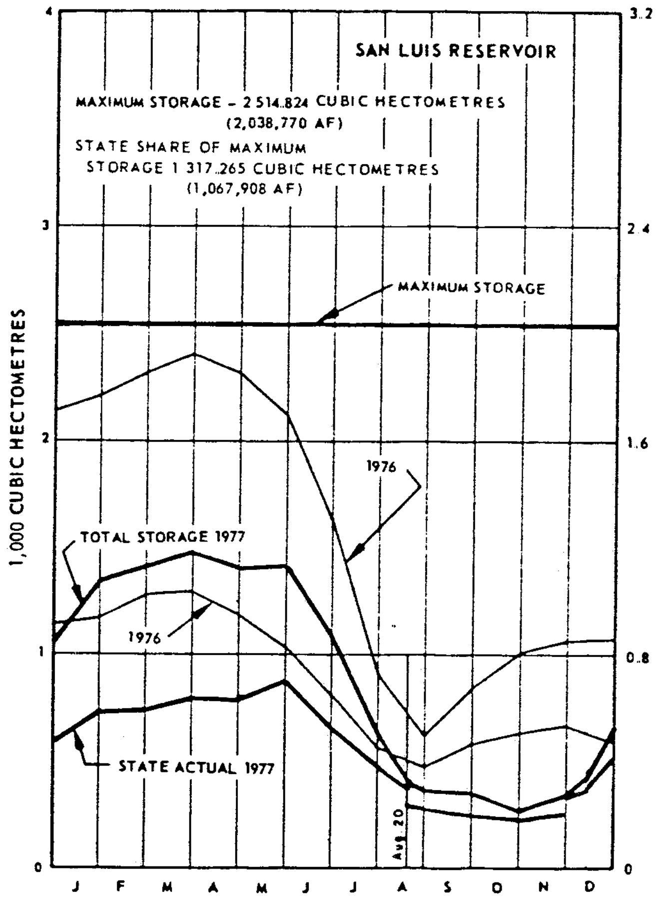


FIGURE 4 San Luis Reservoir Storage in 1976 and 1977 (California Department of Water Resources, 1978b)

operation of the reservoir. No possible negative recreational impacts due to the loan were mentioned in any of the references reviewed by the author. There was apparently no need for a public meeting. This condition decreased loan implementation time. Secondly, the institutional framework for the temporary transfer existed prior to the loan. The framework is given in the Draft Agreement for coordinated operation dated May 13, 1971 by which the agencies have agreed, via an annual letter, to abide and it is reinforced by the numerous water and power exchanges which have been made since that time. Finally, the SWP had water available to loan. In 1977, SWP deliveries to the Southern California Service Area were decreased by 435,000 ac-ft (California Department of Water Resources, 1978b). Southern California had been able to use other sources (the Colorado River and ground water). As a result of this major demand decrease and the fact the end of the irrigation season was approaching, the Department of Water Resources determined the loan would not jeopardize the water supply capability of the SWP for that water year.

d. Summary Comments.

Temporary transfer of water supply from one water supplier to another sharing the same reservoir may be implemented easily and provide assistance to one supplier while not placing the other at risk. To facilitate the temporary transfers, an agreement between the reservoir operators or water supply contractors should be made which specifies loan procedures. This agreement would address how the physical transfer of water will be made, identify the costs involved in the transfer (i. e. operation costs, hydropower or other revenues foregone) and specify how they will be determined, and give the procedure for water repayment and payment of costs.

II.A.2. Consolidation of Storage

A way to increase water supply during droughts is to decrease the evaporation, seepage, and in-stream losses experienced by a reservoir-stream system. This can be done by minimizing the surface-to-volume ratio of a reservoir system and storing as much water supply as possible nearest the users. Consolidation of storage is a method where conservation storage in the reservoir nearest the water supply users is maximized by releases from upstream reservoirs. Releases from the upstream reservoirs are made with the intent of filling the receiving reservoir as quickly as possible. In addition to decreasing the evaporation and seepage losses during storage, in-stream losses are decreased by minimizing the transport time between reservoirs. This method was used in the Orland Project, a project within the Central Valley Project (CVP) in California, in 1976 and 1977.

a. The Orland Project

The Orland Project is located on Stony Creek, a tributary to the Sacramento River, approximately 100 miles north of the city of Sacramento (See Figure 5). It is one of the oldest reclamation projects in the country and one of the first undertaken in California. There are three reservoirs in the project. The oldest and farthest upstream is East Park Dam. It was built in 1910 and has a storage capacity of 50,900 ac-ft. Stony Gorge Dam is about 18 miles downstream from East Park Dam. It was built in 1928 and has a storage capacity of 50,400 ac-ft. Both of these reservoirs are operated and maintained by the Orland Unit Water Users Association (OUWUA) under terms of a contract with the Federal Government (U.S. Bureau of Reclamation, 1978). The

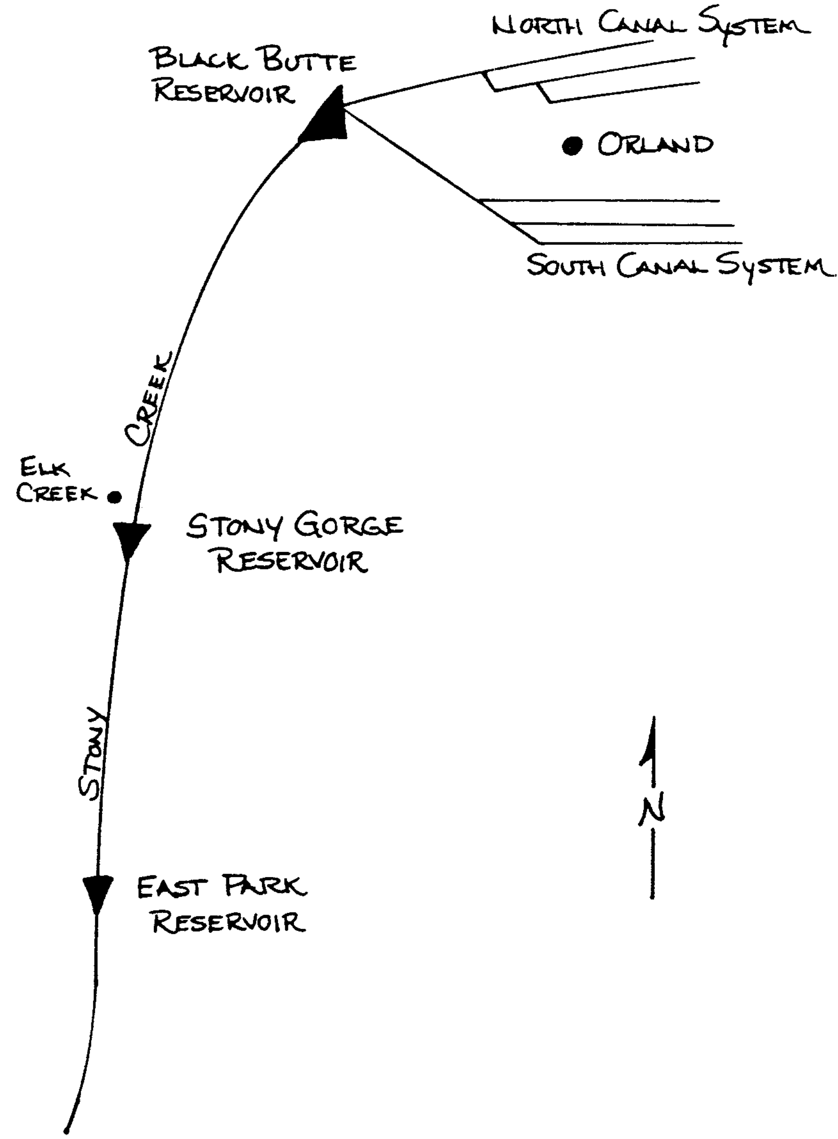


FIGURE 5 The Orland Project, California
(U.S. Bureau of Reclamation, 1978)

third reservoir is behind Black Butte Dam, approximately 24 miles downstream of Stony Gorge Dam and nine miles northwest of the town of Orland. Black Butte Dam and Reservoir provides flood control and about 59,000 ac-ft of water supply annually (U.S. Bureau of Reclamation, 1978). It is operated and maintained by the U.S. Army Corps of Engineers (Corps). The primary function of the Project is to provide irrigation supply via a network of canals to almost 20,000 acres around Orland. There is also a small municipal supply provided by Stony Gorge Dam to the town of Elk Creek. Normal annual demand for the Project is 121,000 ac-ft (California Department of Water Resources, 1978a) with most of this volume taken from April through September.

b. Orland Project Operations in 1976 and 1977.

The Orland area was one of the hardest hit agricultural areas during 1976 and 1977. OUWUA began facing water shortages in early spring, 1976. By the end of March, 46,000 ac-ft was available in Stony Gorge and East Park Reservoirs. The projected irrigation demand was 115,000 ac-ft (Martin, 1976). In an attempt to decrease surface evaporation, infiltration through the reservoirs' bottoms and sides, and in-stream losses, 38,000 ac-ft of supply was released from Stony Gorge and East Park Reservoirs for consolidation into Black Butte Reservoir (U.S. Bureau of Reclamation, 1976a). The remaining storage was left to maintain small pools for recreation and fish and wildlife habitat and to serve as Elk Creek's municipal supply (Martin, 1976). As a rule, no releases from East Park or Stony Gorge Reservoirs are made to maintain streamflow below the dams. Releases began abruptly in April, 1976. There were no releases made on April 2 and by April 4, Stony Gorge releases averaged 400 cubic feet per second (cfs) and East Park releases averaged 250 cfs. (U.S. Bureau of Reclamation, 1976a). These relatively large releases continued until the designated storage remained in each reservoir. The total transfer took 53 days (U.S. Bureau of Reclamation, 1976a).

In 1977, the consolidation of storage was done again. This time, however, Stony Gorge and East Park Reservoirs could provide only 17,800 ac-ft (California Department of Water Resources, 1978a). East Park Reservoir was virtually drained. Stony Gorge Reservoir retained only 3,000 ac-ft as municipal supply for Elk Creek. The pattern of releases is similar to that of 1976. The transfer took 30 days to complete (U. S. Bureau of Reclamation, 1977b).

c. Quantification of Reduced Losses.

For the Orland Project, consolidation of storage conserved a small amount of water during an extremely severe drought period. It is not possible to calculate the actual amount of water saved by the decreased seepage, evaporation, and in-stream losses. All of the required information is not available. An upper limit approximation of the evaporation losses recovered by this operation can be made using the recorded evaporation loss for April in 1976 and 1977 for each reservoir and assuming this loss represents the average monthly evaporation through the six-month irrigation season. Analysis of the 1976 April through June daily operation records indicates this is a conservative, yet reasonable, assumption for the average monthly storage lost to evaporation. The values obtained do not include the evaporation losses attributable to the irrigation supply while it was stored in Black Butte Reservoir, hence its upper limit status. For 1976, this limit is about 3500 ac-ft, 9% of the total irrigation supply available that year

(38,000 ac-ft). In 1977, a maximum of 2800 ac-ft was saved or 16% of that year's 17,800 ac-ft irrigation supply.

d. Summary Comments.

For the Orland Project, consolidation of storage is an operation which is quick and easy to implement. There are two reasons for this. First, restrictions placed upon implementation due to impacts upon fish, wildlife habitat, and recreation in the reservoirs' surrounding areas are not an issue. They are given very little consideration in Stony Gorge and East Park reservoirs' operation (Hunt, 1985). Secondly, the operation is accomplished using existing physical works which not only decreases implementation time but costs as well.

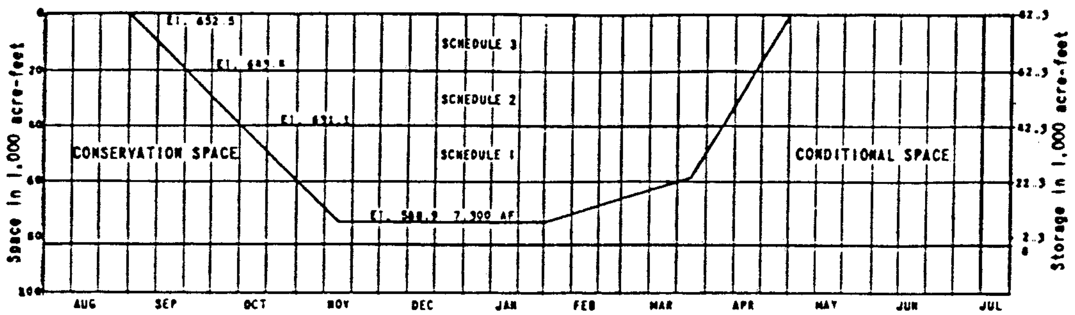
II.A.3. Minimum Pool Releases

Many reservoirs contain water in a pool near the reservoir's bottom which is never released under normal operation. This pool is generally referred to as minimum pool. Minimum pool releases were used during the 1977 irrigation season to augment water supply from several reservoirs in California's San Joaquin Valley. The following discussion describes these reservoirs and their operation. The agency coordination required and legal issues involved in making minimum pool releases are illustrated in a case study of Success Lake.

a. Normal Reservoir Operation.

The reservoirs in the San Joaquin Valley with minimum pools are operated by the U.S. Army Corps of Engineers. They primarily serve two purposes--irrigation and flood control. Flood protection is generally required from October through April with maximum need occurring November through March (U.S. Army Corps of Engineers, 1982). The need for irrigation supplies begins in March, peaks around August, and fades near the end of September. The period of the water year which requires irrigation supply and the one which requires flood control protection are complementary and, therefore, storage space which serves for flood control is allowed to begin filling at the end of spring. This type of operation is called joint-use operation. Figure 6 contains a joint-use operation curve. Withdrawals within the conservation area under the curve are determined by the contractors for the water supply (Countryman, 1984). The conditional area under the curve indicates an operation which attempts to refill the reservoir to capacity while maintaining the project's flood control capability. Water stored in conditional space is subject to release if it is determined that space is required for flood control. A release of this type is called a supplementary release. A nomograph which uses forecasted runoff and irrigation demand, and space available in the reservoir is used to determine the supplementary release. Figure 6 includes the nomograph and required release schedule corresponding to the joint-use operation curve.

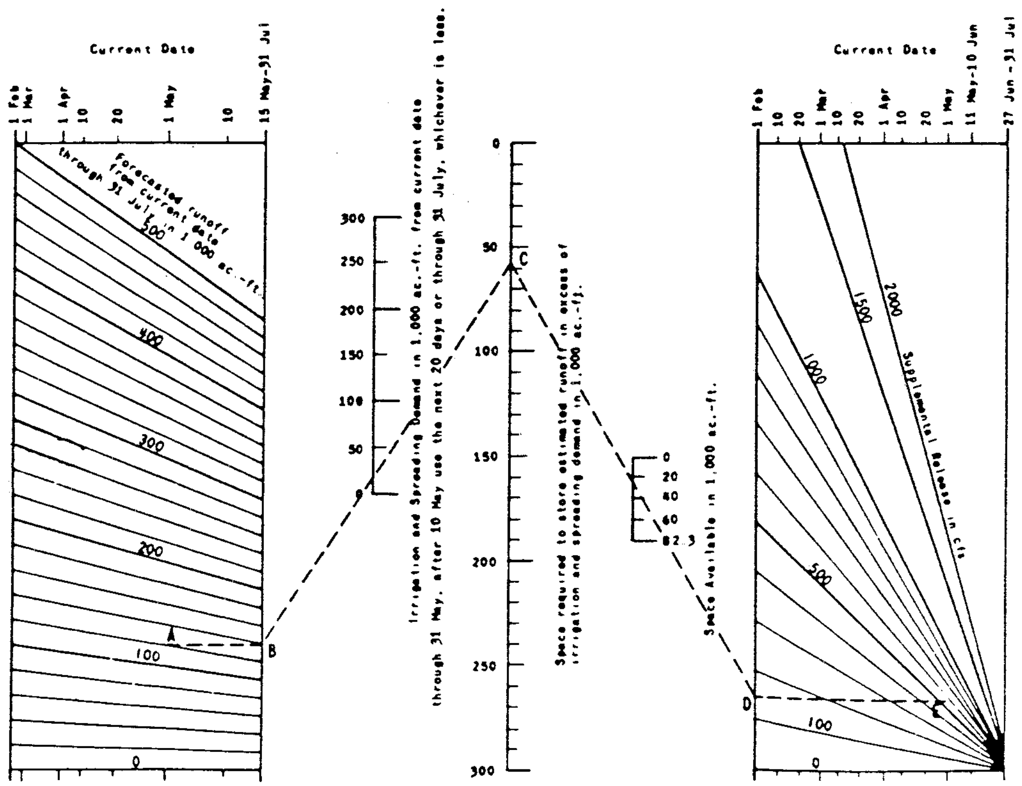
For example, given forecasted runoff from May 1 through July 31 is 120,000 ac-ft, point A is located on the nomograph. A horizontal line is drawn to point B. Given estimated irrigation demands from May 1 through May 31 is 20,000 ac-ft and the irrigation demand on May 1 is 250 cfs, points C and D are located. The intersection of a horizontal line from point D and a vertical line from May 1 gives point E and indicates a supplementary release of 550 cfs. The total release would be the sum of the irrigation demand and supplementary release (800 cfs). The objective of the operation is to maintain the reservoir's flood protection ability and maximize the amount of carryover storage at the



Joint Use Operation Curve

MONTH	SCHEDULE 1 1/		SCHEDULE 2 2/		SCHEDULE 3 3/
	AVG CFS	1,000 AC-FT	AVG CFS	1,000 AC-FT	AVG CFS
Oct	520	31.9	1,075	66.0	3,200
Nov	505	30.1	1,060	63.1	
Dec	500	30.6	1,055	64.7	
Jan	500	30.7	1,055	64.8	
Feb	510	28.3	1,065	59.1	
Mar	635	38.9	1,190	73.0	
Apr	625	37.1	1,180	70.1	
May	510	31.3	1,065	65.5	
Jun	570	33.8	1,125	66.8	
Jul	650	40.1	1,205	74.2	
Aug	615	37.8	1,170	71.9	
Sep	460	27.4	1,015	60.4	3,200

Required Release Schedule



Supplemental Release Nomograph

FIGURE 6 Joint Use Operation Diagrams for Success Lake, Tule River, California

(U.S. Army Corps of Engineers, 1982)

end of the flood season.

In addition to the joint-use storage, these reservoirs usually contain a minimum pool. The top of minimum pool storage is designated by a fixed elevation and the bottom is usually at the lowest outlet invert. When reservoirs are at minimum pool, normal operation requires releases to be no greater than inflow to the reservoir allowing for maintenance of the pool. In Figure 6, minimum pool storage is at 5,100 ac-ft. Minimum pool storage provides fish habitat and water supply for the project's local facilities, fire protection, and recreational areas.

b. Minimum Pool Release from Success Lake

Beginning in March, 1977, contractors for irrigation supply requested both the Bureau and Corps to allow minimum pool releases from several reservoirs (Weddell, 1977b; Green, 1977). Low precipitation and large irrigation releases the previous year had produced storage far below normal and the contractors were very concerned with meeting their needs through the coming growing season. Some requests were approved and some denied. A description of the events surrounding minimum pool releases from Success Lake on the Tule River in California will help to define the issues involved in minimum pool releases.

Success Lake and Dam provide flood control protection and irrigation supply. The contractor for irrigation supply is the Tule River Association (Association). The minimum pool provides fish habitat and recreation uses. Its level is governed by a legal agreement between the County of Tulare (County) and the Association (Weddell, 1977b). This agreement specifies the minimum pool elevation during years of adequate runoff (587 feet mean sea level) and allows the elevation to be lowered to 583 feet during years with inadequate runoff (Weddell, 1977b). In addition to the County, whose interest is recreational, the California Department of Fish and Game (DFG) is concerned with the impact minimum pool management has upon the fish population.

In April, 1977, the Association requested the Corps to allow the pool to drop to the outlet invert (559 feet msl) during the irrigation season (Weddell, 1977b). The Association had already contacted DFG and the County regarding their desire to use all minimum pool storage (Weddell, 1977b). If this were done, the storage remaining would be nominal (560 ac ft). The fish habitat would be gone along with most recreational use. DFG agreed to the releases because they intended to eradicate "rough" fish species when the pool was at its lowest level (Weddell, 1977b). After assurances that water taken from minimum pool would be replaced by the Association the following year regardless of water supply conditions, the County also agreed to the releases (Weddell, 1977b).

Because the Corps exercises no water rights in the CVP, there was and is no legal basis for them to permit or deny the releases (Weddell, 1977b). Release approval lies with the owner of the minimum pool storage. For CVP reservoirs in official operation, the Bureau has release approval authority (U.S. Army Corps of Engineers, 1977). The Bureau confirmed that the Association, County, and DFG had come to agreement regarding the releases and approved the request shortly after it was received. Their approval was given with the stipulation that this approval would not bind their actions in future years. Releases from Minimum Pool began in mid-September and continued through October (U.S. Army Corps of Engineers, 1982). The entire minimum pool was never used. The lowest pool elevation was 579 feet msl (approximately

4,000 ac-ft remaining). Small quantities of inflow refilled the minimum pool by December (U.S. Army Corps of Engineers, 1982). The water supply made available by this operation amounted to approximately 1,150 ac-ft. Presented in Figure 7 are storage levels for Success Lake during 1975 and 1977. Inflow in 1975 is representative of a normal water year. For the period 1963-1975, about half of the annual inflows are greater than and half less than the inflow in 1975. Its storage levels are presented to provide a comparison and emphasize the extreme circumstances existing in 1977.

c. Quantification of Increased Irrigation Supply

Requests were also received for minimum pool releases from Hidden, H. V. Eastman, and New Hogan Lakes, all located on streams flowing down the east side of the San Joaquin Valley. They are also operated using joint use operation. Their institutional arrangements for minimum pool release approval are similar to Success Lake. The parties involved are the owner of the minimum pool, any consumers of minimum pool water for local project facilities (Success Lake had none), recreation interests (usually local), and fish and wildlife managers (State agency). Minimum pool releases were made from Hidden and H. V. Eastman Lakes (California Department of Water Resources, 1978a). Minimum pool releases were prevented by local recreational interests at New Hogan Lake (California Department of Water Resources, 1978a). The irrigation supply made available in 1977 by the minimum pools for Success, H. V. Eastman, and Hidden Lakes is approximately 8,000 ac-ft (California Department of Water Resources, 1978a). Because of the projects' recent completion, Hidden and H. V. Eastman's minimum pools were not full. If they had been, a total of about 15,000 ac-ft would

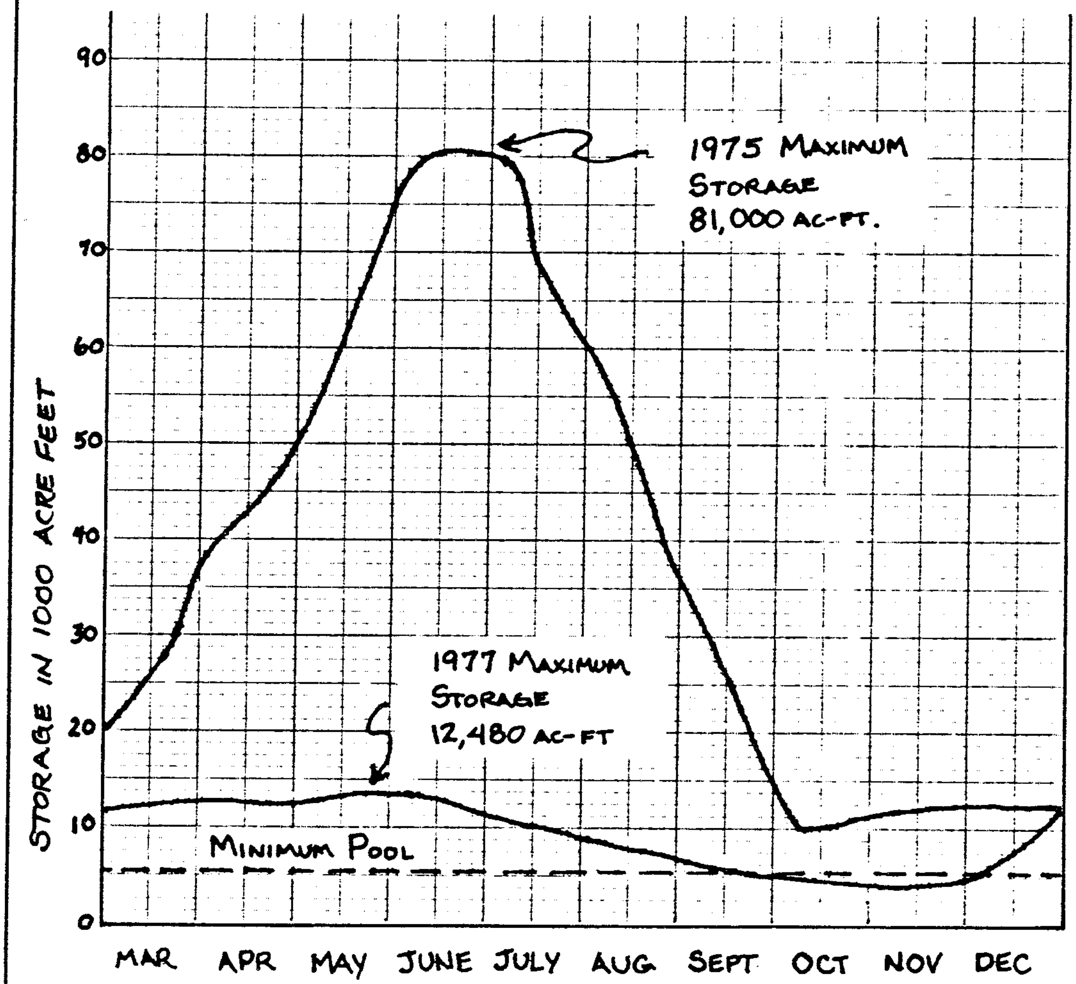


FIGURE 7 Success Reservoir Storage in 1975 and 1977

have been available (U.S. Army Corps of Engineers, 1973).

d. Summary Comments

Releases from minimum pool are a feasible way to increase water supply during a drought. Minimum pool storage is not affected by normal reservoir operation or inflows and, therefore, is not dependent upon forecasting. Considerable Federal, State, and local agency interaction is required to obtain release approval. The time for this approval ranges widely. Minimum pool releases require no modification to the physical works of the dam and can therefore, once approved, be implemented easily with no additional cost. The amount available from minimum pool releases is not large. For the reservoirs investigated, minimum pool capacity averaged 5,000 ac-ft or about 6% of maximum conservation storage. Primary negative impacts of such an operation are upon recreation and fish habitat. In the case where minimum pool releases were not made, they were prevented by local concerns regarding recreation impacts.

II.A.4. Project Purpose Change

Water supply in an area can be greatly increased if private or public water resources projects which are operated for purposes other than water supply are converted to water supply facilities. Such an occurrence is rare because few water management agencies have legal authority to take such action. In 1965 however, Federal flood control facilities and private hydropower projects were operated for water supply in the Delaware River Basin. The following text describes the reservoirs in the Basin during 1965, the legal/institutional background of the Delaware River Basin Commission (DRBC), and the reservoirs' operation during 1965. In addition, the amount of additional supply provided to the water supply reservoirs is quantified and a few summary comments are made.

a. The Delaware River Basin.

Figure 8 is of the Delaware River Basin reservoirs which existed during the 1961-1967 drought. Neversink, Pepacton, and Connonsville Reservoirs are owned by New York City (NYC). Diversions from the three are accumulated out of the Basin in Rondout Reservoir and transported to NYC via their Delaware Aqueduct. During 1965, Cannonsville Reservoir was under construction. Lake Wallenpaupack and the Mongaup reservoir system, composed of Mongaup and Rio reservoirs, are privately-owned hydropower generating facilities. Prompton and Francis E. Walter Reservoirs are primarily Federal flood control facilities. Reservoir storage capacity is listed in Table 2. Notice, in 1965, NYC owned over 70% of the conservation storage (excluding Cannonsville) in the Basin.

As seen in Figure 8, all of the Basin's conservation storage was above Montague, New Jersey, in an area referred to as the Upper Basin. Any decrease in the minimum flow at Montague directly affected the flow to the Delaware Estuary (measured at Trenton, New Jersey) because no regulation or augmentation of the flow could be done downstream of Montague. Outflow of the Delaware River into the estuary was then and is now a critical concern to the Basin's water resources managers because it determines the extent of estuary salinity intrusion. If the salinity front were allowed to progress upriver, much of the municipal and industrial intake supplies of Philadelphia and Camden would be contaminated.

b. The Delaware River Basin Reservoir Management.

Operation of the NYC reservoirs has been governed since 1954 by an

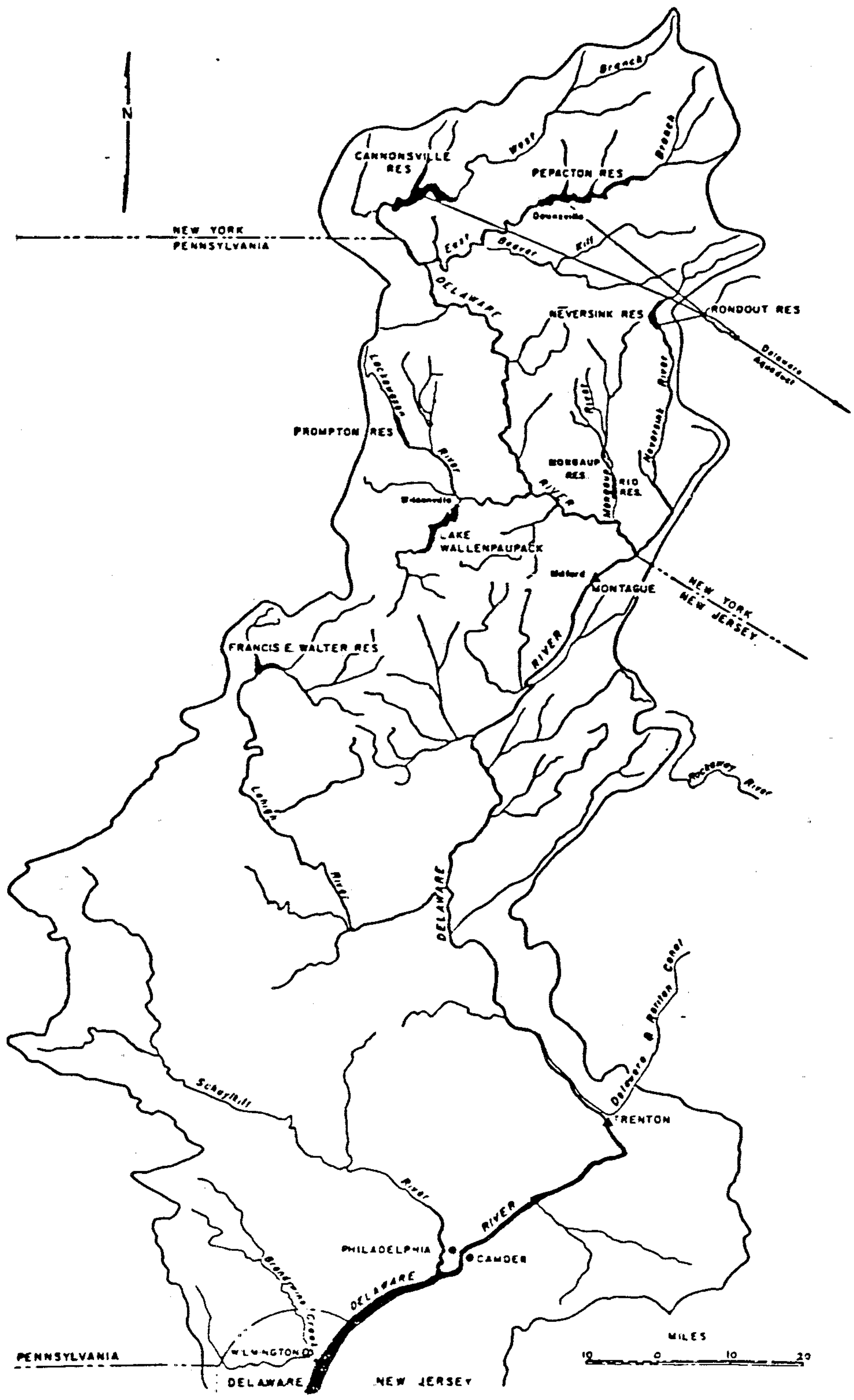


FIGURE 8 Major Storage Facilities in the Delaware River Basin, 1965
(Revision of Figure 1, Schaefer & Fish, 1982)

TABLE 2: DELAWARE RIVER BASIN RESERVOIRS, 1965

RESERVOIR (OWNER)	CAPACITY, ACRE-FEET	
	CONSERVATION STORAGE	FLOOD CONTROL SPACE
NEVERSINK (NYC)	109,200	--
PEPACTON (NYC)	454,000	--
CANNONSVILLE (NYC)	302,000 (1)	--
WALLENPAUPACK (Private)	157,240	--
MONGAUP SYSTEM (Private)	65,630	--
WALTER (Federal)		108,000
PROMPTON (Federal)	5,600	20,300

(1) Not available during the 1961-1967 drought.

Reference: Delaware River Basin Commission, 1981.

United States Supreme Court decree (Wells and Fish, 1966). Parties to the Decree are New York City, New York State, and the states of Pennsylvania, New Jersey, and Delaware. The Decree designates releases and diversions from the NYC reservoirs and authorizes the Delaware River Master (of the U.S. Geological Survey) to direct them in accordance with the Decree. In addition, the Decree specifies the flow objective to be maintained at the Montague gage at Milford, PA. During mid-June through October, the flow objective consists of a minimum flow plus an excess flow.

The Delaware River Basin Commission (DRBC) oversees reservoir operation for the entire Delaware River Basin. The Delaware River Basin Compact (Delaware River Basin Commission, 1967), created the DRBC on October 27, 1961. The signatory parties of the Compact form the DRBC. These members are the governors of New York, New Jersey, Pennsylvania, and Delaware, and the Secretary of the United States Department of Interior. The Compact authorizes the DRBC to plan, manage, develop, protect, and control the water resources of the Delaware River Basin (Basin). The principal duties of the DRBC are to maintain a comprehensive water resources development plan, insure this plan is followed, determine future allocations of Basin waters to the four states of the Basin, and regulate the volume of withdrawals or diversions during a water shortage. Section 10.4 of the Compact is the specific section authorizing the DRBC to control all diversions or withdrawals during a drought. The section reads as follows:

> "In the event of a drought or other condition which may cause an actual and immediate shortage of available water supply within the basin, or within any part thereof, the commission may, after public hearing, determine and delineate the area of such shortage and declare a water supply emergency therein. For the duration of such emergency as determined by the

commission no person, firm, corporation or other public or private entity shall divert or withdraw water for any purpose, in excess of such quantities as the commission may prescribe by general regulation or authorize by special permit granted hereunder." (Delaware River Basin Commission, 1967.)

c. 1965 Reservoir Operation.

During the years 1961 through 1967, the entire Northeastern United States experienced severe drought. This drought has been estimated as having a recurrence interval of several hundred years for the Upper Basin (Delaware River Basin Commission, 1981). The recurrence interval for the entire basin at the mouth of the Schuylkill River is estimated near 100 years (Delaware River Basin Commission, 1981). The second most severe drought of record for that area occurred in the 1930's and has a recurrence interval below 15 years (Wells and Fish, 1968). 1965 was the most critical year for water supply in the Basin (Wells and Fish, 1968).

On December 1, 1964, the storage in Pepacton and Neversink Reservoirs was 2.5% of their combined capacities (14,080 ac-ft) (Wells and Fish, 1966). The River Master concluded that, due to the extreme water supply shortage, no excess flow was available in the NYC reservoirs. He determined it was within his authority to forego any excess flow requirement however, he was not authorized to lower the minimum flow rate (1525 cfs) at Montague in order to conserve water supply in the NYC reservoirs (Wells and Fish, 1966). The releases he directed the NYC reservoirs to make to the Delaware River were unacceptable to NYC. On June 14, 1965, NYC stopped making them and began making releases which were equal to the reservoirs' inflow (Wells and Fish, 1966). Flow at Montague dropped to about 650 cfs (Wells and Fish, 1966).

The legal constraints of the River Master prevented prudent management of the Upper Basin. On July 7, 1965, under the authority of Section 10.4, the DRBC declared a drought emergency, suspended the 1954 Decree, and prescribed the withdrawals and diversions from the Basin's major reservoirs. With respect to the Upper Basin, the DRBC decreased the maximum allowable diversions by NYC and lowered the Montague flow objective (Wells and Fish, 1966). In addition to these changes, the DRBC ordered 1) water supply releases to be made from the hydropower facilities and 2), in a later order, water supply storage to begin in Prompton and Walter Reservoirs. The daily releases from the Upper Basin reservoirs was determined by the River Master with limitations specified by the DRBC (Wells and Fish, 1966).

Release records of the River Master (Wells and Fish, 1966) indicate that during the critical months of July through September, Lake Wallenpaupack and the Mongaup Reservoir system (privately owned hydropower storage facilities) contributed 63,500 ac-ft to the flow at Montague. Releases averaged 300 cfs from Lake Wallenpaupack and 100 cfs from the Mongaup Reservoir system. Releases during weekdays were rarely below these values. In consideration of recreational impacts, the releases decreased over the weekends and, during Labor Day holiday, they virtually ceased (Wells and Fish, 1966). Figure 9 illustrates the components of flow of the Delaware River at Montague for June-November, 1965. The low components of flow attributed to the NYC reservoirs for the period June 17 to July 10 are the releases which equalled the reservoirs' inflow. After July 10, the power reservoir releases are relatively uniform and become an integral flow component. Decreasing hydropower facility releases over the weekends helped to minimize recreation impacts however, both facilities experienced recreation

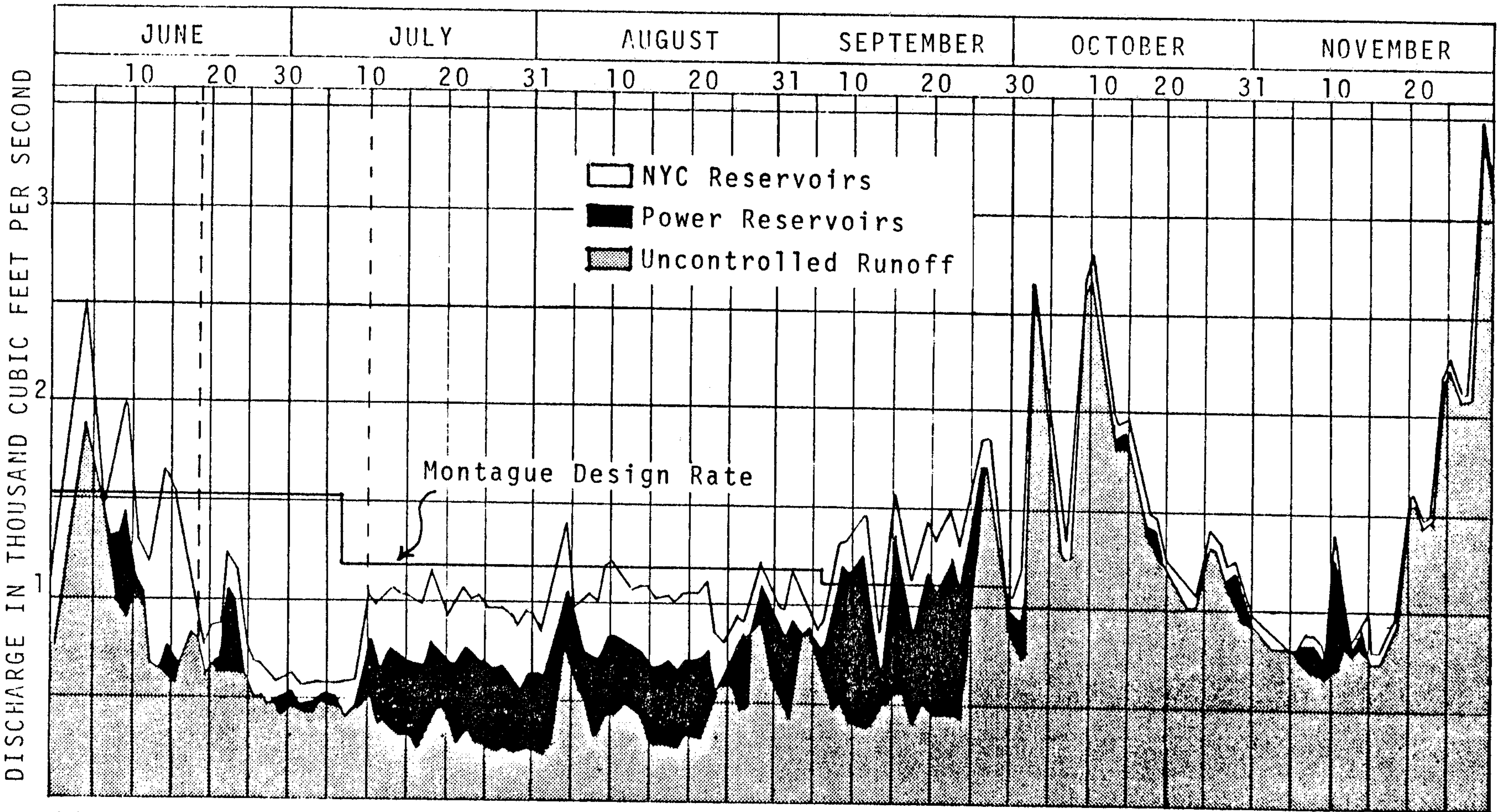


FIGURE 9 Components of Flow, Delaware River at Montague, New Jersey, 1965 (Wells and Fish 1966)

impacts during this period. Any financial or contractural impacts due to this change in operation is unknown. It is very interesting to note neither utility was financially reimbursed for their cooperation (Thompson, 1985).

During the July-September period, the releases contributed 33% of the streamflow at Montague. During the other drought years, when the hydropower facilities' releases were not directed in response to the drought, they are much less uniform and amount to only 18% of the streamflow at Montague. The difference between the average volume of releases from the hydropower facilities during July-September in the three years prior to 1965 and the volume of their directed releases for July-September in 1965 approximates the increased volume of water supply attributable to this operation. The facilities released an average of 52,000 ac-ft during July-September of 1962-64 and 64,000 ac-ft for this period in 1965. Therefore, the directed hydropower facility releases increased NYC reservoirs' water supply storage by 12,000 ac-ft.

In their Resolution 65-18, the DRBC directed storage to begin accumulating behind Walter and Prompton Reservoirs on August 6, 1965 (Wells and Fish, 1966). In doing so, they cited a Report to the President, entitled "Drought in Northeastern United States" dated July 21, 1965 where the Water Resources Council recommended "That the Army Corps of Engineers, on an emergency basis, temporarily utilize flood control space or recreational storage in its reservoirs to relieve critical water shortage when determined to be in the public interest." The DRBC defined the operation of the projects. It requested the Corps to retain any flow over 70 cfs in Walter Reservoir and to make releases on their order (Wells and Fish, 1966). Prompton Reservoir was to store all but its conservation release (that release required to maintain the stream below the dam) whenever a flow of 1200 cfs was maintained at Montague without storage releases from the other Upper Basin reservoirs (Wells and Fish, 1966). As shown on Figure 9, that condition never happened and, therefore no storage accumulated in Prompton Reservoir during the critical August-September period. Walter Reservoir was able to accumulate water supply. Its DRBC directed releases began August 24 and ended November 25. Initial releases were 170 cfs increasing over time to final releases of 440 cfs (Wells and Fish, 1966). Over this period, Walter Reservoir provided almost 48,400 ac-ft to the Delaware River.

Walter Reservoir releases allowed decreased releases from Upper Basin reservoirs yet maintained enough outflow at the Trenton gage to prevent salinity intrusion. This was accomplished by lowering the flow requirement at the Montague gage. The initial releases from Walter Reservoir were controlled by the DRBC. The DRBC met a Trenton flow objective, while the River Master coordinated all the Upper Basin reservoirs to meet a Montague flow objective. On October 9, the DRBC designated the River Master to coordinate all reservoir releases in the entire Basin to meet the Trenton flow objective only (Wells and Fish, 1966). The DRBC specified maximum reservoir releases and assigned a release priority. Walter Reservoir began to serve a much larger role after this date because it was first in priority. Its releases jumped from 136 cfs on October 9 to 563 cfs on October 10. The River Master decreased NYC reservoir releases to just above conservation releases and required no hydropower facility releases to be made.

d. Summary Comments

The combined effect of these two operational changes is to increase conservation storage in the NYC reservoirs. Pepacton and Neversink reservoirs began the 1965 water year (December 1, 1964-November 30, 1965) with a combined storage of 2.4% of their conservation capacity and ended the water year at 26% (Wells and Fish, 1967). These two operational changes were very successful in improving the water supply conditions in the Basin during that year. They contributed approximately 60,400 ac-ft of water supply during the water year. DRBC's current drought operation plan, which incorporates these two operations, is discussed in a later section.

II.A.5. Quantification of Increased Supply

If the operations discussed in the four previous sections were adopted as designated drought operations for the individual case studies, what amount of water supply increase could be expected during a drought? The maximum potential of Minimum Pool Release is easy to evaluate. It amounts to the size of the Minimum Pool. Consolidation of Storage is harder to quantify because it is limited by the volumes present in the upstream reservoirs. Three thousand ac-ft represents the approximate potential of the operation. The potential of the remaining operations is harder to quantify. The potential of water supply loans between the SWP and CVP is dependent upon many factors which include the ability and willingness of Southern California contractors to use alternative supplies and the timing of the loan. The 1977 loan indicates a fairly high potential may exist for this type of operation. Project Purpose Change appears most promising as a way of increasing water supply during droughts in the Delaware River Basin. With refinement in the timing of the operation, such as retaining supply in the flood control reservoirs and operating for the Trenton flow objective earlier in the drought, more supply could be provided.

Table 3 is a summary of the estimated amount of water supply increases provided by these operations. The percent increase in supply is also given as an attempt to normalize the volumes of increase with respect to the size of the water supply system. This percentage is equal to the amount of increase divided by the reservoir system's active capacity. The percentage for Water Supply Loans uses Lake Shasta's active capacity because its storage would have been used if the loan had not been made. For the California operations, the percentage value is 2% and, for the Delaware River Basin operation, it is 10%. These percentages support the fact that reservoirs in arid environments have less potential to increase supply during droughts than reservoirs in non-arid environments. This is due to the fact that by the time a drought is identified in arid areas, most of the rainfall runoff has occurred. Snowmelt will usually continue after a drought has been identified but many reservoirs receive no snowmelt as inflow. During droughts in a non-arid area, water sources may be untapped, as were the rivers upon which the flood control reservoirs of Francis B. Walters and Prompton are built. Basically, the potential to increase supply during a drought is greater in non-arid areas because sources of supply remain, although diminished, during the critical water supply period.

II.B. OPERATIONS TO MEET OBJECTIVES

Section II.A discusses methods of increasing supply for consumption during droughts. The following sections describe management of a limited supply to meet the various demands upon a reservoir system. For multipurpose reservoirs, drought management involves the analysis of

TABLE 3: SUMMARY OF WATER SUPPLY INCREASES DUE TO RESERVOIR OPERATIONS INDUCED BY DROUGHT.

OPERATION METHOD	APPROXIMATE WATER SUPPLY INCREASE (ACRE-FEET)	INCREASE AS PERCENTAGE OF SYSTEM'S ACTIVE CAPACITY
CONSOLIDATION OF STORAGE (Orland Project)	3,000	2%
MINIMUM POOL RELEASE (Success Lake)	5,000	2%
WATER SUPPLY LOAN (SWP and CVP)	75,000	2%
PROJECT PURPOSE CHANGE (Delaware River Basin)	60,000	10%

impacts a particular management scheme for one purpose has upon the others. It also may require discontinuing operation for certain purposes. Section II.B.1 and II.B.2 are examples of multipurpose reservoir operation during drought. For a reservoir which provides only water supply, the only available management option, other than obtaining supply elsewhere, is to decrease consumption. Section II.B.3 contains an example of how a water supply agency decided when to implement consumption conservation measures.

II.B.1. Multipurpose Reservoir Operation

When a Federal reservoir project is authorized by Congress, the purposes the project will serve are specified. These purposes can be flood control, water supply, navigation, hydropower, water quality, fish and wildlife habitat, and recreation. Once completed, the reservoir is operated to serve all its authorized purposes to the greatest extent possible. If water storage is low, it is obvious operation must attempt to meet the needs of each purpose through the critical period. As the system becomes more stressed, service to each purpose may either decrease or stop completely. The Shasta/Trinity system is a Federal multipurpose reservoir system in Northern California. A case study of its operation during 1977 will provide insight to Federal multipurpose reservoir operation during times of critically short water supply.

a. Shasta/Trinity Project Description

Reservoirs on the upper Sacramento River to be discussed are Clair Engle Lake behind Trinity Dam and Whiskeytown Lake, both in the Trinity System, and Shasta Lake on the Sacramento River. The Trinity System serves a transbasin diversion from Trinity River Basin to the Sacramento River Basin. Releases from the Shasta/Trinity system flow down the

Sacramento River to meet in-basin needs and Delta water quality requirements, and to be pumped out of the Delta for exportation to contractors. A schematic of the system is given in Figure 10. The Shasta/Trinity system is the major storage component in the CVP. Active storage capacities of Clair Engle, Whiskeytown, and Shasta Lakes are 2,135,000 ac-ft, 213,600 ac-ft, and 4,493,000 ac-ft respectively (U.S. Bureau of Reclamation, 1976a and 1980). These three reservoirs contain approximately 75% of the active conservation storage in the CVP. Lewiston Lake is also a reservoir in the system. Its afterbay storage provides for reregulation of Trinity Powerplant releases. Its active capacity is under 3,000 ac-ft (U.S. Bureau of Reclamation, 1980)

Generally, these reservoirs are authorized by Congress to serve all of the above mentioned purposes. The priorities established by these authorization Acts, particularily the Rivers and Harbors Act of 1937, provide that CVP dams and reservoirs shall be used: first, for river regulation, improvement of navigation, and flood control; second, for irrigation and water supply uses; and third, for power (U.S. Bureau of Relcamation, 1981). With respect to the Shasta/Trinity system, this Act dictates that during short supply navigation releases have priority over irrigation and water supply releases and both of these releases surpass hydropower releases in importance. Priority for the remaining purposes at Shasta/Trinity is not Federally specified. It is determined by interaction with State government and local citizens.

b. Shasta/Trinity System Operation in 1977

The following discussion identifies constraints and concerns to managers of the Shasta/Trinity system by summarizing its operation during 1977 for each of the purposes it serves.

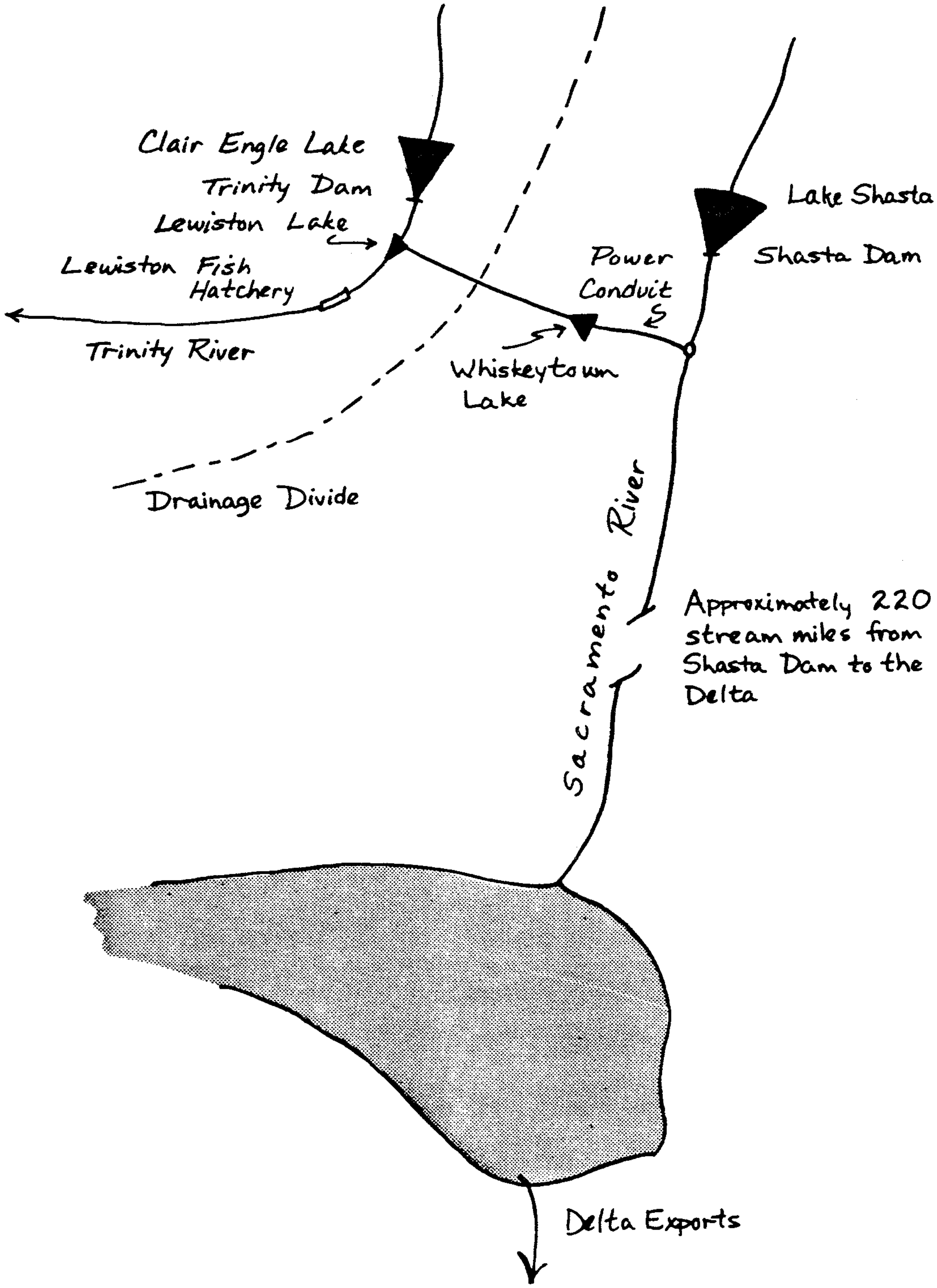


FIGURE 10 The Shasta/Trinity System, Central Valley Project, California

Irrigation and Municipal and Industrial Supply. Carryover storage beginning the 1977 water year in the Shasta/Trinity system was approximately 2.8 million ac-ft, 50% of normal, due to low reservoir inflow in 1976 (U.S. Bureau of Reclamation, 1977a). The 1977 water year is the only time the Shasta/Trinity system, and the CVP in total, operated for drought conditions. Although 1976 is also considered a drought year, the CVP was not operated for drought conditions primarily because of a legal constraint in many of its water supply contracts.

Almost half of the water supply contracts contain a critical-year clause which stipulates no decrease in the allocated amounts of water supply is allowed if the projected inflow to Lake Shasta is greater than 3.2 million ac-ft (U.S. Bureau of Reclamation, 1976e). Other contractors are not subject to the critical-year clause and the Bureau may decrease deliveries whenever it is determined necessary. Projected inflow to Lake Shasta for 1976 ranged from 3.2 to 3.6 million ac-ft (U.S. Bureau of Reclamation, 1976e). The actual inflow to Lake Shasta in 1976 was 3.6 million ac-ft (U.S. Bureau of Reclamation, 1976e). The Bureau decided placing restrictions upon contractors who are not under the critical-year clause while placing none upon the others was unfair and, consequently, did not operate for drought conditions in 1976 (U.S. Bureau of Reclamation, 1976e).

In 1977, the projected (and actual) inflow to Lake Shasta was 2.6 million ac-ft and decreases in contracted deliveries were made (U.S. Bureau of Reclamation, 1977a). The amount of decrease is specified in the water supply contracts. Reductions in 1977 were 25% for water rights users, 50% for municipal and industrial users, and 75% for agricultual contractors.

Navigation. Recognizing the possibility of 1977 being a critical water year, the Bureau discontinued navigation releases to the Sacramento River. Abandonment of navigation, the primary purpose of the project, was done simply by written notification in October, 1976 from the Bureau's Mid-Pacific Region office to the Corps Mid-Pacific Region office. These are the offices which operate and maintain Federal water resources projects in the Central Valley. The reasons the Bureau gave supporting their action are 1) commercial traffic was virtually non-existent on the Sacramento River and 2) tributary inflow to the Sacramento River was low (U.S. Bureau of Reclamation, 1976b). Low tributary inflow meant larger releases would be required from the Shasta/Trinity project to maintain required navigation river levels. The Corps responded verifying the Bureau's observations and stated they had no objection to the Bureau's plans (U.S. Bureau of Reclamation, 1976c). Conserving navigation releases saved at least 100,000 ac-ft of water supply in the Shasta/Trinity system (U.S. Bureau of Reclamation, 1976c).

Hydropower. Most of the power generated by the CVP is done by the Shasta/Trinity system. Hydropower operation is governed by CVP pumping needs (which amount to approximately 30% of normal annual generation of the entire CVP), contracts with "preferred" power consumers, and a "banking" arrangement for excess power. The "banking" arrangement is specified in the Pacific Gas and Electric (PGE) Interchange Agreement. Under this Agreement, excess power is sold to PGE with the provision that an equal amount may be re-purchased at a later time, when needed, by the CVP (U.S. Bureau of Reclamation, 1981). The agreement requires the Bureau to provide PGE with monthly forecasts of capacity and energy.

In March, 1977, the monthly forecasts of capacity and energy made by the Bureau indicated the CVP would not be able to support its Project Dependable Capacity (PDC) of 849 megawatts (MW). The Bureau conducted studies using very adverse hydrology and determined a PDC of 554 MW could be supported that year (U.S. Bureau of Reclamation, 1977a). The hydrology used was very similar to the actual conditions which occurred that year and the calculated PDC of 554 MW held through the year. In addition to lowering the PDC, the Bureau was required to draw upon its "banking" account with PGE to meet its contractural committment to its preferred customers.

During that year, only 3,418 million kilowatt-hours (kWh), 60% or normal, was generated by CVP (U.S. Bureau of Reclamation, 1977a). Hydropower revenues for 1977 experienced decreased revenues in three areas. First, there was less power to market. Second, "banked" power used to meet "preferred" consumers' needs had to be purchased by the Bureau. Third, lowering the PDC lowers the price PGE will pay per kilowatt of CVP power (Link, 1984).

As the drought wore through the summer of 1977 and reservoir levels dropped, generating power became more difficult. The Bureau borrowed 75,000 ac-ft from DWR at San Luis Reservoir in an attempt to avoid drawing Shasta Lake below the design designated minimum power pool of 580,000 ac-ft (elevation 858). This attempt failed. The Director of Design and Construction at the Bureau's Denver office approved power generation below 580,000 ac-ft as long as the trash racks were kept clean at all times and generation would stop at the first sign of air entrainment (U.S. Bureau of Reclamation, 1977c). Air entrainment is indicated by a vortex on the water surface above the power intake, Shasta Lake's level went below elevation 858 on August 29. The wicket gate opening was reduced by 75% and there were no vortex problems (U.S. Bureau of Reclamation, 1977d). The lowest level reached by the lake was 836.7 feet (562,600 ac-ft) on September 13. The actual minimum power pool was never reached.

Water Quality. Operation for Delta water quality dominated the entire CVP in 1977. Understanding CVP water quality operation requires background information on CVP and SWP water quality objectives for the Delta. Major reservoirs for both the CVP and the SWP make releases which flow to the Delta (see Figure 11). The Bureau's Delta water quality objectives were set in 1965 to meet the standards for irrigation supply exported from the Delta. CVP water supply has since evolved to serve municipal as well as agricultural needs. With this in mind, the Bureau tries to upgrade the quality of its deliveries but it does not view itself as legally bound to do so. The SWP must insure that water quality in the Delta meets criteria specified by California's Water Resources Control Board (WRCB). These criteria are much stricter than the Bureau's and are set by municipal and industrial supply limits and fish habitat requirements. When CVP releases to the Delta (via the Sacramento River) are not meeting WRCB quality limits, the SWP must increase its releases to the Delta. California's Department of Water Resources (DWR), SWP's managing agency, therefore interprets any failure of the CVP to meet WRCB standards as placing an unjustified burden upon the SWP and it believes the Bureau should accept WRBC specifications as CVP operating criteria.

On December 16, 1976, the agencies entered into an agreement to share in meeting negotiated Delta water quality objectives during 1977.

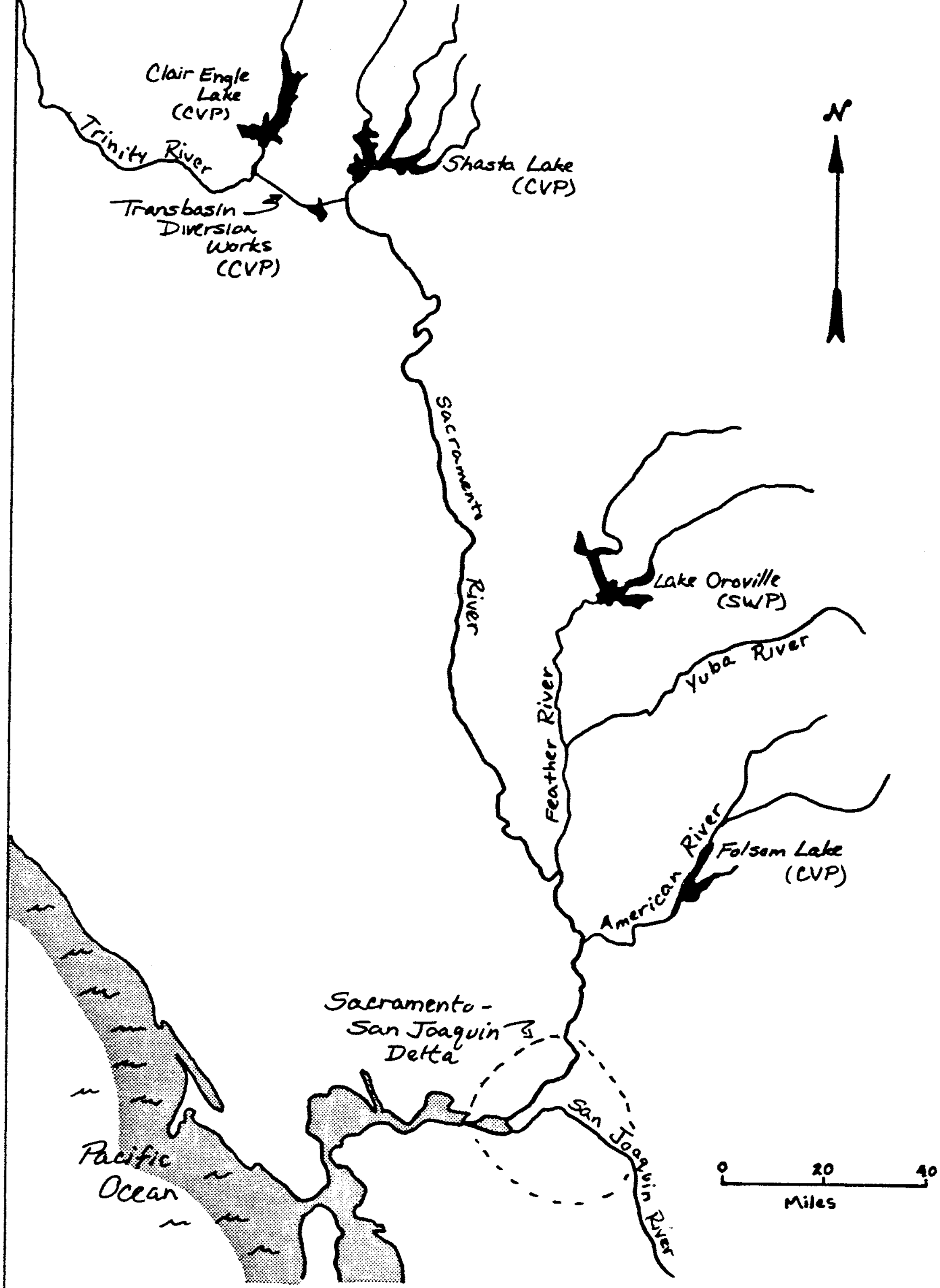


FIGURE 11 Major Reservoirs contributing to the Sacramento-San Joaquin Delta for Water Quality.

The agencies coordinated daily to determine releases required to produce "balanced water conditions". "Balanced water conditions" are periods when releases from CVP and SWP storages to the Sacramento River basin plus unregulated flow approximately equals the water supply needed to meet Sacramento River basin uses, WRCB Delta water quality objectives, plus exports from the Delta. In spite of the agreement, there were at least two occasions where DWR refused to wheel CVP water through SWP facilities because WRBC Delta water quality standards were not being met by the CVP.

Recreation. Of all the multipurpose functions provided by the Shasta/Trinity system in 1977, recreation was one of the most severely impacted during the drought. Maintaining reservoir levels for recreation use is not included in the projects' authorizations or in legal contracts with lake marinas. Operation of Lake Shasta and Clair Engle Lake could not give any consideration to recreation interests during the drought because both lakes are major water supply storage facilities. Whiskeytown Lake is not a major water supply facility. Its active storage amounts to 3% of the total active capacity of the Shasta/Trinity system.

The major purpose of Whiskeytown Lake is to hold Trinity River diversions for release through a power conduit to the Sacramento River. Normal operation of Whiskeytown Lake keeps maximum annual water level fluctuations under 5-10 feet. Minimizing fluctuations serves two purposes. First, the power generation ability of releases through the power conduit is maximized by a high lake level. Secondly, the 12-15 million dollars in annual revenue to Shasta County by recreation on the lake is maintained (Martin, 1977b).

The Bureau originally planned Whiskeytown Lake to be drawn down below its normal level during the summer of 1977. When the Bureau proposed this operation to public and private interests during four meetings in January, 1977, many complaints were made regarding the impact it would have upon recreation (U.S. Bureau of Reclamation, 1977a). Re-examination showed Whiskeytown Lake levels would be held within normal levels. Normal lake elevation is 1210 feet. By September 1, 1977, the level had dropped only 7.5 feet (elevation 1202.5).

Recreation usage of Shasta, Clair Engle, and Whiskeytown Lakes is listed in Table 4. There are drastic drops in attendance at Shasta and Clair Engle Lakes. Their attendance dropped over 65% and 80% respectively from 1975 to 1977. This phenomenon is understandable given the lake levels occuring during the summer of 1977. Shasta and Clair Engle lake levels were each almost 200 feet below normal (U.S. Bureau of Reclamation, 1977a). Whiskeytown Lake's attendance increased over the two years with 1977 attendance 25% over that in 1975.

Fish Habitat. The Shasta/Trinity system did not make releases to the Sacramento River for fish habitat in 1977. Water stored in Lake Shasta was too warm for fish fry survival. Trinity Dam made releases of cooler water from its low-level outlets to Trinity River to meet its fish spawning needs. Power generation at Trinity Dam was completely lost at times due to these releases. The loss in hydropower revenue resulting from this operation was compensated by Federal drought emergency funds (U.S. Bureau of Reclamation, 1977a).

c. Summary Comments

Table 5 summarizes the status of each project purpose and the reason directly governing operation for that purpose. As contained in

TABLE 4: RECREATION USAGE AT THE SHASTA/TRINITY SYSTEM RESERVOIRS (VISITOR-DAYS)

	1975	1976	1977
LAKE SHASTA	2,161,000	1,176,000	726,000
CLAIR ENGLE LAKE	174,000	153,000	31,000
WHISKEYTOWN LAKE	1,274,000	1,632,000	1,617,000

Reference: California Department of Water Resources, 1978a.

TABLE 5: 1977 PURPOSE STATUS AND OPERATION CONSTRAINTS FOR THE SHASTA/TRINITY SYSTEM

PROJECT PURPOSE	1977 STATUS	OPERATION CONSTRAINT
Navigation	Abandonned	U.S. Congressional Project Authorization (1937 Rivers and Harbors Act).
Water Supply	Deliveries cut 25% to 75%	Legal contracts between U.S. Government and consumers.
Hydropower	CVP and "Preferred" 25% to 75% consumer demands completely met.	Legal contracts between U.S. Government and consumers.
	Project Dependable Capacity dropped from 849 MW to 554 MW.	Inadequate water supply.
Water Quality	CVP water quality criteria deferred to State water quality criteria.	Agreement between State agencies and Bureau. (Not legally binding.)
Recreation	Provided at Whiskey-town Lake. Abandonned at Lake Shasta and Clair Engle Lake.	Local concerns over recreation revenue impact. Inadequate water supply.
Fish Habitat	None made by Shasta Dam. Releases made to Trinity River by Trinity Dam.	Temperature of stored water.

the Table and the previous discussion, Congressional project purpose assignment does not play a direct role in project operation in 1977. Navigation, the first priority purpose in the Congressional purpose hierarchy, was abandonned simply and quickly through the Mid-Pacific Region offices of the Corps and Bureau. The Congressional directives indirectly constrained Shasta/Trinity operations during 1977 in that they shape the form and substance of water supply and hydropower contracts of the CVP. These contracts, in turn, directly constrain Shasta/Trinity operation.

There are diverse reasons for project operations for water quality, recreation, and fish habitat. Operation for water quality is defined by institutional interaction. Recreation operation is not bound by legal commitments however, local concerns may modify project operation. The physical limitation of high water temperature prevents fish releases in Lake Shasta and modifies releases from Trinity Dam.

Great variation exists in the legal, institutional, and physical arrangements of Federal multipurpose reservoirs. The project purpose operation constraints to the Shasta/Trinity system help define areas where operation constraints during drought for any Federal multipurpose reservoir may originate.

II.B.2. Special Operations for Fish Habitat

Multipurpose reservoir management requires balancing the benefits and negative impacts any operation may have upon the reservoir purposes. The following section illustrates an operation option for fish habitat and its impact upon hydropower generation.

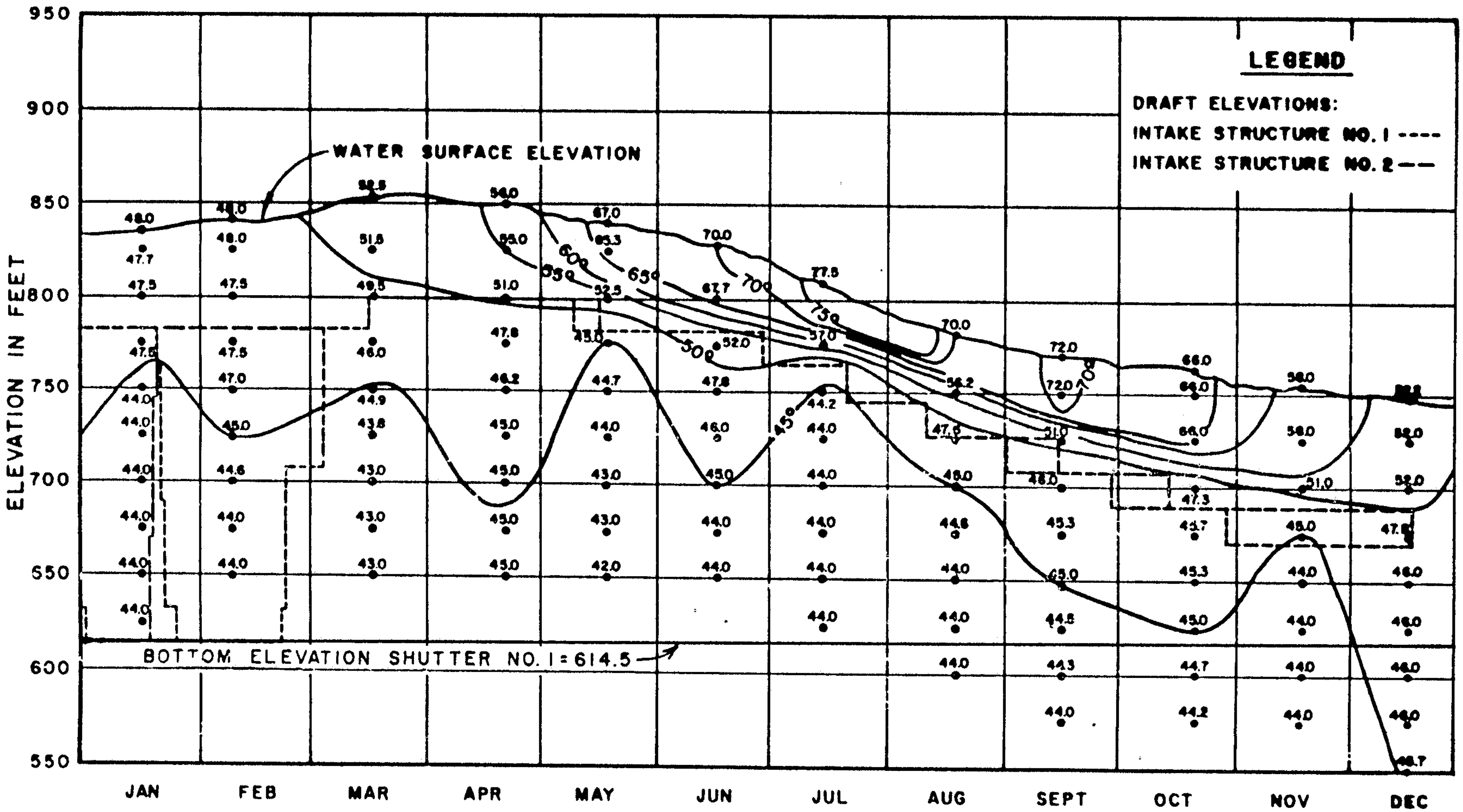
a. Thermal Stratification in Reservoirs

Thermal stratification is a common occurrence in reservoirs. It is caused by solar energy warming the reservoir surface. This energy is conducted downward, heating the upper depths of the reservoir. Figure 12 contains a plot of isotherms for Lake Oroville, a reservoir on the Feather River in Northern California. The isotherms vary with solar intensity, warming the reservoir's surface to a maximum of 77.5° F in mid-July. Depths below 650 feet remain close to 45°F throughout the entire year.

Thermal stratification may complicate reservoir operation if reservoir releases are used to support natural fish habitat or fish spawning conditions in hatcheries. The problems occur when the temperature at the normal outlet is too high for fish fry or egg survival. This is most likely to happen during droughts where warm surface layers are drawn closer to the outlet as water supply dwindles. Near the end of the critically dry Fall of 1977, Lake Oroville was operated to maintain fish spawning conditions on the Feather River during a period when thermal stratification prevented releases through its normal outlets. The following text discusses the special operation and its economic issues and impacts.

b. Oroville-Thermalito Complex Description.

Lake Oroville is the primary storage facility for California's State Water Project (SWP), providing 4.2 million ac-ft of water supply annually (California Department of Water Resources, 1975). It is one facility of the Oroville-Thermalito Complex (see Figure 13). The Complex provides recreation, hydropower, and fish habitat benefits. Releases from Lake Oroville normally flow through Oroville Dam's Edward Hyatt Power Plant down the natural channel of Feather River to the Thermalito Diversion Dam. Here, the releases are regulated to proceed



Temperature in degrees Fahrenheit.

FIGURE 12 Lake Oroville Isotherms, 1976

(California Department of Water Resources, 1976)

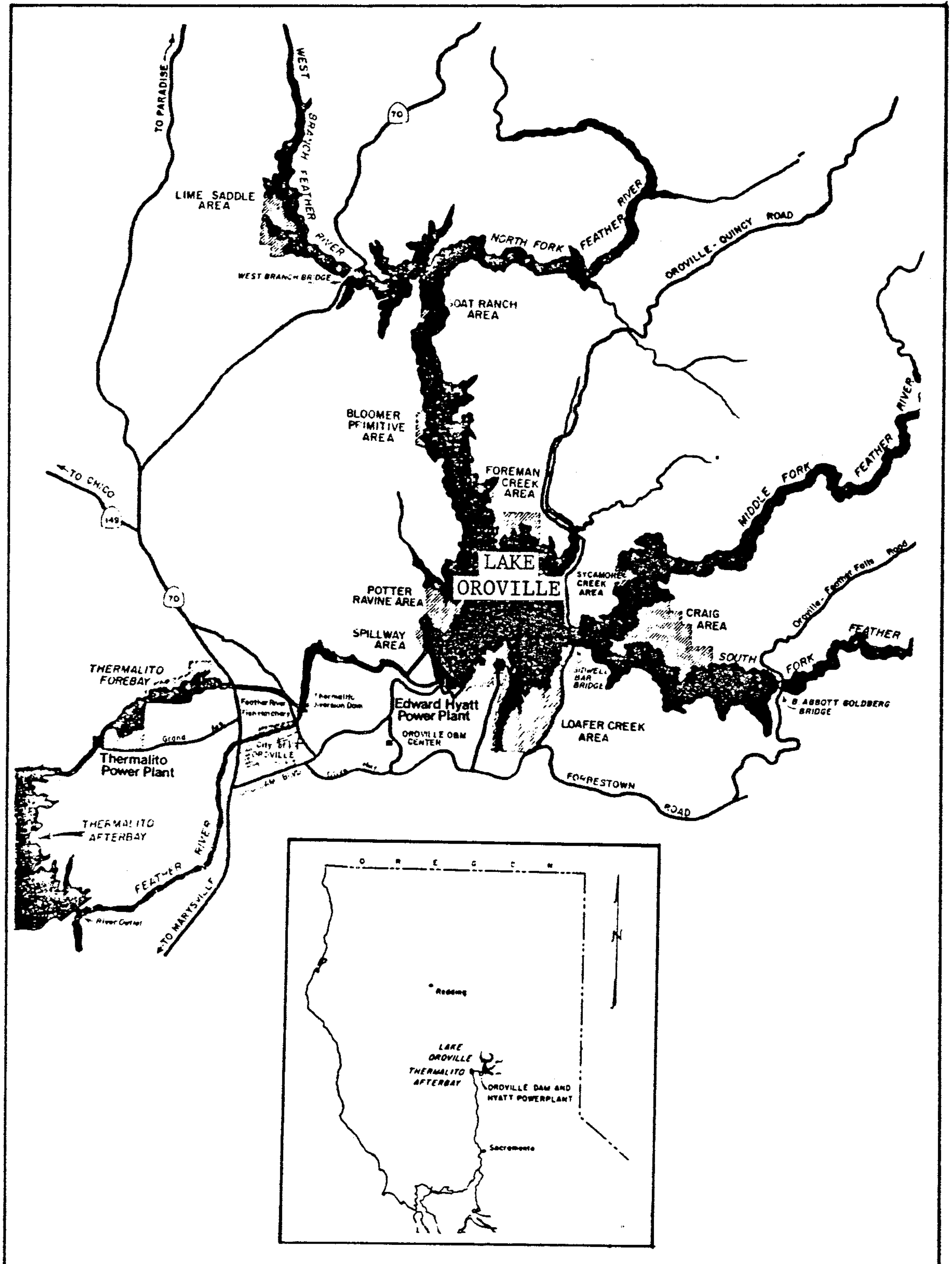


FIGURE 13 The Oroville-Thermalito Complex, Oroville, CA

(California Department of Water Resources, 1975 and 1976b) down the natural channel through the Feather River Fish Hatchery or be diverted to pass through the Thermalito Power Plant. Average annual energy output totals 2.8 billion kWh, 2.4 billion being generated at Edward Hyatt Power Plant and the remaining at Thermalito (California Department of Water Resources, 1975).

The Feather River Fish Hatchery compensates the anadromous fishery for spawning habitat which was lost to inundation by Lake Oroville. Spawning conditions at the hatchery require flows regulated for quantity and temperature. The diversion dam regulates the amount of flow. Edward Hyatt Power Plant's variable intake structure regulates the release temperature, in normal years, by adjusting the intakes to the 45 F to 55^{o}F isotherm elevation. Intake elevations are included in Figure 12.

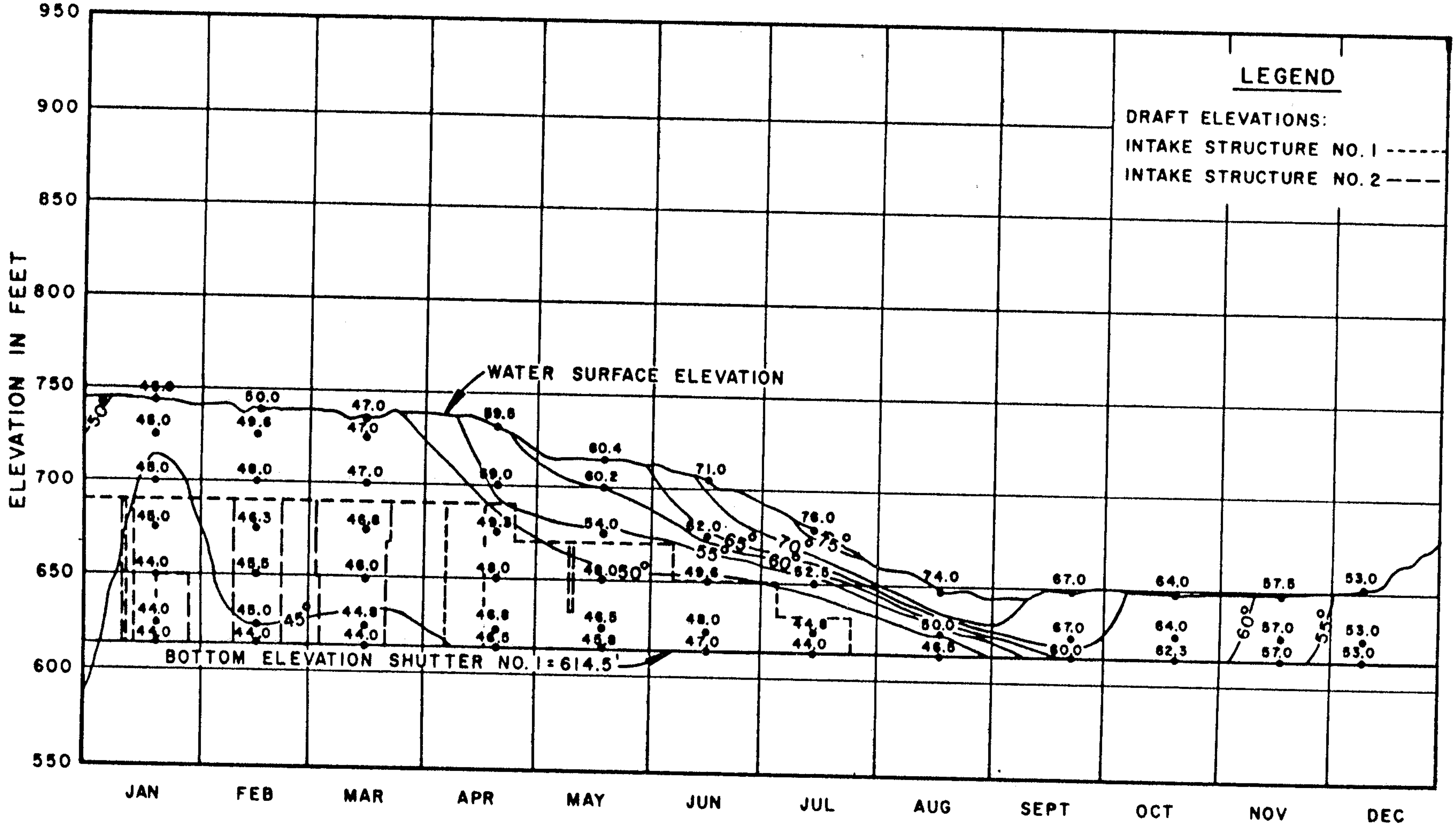
c. 1977 Fish Operations.

In 1977, anadromous fish spawning conditions could not be maintained on the Sacramento or American Rivers because water in the major storage facilities was too warm for fish fry and egg survival. As a result, Feather River and its hatchery became the sole location of fish spawning activities in the Sacramento River Basin. Fish at other Basin facilities were brought to the Feather River Hatchery by a special State Department of Fish and Game program (California Department of Water Resources, 1978a). As a result of this program, the Oroville-Thermalito Complex was operated primarily for fish habitat during September through mid-November. These operations directly impacted hydropower generation at the Edward Hyatt and Thermalito power plants.

Thermal stratification within Lake Oroville in mid-September produced temperatures of 60°F an the bottom elevation of the powerhouse intake (see Figure 14). In order to meet the 57°F limitation set by the Department of Fish and Game for water temperature at the hatchery, releases from the powerhouse intake were mixed with special releases from a river outlet valve system (elevation 227 ft). This outlet was designed for making releases only during the initial filling of the reservoir in the fall of 1968. It is not considered a normal operation feature. Releases began in mid-September and were made only as needed to maintain water temperature below 57°F at the hatchery when combined with the power generation releases. The total volume of water released through the valve system amounted to 47,500 ac-ft (California Department of Water Resources, 1978a). The energy foregone by this operation was 17.7 million kilowatt hours and worth about $46,000 (Henkel, 1984).

Generation at Thermalito Power Plant was not impacted by the outlet-valve releases at Oroville Dam however, fish habitat operations for a segment of the Feather River did decrease its generation for one month. From October 4 through November 11, increased streamflow was required in Feather River between the hatchery and the Thermalito river outlet to enhance natural spawning conditions. As a consequence, flows to the river at the diversion were increased from 400 cfs to 800 cfs. About 31,200 ac-ft bypassed the Thermalito Power Plant costing $6,250 in foregone hydropower revenue (Henkel, 1984).

Total worth of hydropower revenue foregone due to these operations is $52,250. This cost was repaid through grants authorized by the Federal Emergency Act of 1977 (Public Law 95-18) (U.S. Bureau of Reclamation, 1977a). The amount of foregone hydropower revenue would have been much larger had not the CVP and SWP cooperated during the fish



Temperature in degrees Fahrenheit.

FIGURE 14 Lake Oroville Isotherms, 1977

(California Department of Water Resources, 1977b) habitat operation. This cooperation allowed the releases from Lake Oroville to be restricted to only those required for hydropower generation and the temperature-modifying, low-level releases. As discussed in Section II.B.1, "Multipurpose Reservoir Operation", both the SWP and CVP were operating for "balanced water conditions" in the Sacramento River Basin and the Sacramento-San Joaquin Delta. To provide "balanced water conditions" in mid-September, approximately 2000 cfs would have been required from DWR's Lake Oroville. If DWR were to meet this commitment, it would mean a substantial loss of energy because much water would be required to be released from the low-level valves to mix with the warmer water coming through the power plant. The Bureau agreed to allow DWR to go deficit in the "balanced water conditions" with the Bureau making up DWR's share. This was accomplished without increasing withdrawals from Trinity or Shasta Reservoirs but by decreasing exported water pumped at Delta facilities.

Henkel has calculated a return of $192 for every dollar of hydropower revenue lost during the special fish habitat operations conducted at the Oroville-Thermalito Complex (Henkel, 1984). This figure is based upon the number of fish returning to spawn in Feather River and the hatchery in 1981. The fish return large fish return is subject to several other factors. The Oroville-Thermalito Complex operation for fish habitat was, however, a primary reason for the return so, although the 192-1 ratio may not be exact, it does prove the operation to be very cost effective. It would be interesting to compare the cost of the Department of Fish and Game's program plus the foregone hydropower revenue to the estimated value of the fish returning to the Sacramento, American, and Feather rivers. This comparison would give an estimation of the fish habitat program's overall economic success from the State's viewpoint.

c. Summary

Lake Oroville's operation during September to mid-November illustrates several points for reservoir operation for fish habitat during droughts. First, thermal stratification may prevent a reservoir from supporting stream fish habitat or require reservoir operation changes to support the habitat during drought. Secondly, these operational changes will involve releasing cooler water deep in the reservoir to the stream. For some reservoirs, a low-level outlet may exist which will accomodate these releases. Thirdly, coordination with other reservoir systems may help minimize foregone hydropower revenues by allowing fish habitat operation to predominate the reservoir operation. Finally, for reservoirs which also operate to generate hydropower, the revenue foregone by fish habitat operation may be small when compared to the financial benefit of maintaining the fishery.

II.B.3. Drought Risk Analysis

This section illustrates first, how a change in the choice of critical period in a reservoir's safe yield analysis changes the perceived severity of a drought and, second, how risk assessment analysis provides direction in water supply system management.

A reservoir's safe yield is generally defined as a constant rate of withdrawal which will just empty the reservoir during a recurrence of a specified historical critical period. In most cases, the critical period is the period which requires the largest volume of stored water to meet the designated demands. During a safe-yield analysis, the reservoir is assumed full at the beginning of the critical period. Its storage decreases as withdrawals exceed inflows to the point where reservoir storage is depleted. If the withdrawal rate is the safe yield, the inflows will begin to exceed the withdrawals immediately after reservoir depletion, and the reservoir begins to refill. Safe yield is dependent upon the choice of the critical period. If, for a given system, a more severe critical period is found by either a more detailed analysis or by the addition of years to the historical record, the safe yield will decrease.

a. Occoquan Reservoir's Safe Yield

Examples of this occurrence are the safe-yield analyses done in 1976 and 1977 for Occoquan Reservoir. In 1977, Occoquan Reservoir was the primary source of water supply for the Fairfax County Water Authority (FCWA). FCWA serves approximately 650,000 people in Fairfax County, Virginia, a Washington, D.C. suburb (Sheer, 1980). Occoquan Reservoir lies on Occoquan Creek, a tributary to the Potomac River (see Figure 15). During August, 1977, withdrawals from Occoquan Reservoir were averaging 70 million gallons per day (mgd) (Sheer, 1980). This was over the safe yield value of 65 mgd, which was developed by a study done in 1976. FCWA felt October's normal seasonal reduction in water consumption would produce an average demand below 65 mgd and, therefore, did not intend to implement any conservation measures. However, because the water level was dropping quickly and to gain the public's support of conservation measures, another safe yield analysis was conducted in late August. This analysis used a different critical period and placed the safe yield at 54 mgd (Sheer, 1980). The new safe yield value increased the perceived severity of the water supply situation.

With respect to reservoir operation during a drought, safe yield

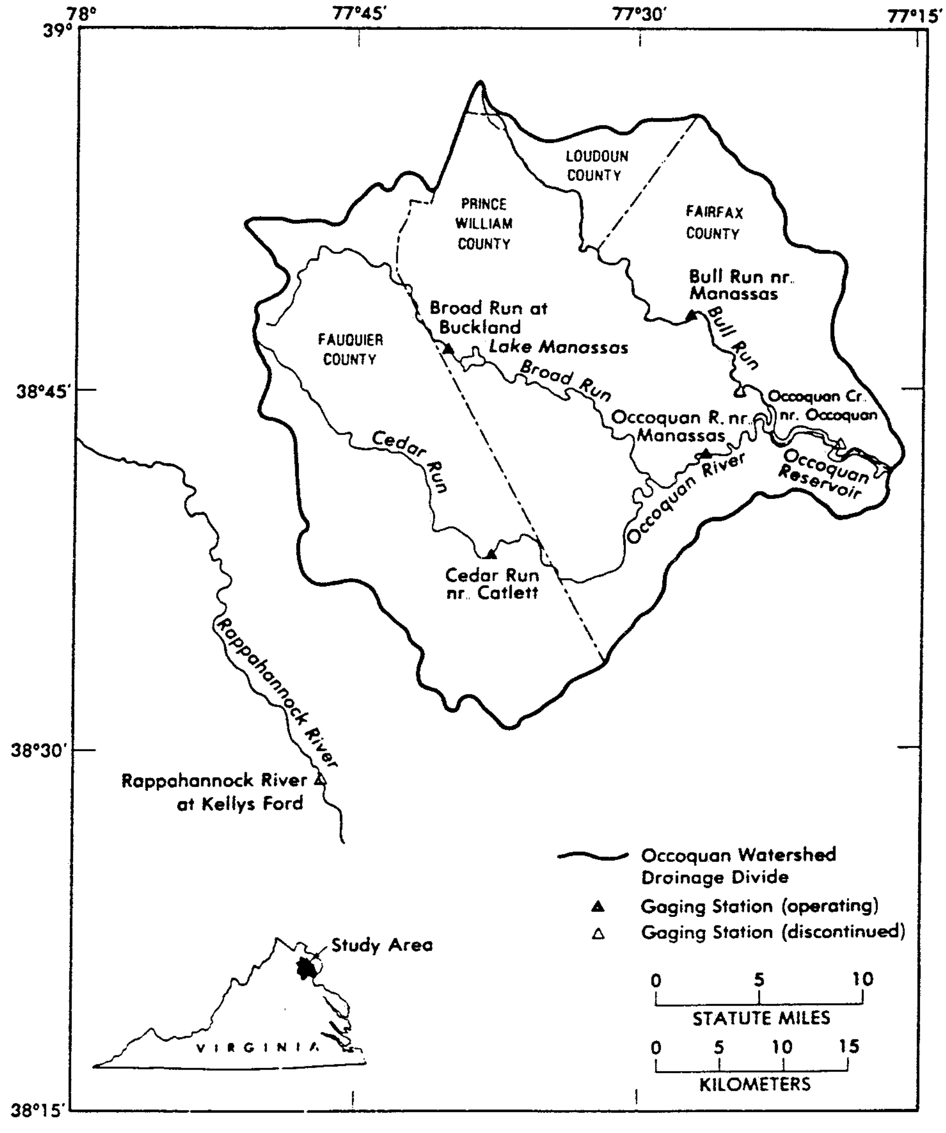


FIGURE 15 Occoquan Reservoir, Fairfax County, Virginia (Sheer, 1980)

can provide only a general operation guideline. Given a safe yield of 65 mgd, the FCWA thought normal consumption decreases, as opposed to implemented consumption restrictions, would see the supply through the drought. With a safe yield of 54 mgd, the FCWA knew mandatory conservation measures had to be taken but the safe yield value gave them little information regarding the amount of reduction. FCWA managers needed information regarding the chance of running out of supply given the current conditions and information addressing the amount and timing of reduction measures. To develop this type of information, a risk assessment analysis was conducted.

b. Risk Analysis of Occoquan Reservoir

The FCWA began their assessment with a simple position analysis, a specialized application of risk assessment. The analysis was done using the current reservoir storage of September 1, 1977, historical monthly inflows beginning September 1, and expected consumption and evaporation losses (Sheer, 1980). Each year's recorded inflows were routed through the reservoir to discern if the reservoir would be depleted that year. The analysis showed Occoquan Reservoir would have run dry during 4 of the 26 years of record (Sheer, 1980). This produces a risk of 15%. FCWA, therefore, had a 15% chance of running out of water in the near future.

The general equation used in the position analysis is contained in Table 6. Further studies were done for the FCWA by the U.S. Geological Survey (USGS) and the National Weather Service (NWS) to refine the estimate of risk. The refinement was done by modifying 2 terms of the general equation, monthly inflow and withdrawals. The USGS extended the data using linear regression of flows at gages on Occoquan Creek with

TABLE 6: GENERAL EQUATION FOR POSITION ANALYSIS FOR THE OCCOQUAN RESERVOIR

$$S(i,t+1)=S(i,t)+I(i,t)+M(t)-E(i,t)-W(t)$$

where $t=1, 2, \ldots, 11$
$i=1, 2, \ldots, n$
$S(i,1)=V$

V=Storage at the beginning of the present month.

n=Number of years of record.

I(i,t)=Inflow during month t for year i.

M(t)=Purchased water flowing into Occoquan Reservoir during month t.

E(i,t)=Evaporation during month t in year i.

W(t)=Withdrawals during month t.

S(i,t+1)=Storage at beginning of month t+1 during year i.

(Hirsch, 1978)

longer flow records on nearby drainage basins. This extended record was adjusted to remove those years which were not similar to the current year (i.e. the "wet" years). The NWS used their River Forecast System model (NWSRFS) and historical meteorological data to produce a set of streamflow series which were more representative of possible future conditions than the historical record. Because the information most useful for FCWA water supply managers was the amount of withdrawal decrease which with reasonable certainty would prevent the storage from going below a specified storage level, the withdrawal amount was varied between realistic limits.

Specifically, the questions addressed by both position analyses were: 1) What is the probability that the storage will fall below 1,100 million gallons in the next six months, given a withdrawal of 40 mgd? 2) How would this probability change if the withdrawal rate for the entire period were changed to 32 mgd or 48 mgd? (Hirsch, 1978). The USGS study answered these questions using the derived monthly inflow values for the months September-March and a constant withdrawal rate for each of 22 years of record (Hirsch, 1978). Another study showed Occoquan Reservoir's risk of shortage was virtually zero in any year for the period March through August and, hence, the study was limited to September 1, 1977 through March 31, 31, 1978. If it were shown Occoquan Reservoir's storage would fall below 1,100 million gallons two out of the 22 years of inflow data with a withdrawal rate of 40 mgd, a 10% chance existed that the reservoir storage would be at or below that level in the near future. This information is summarized in a plot of the Cumulative Distribution Function (CDF). Figure 16 is a plot of the CDFs for the minimum storage in Occoquan Reservoir for withdrawal rates

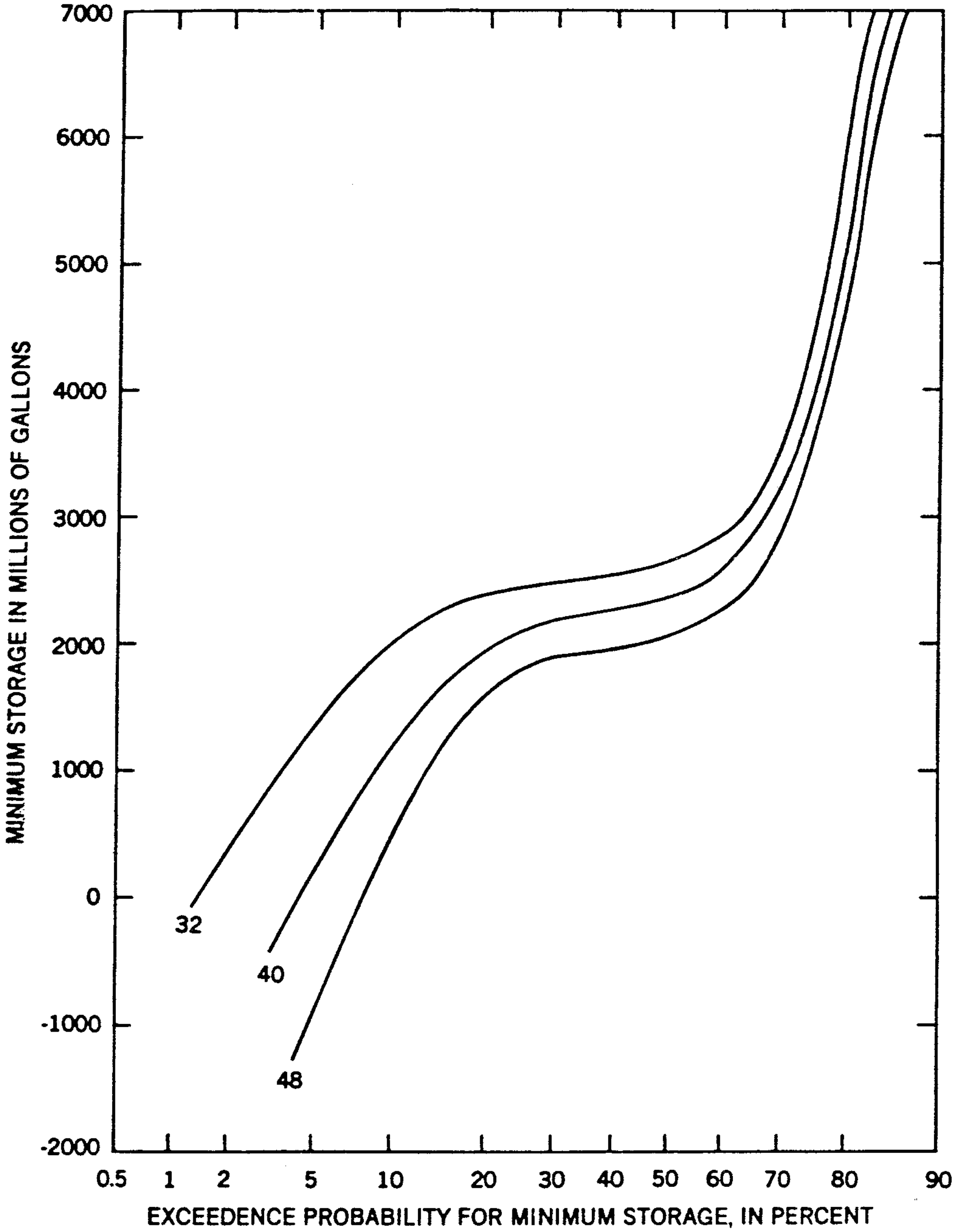


FIGURE 16 The Cumulative Distribution Functions for Occoquan Reservoir for withdrawal rates of 32, 40, and 48 million gallons per day. (Hirsch, 1978)

of 48, 40, and 32 mgd. One sees there is a 10% chance that the minimum storage will be less than or equal to 1,100 million gallons given a withdrawal rate of 40 mgd. (There is also a 90% chance that storage will be greater than or equal to 1,100 million gallons given the same withdrawal rate.)

The CDF plot provides a simple and visual summary of the risk of reaching any storage level (or deficit) given the withdrawal rate. This information is valuable to water supply managers because they can decide the risk they are willing to accept and develop their course of action. For instance, they may balance the withdrawal rate reduction they decide is achievable with the use of other supplies or decide to install very strict water use restrictions immediately.

One element which distinguishes a good position analysis is that the results are useful to the water supply management group (water suppliers and local government officials). To obtain these results, the results of the analysis must be defined through interaction with this group. Technical-political interaction for the FCWA risk assessment was done by forming an advisory group of local government staff members at the inception of the study (Sheer, 1980). This group assisted in determining the objective of the analyses by describing the existing conservation plan and determining what risk was to be controlled. In this case, the officials desired to avoid the measure of closing schools and businesses to conserve water supply. The technical teams (USGS and NWS) were aware of the length of time involved to obtain various types of information, so they also helped to shape the objective to one that could be obtained relatively quickly.

The advisory group also kept local government officials informed of the studies' progress. This helped to maintain the cooperation of the local governments and, in turn, the public. Also, by continually interacting with the study teams, the advisory group was kept aware of preliminary results regarding the risk of reaching the critical level with the current withdrawal. This information helped them to judge the severity of their water supply condition and to decide if emergency withdrawal reductions should be implemented immediately. The decision was assisted by an analysis which determined the effect of delaying implementation of conservation measures. Preliminary results indicated a 12 gallon per day per person (gpcd) reduction would decrease the risk of reaching the critical level from 10-15% to approximately 3-5% (Sheer, 1980). The advisory group was to determine whether to implement this reduction immediately or wait for confirmation of the results. The probable results of this delay were analyzed. Delaying the reduction two weeks would mean using an additional 112 million gallons of water (Sheer, 1980). This represented about a four days supply or at the most an additional week of time to wait for rain if the drought extended into the winter (Sheer, 1980). The advisory group decided to delay the decision for two weeks to be certain reductions were necessary. The study team confirmed their decision knowing the 112 million gallons would not impact the risk significantly.

Although not discussed here, interaction between technical groups and political groups was particularily important during the FCWA experience. Even under these circumstances, meetings between the two groups occurred only three times. The first meeting determined the analysis objective and described the consumption reduction program to be implemented. The second meeting discussed preliminary results and established criteria to indicate when the consumption restrictions could be removed. Results of the analysis were presented at the third meeting and the amount and time of implementation of conservation restrictions were decided upon. All meetings were held within a 25 day period, which is also the time required to conduct the position analyses. The subject matter, timing, and number of meetings during the FCWA position analyses appear to be ideal. Meeting less would probably prevent full information transfer between groups. Meeting more would imply unforeseen complications in the analysis.

c. Summary Comments

The FCWA experience illustrates the dependency of a reservoir's safe yield upon its critical period and how a safe yield value gives only a qualitative assessment of a reservoir's ability to supply water during an existing drought. It also gives an example of how drought risk analysis serves to alter operating objectives by quantifying the risk of their implementation.

Position analysis is a valuable decision tool which has a simple, straightforward basic equation which is easily modified to describe any water supply system. Modification is done by adding or subtracting terms to the equation. Refinement of the analysis comes with the description of these terms. The FCWA has incorporated the USGS model into its computer system and performs a position analysis each month (Sheer, 1980). Other water supply agencies could do the same. With a moderate investment of time and money, a large return in understanding the status of their water supply situation could be obtained.

III CURRENT DROUGHT OPERATIONS

The water supply systems studied in this report have changed their reservoir operations or have developed drought operation plans as a result of their drought experiences. The following sections describe these operation changes and drought operation plans and gives background information regarding the technical analyses, institutional and public interaction, and other components required for plan development. For the systems where no drought operation plan exists, the reasons for its lack of development are given.

Comparison of the water supply systems' actual drought operation with their drought operation plans will give a general understanding of the evolution of drought operation plans. Comparison of the drought operation plans with one another will identify similarities in development and plan components that can be expected to form the basis of any drought operation plan. The conclusions from these comparisons are presented in the "Conclusions" section, Section IV.

III.A. CALIFORNIA'S CENTRAL VALLEY

III.A.1. State Water Project

In 1976, SWP operation was based upon projected annual inflow to Lake Shasta. Because the projected value was 3.6 million ac-ft in 1976, the SWP met all its contractural deliveries and released 580,000 ac-ft of surplus water. As a result, SWP carryover storage for 1977 (storage existing on October 1, 1976) was 2.9 million ac-ft, 69% of normal (California Department of Water Resources, 1984). The events of 1976 and 1977 illustrated the inadequacy of inflow to Lake Shasta as a criterion for reservoir (and project) operation. In mid-1977, the DWR began developing operation plans based upon unimpaired runoff of the four major rivers in the Sacramento River Basin. The plan development was done in conjunction with the State Water Resources Control Board (WRCB), the agency which sets and enforces Delta water quality standards. The four rivers are the Sacramento, American, Yuba, and Feather (see Figure 11). They contribute most of the inflow to the Delta and, along with the exports out of the Delta, determine extent of salinity intrusion. The WRCB's goal was to develop an indicator which would allow the standards to be lowered during dryer years yet maintain Delta water protection. DWR's goals for the operation plan were to meet Delta water quality objectives and maintain a specified carryover storage (storage remaining at the end of the water year) in the project by adjusting water supply deliveries.

The SWP was then and is now free to pursue new operation criteria because it is not contracturally constrained to any particular operation criteria. Water supply contracts allow much operation flexibility, requiring only that operation plans not be "arbitrary, capricious, or unreasonable" (California Department of Water Resources, 1977c). Power contracts do not restrict reservoir operation for fish habitat, Delta water quality, or water supply deliveries to water-rights holders or contractors. In the contracts, the term "deliveries" includes those for the current and future years hence operation to maintain carryover storage is not constrained (California Department of Water Resources, 1977c).

The decision tool developed by the SWP to estimate deliveries is called its "Water Delivery Rule Curve" (Rule Curve). It has been used every year since 1977. The Rule Curve was developed via computer simulations of SWP operations for various types of water years ranging from critical (99% chance of exceedance) to wet. The water year type was determined by probability analysis of the four rivers' annual flow totals. Operational assumptions regarding Delta water quality objectives, CVP operation, local reservoirs' operation, system losses, etc. were included in the computer simulations. Carryover storage requirements were also included.

The carryover storage amount is based upon the project's ability to make deliveries to contractors the year following the primary year of interest. For example, 2.9 million ac-ft of storage is required at the end of the year if only the contracted deliveries are to be met during that year. This automatically assumes the following year's deliveries could be cut up to 50%. If any additional water is to be delivered during the first year, then storage at the end of that year must be 3.2 million ac-ft. This volume implies cuts in deliveries during the second year of a maximum of 25% if necessary. Both carryover storage values provide for 2.0 million ac-ft of carryover storage to begin the third water year. This volume is a "bare bones" amount which would meet Delta water quality requirements and provide minimum, emergency supplies. With these assumptions, the Rule Curve provides operational guidelines for three years of unimpaired runoff that are each near the lowest of record (California Department of Water Resources, 1977c).

The Rule Curve incorporates the risk of reduced water deliveries by allowing delivery forecasts to be based upon a range of exceedance probabilities of four-river runoff for the first year of a two year period. The official delivery forecast is based upon four-river runoff for the first year with a 99% probability of exceedance. There are, however, delivery forecasts for four-river runoff values with 90%, 75%, 50%, and 25% exceedance probability. Delivery forecasts begin in December and are revised each month. An annual report issued by the DWR in January discusses the probabilities in layman's terms and public meetings are held to discuss the forecasted deliveries. The agricultural water contractors are given a good sense of the potential water supply situation and can make informed decisions regarding the amount and type of crop to plant.

The first Rule Curve, developed for 1978, illustrates use of the decision tool well and is included here as Figure 17. Runoff forecasts at that time were done for 99%, 75%, 50%, and 25% chance of exceedance. (90% chance of exceedance was not included.) The runoff forecasts were based upon precipitation criteria for the first year listed in Table 7. The second year's runoff is assumed to be the same as the second worst drought of record for the CVP (1924, with approximately a 98% probability of exceedance). Because the approved delivery schedule is based upon very conservative conditions, the projected amount of deliveries is expected to increase as actual runoff supersedes the prediction.

For example, if in December the approved deliveries are based upon an unimpaired flow value of 8.0 million ac-ft, the approved delivery amount given by Figure 17 is 1,100,000 ac-ft. By March, the actual flow has amounted to 6.1 million ac-ft. At that time, an additional 3.4 million ac-ft is projected for the remainder of the year using the minimum precipitation of record for April, May, and June, and the actual snowpack on the forecast date. This is the criteria for the runoff with 99% probability of exceedance listed in Table 7. The total projected unimpaired runoff for the water year is therefore revised to 9.5 million

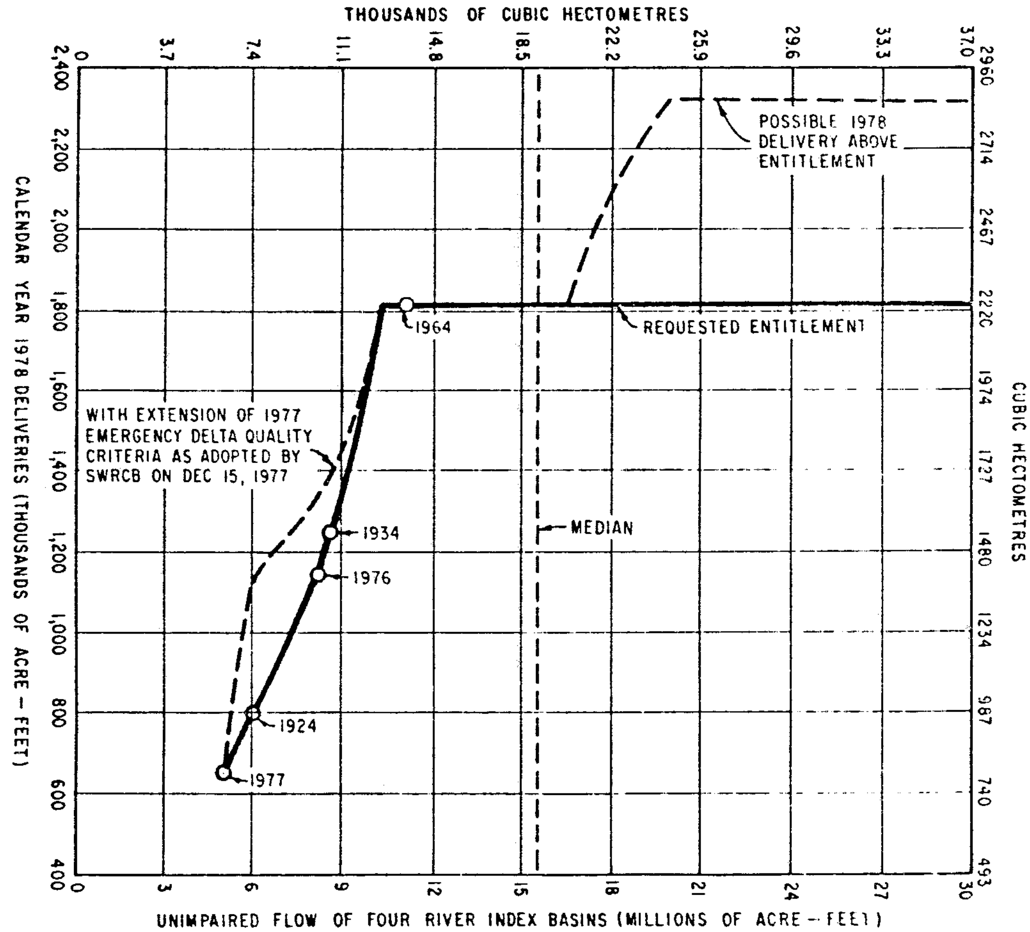


FIGURE 17: California State Water Project Rule Curve for 1978 (California Department of Water Resources, 1977c)

TABLE 7: ASSUMPTIONS REGARDING FUTURE PRECIPITATION FOR DETERMINING THE EXCEEDANCE PERCENTAGE FOR THE ANNUAL FOUR-RIVER RUNOFF FORECAST

RUNOFF FORECAST	PRECIPITATION ASSUMPTIONS
Minimum runoff with a 99% chance of being exceeded--for use in approved delivery schedule.	Minimum precipitation of record for the remaining months through June and actual snowpack on forecast date beginning February 1.
Runoff with a 75% chance of being exceeded	Lower quartile precipitation for balance of the year and actual snowpack on the forecast date.
Runoff with a 50% chance of being exceeded	Median precipitation for balance of the year and actual snowpack on the forecast date.
Runoff with a 25% chance of being exceeded	Upper quartile precipitation for balance of the year and actual snowpack on the forecast date.

(California Department of Water Resources, 1977c) ac-ft which gives, again from Figure 17, an approved delivery capacity of 1,600,000 ac-ft. Projected deliveries based upon runoff with 75%, 50%, and 25% probabilities of exceedance are found the same way.

The Rule Curve underwent a major change in 1982 when it was discovered to not be as conservative as originally thought. In lieu of being based upon unimpaired flow for the entire water year, the projected deliveries are based upon unimpaired flow for the remainder of the water year. The Rule Curve is now a family of curves (see Figure 18). This was done to correlate the four-river index more closely to delivery capability. When high runoff occurs early in the water year, the index is increased without a commensurate increase in project delivery capability. This is because most of the runoff is not stored in Lakes Oroville, Shasta, or Folsom but is released to maintain flood storage space (California Department of Water Resources, 1982). For example, if four MAF were predicted to flow in the four basins during the period December through September, Figure 18 indicates the water delivery capability of the SWP would be only 750,000 ac-ft. If the four MAF were predicted to runoff during the period February through September, 1,600,000 ac-ft could be delivered by the SWP. This is because more flood control space must be maintained in the reservoirs during December and January than in February. Consequently, runoff that is received in December or January is likely to be released rather than conserved.

The approved delivery schedule is very conservative and as such may indicate a shortage when there actually will be none. This is a problem of which the water resources manager must be aware. An incident which occurred in Yakima, Washington illustrates what can happen when a water

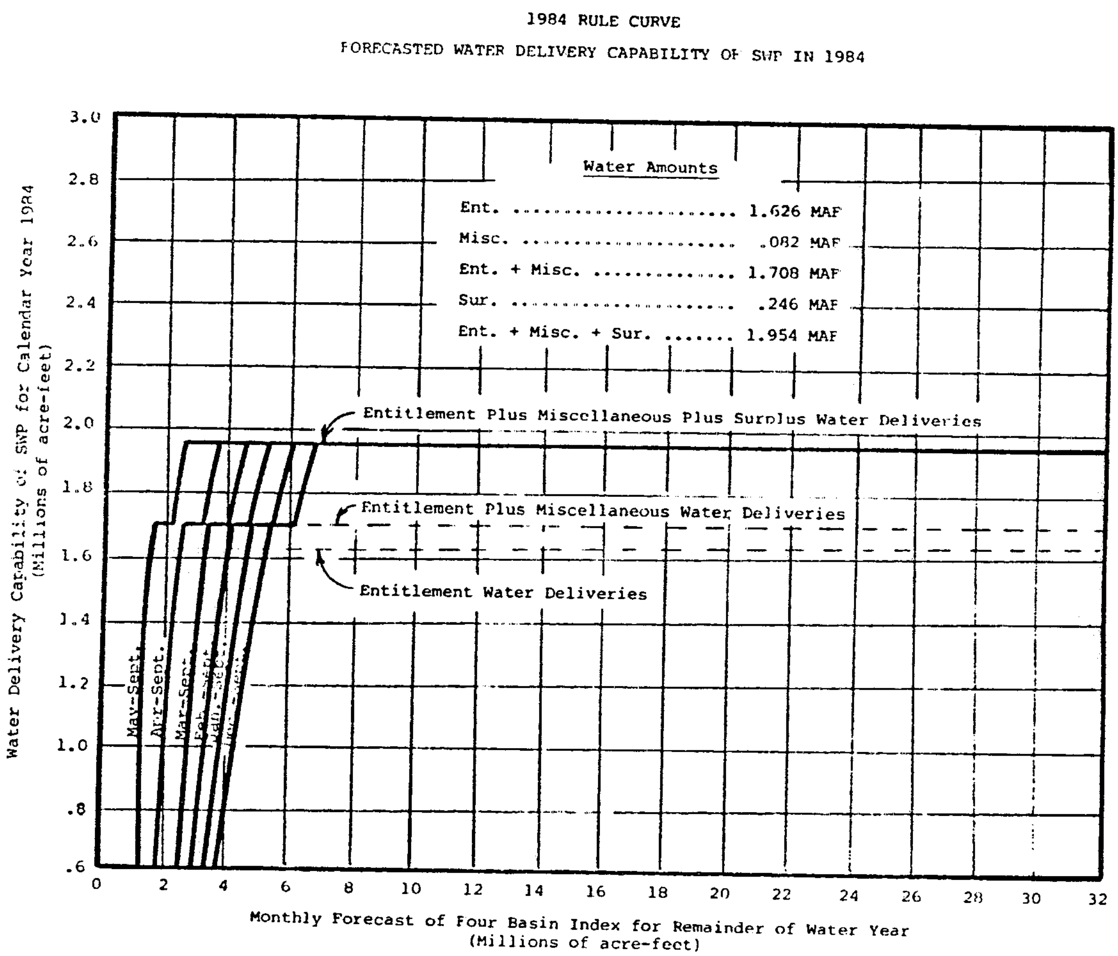


FIGURE 18: California State Water Project Rule Curve for 1984
(California Department of Water Resources, 1984)

supply forecast is overly conservative. In 1977, the Bureau office at Yakima predicted 94% cutbacks to junior (pro-ratable) water rights holders. This forecast caused Yakima water users to take costly actions they normally would not have done (such as drilling new wells and leasing water rights at inflated prices). As it happened, junior holders received 70% of their normal allocation. This situation prompted many farmers to take legal action against the Bureau as an attempt to regain their losses. (For a penetrating account of the 1977 Yakima incident see Glantz, 1982.) Although providing conservative estimates for the approved water deliveries, the Rule Curve lessens the possibility of such an occurrence happening with the SWP. The Rule Curve incorporates drought reservoir management as part of a continual delivery/reservoir management process. (The Yakima forecast was a singular forecast prompted by perceived water shortage.) By comparing the Rule Curve's predictions with what actually occurred, the SWP can determine its value as a decision tool and refine it where necessary.

III.A.2. Central Valley Project

The CVP currently has no formal plan for reservoir operation during droughts. CVP reservoir operators rely on documentation of reservoir operation obtained from the CVP annual reports for 1976 and 1977 (U.S. Bureau of Reclamation 1976e and 1977a) other miscellaneous reports. Operation of the CVP has changed markedly however since the 1976-1977 drought. The changes are a result of the specification of Delta water quality requirements by California's Water Resources Control Board in their Decision 1485, the agreement by the Bureau to operate the CVP to meet these requirements, and the development of a Coordinated Operations Agreement (COA) between the CVP and SWP. The CVP and SWP have been coordinating their operations under a draft COA since 1982. A final COA has been submitted to the United States Congress (as House Resolution 3113) and is pending their approval. The COA establishes the percentage of flow each project contributes to meet the Decision 1485 water quality standards and defines an accounting procedure for the repayment of water from one project being used by the other.

Decision 1485 water quality standards vary with water-year type becoming less strict as the type becomes dryer. This allows storage to be retained in both projects' reservoirs. If a drought were to occur today, coordination of the two projects would be much more efficient because they would be operating for the same Delta water quality standards and the accounting for water supply loans is defined.

The water supply available to the CVP in 1977 would have been greater if the carry-over storage at the end of 1976 had been larger. This would have been possible if delivery cutbacks had been implemented and curtailments placed upon delivery of interim water in 1976. Interim water is defined as firm CVP yield which is uncontracted. As stated before almost half of the contracts for CVP water supply contain a stipulation that cutbacks in delivery amounts will be made only if projected inflow to Lake Shasta for the water year (October 1 - September 30) is below 3.2 million ac-ft. In addition to this legal constraint, it was the Bureau's policy to "treat all users as equally as possible" (U.S. Bureau of Reclamation, 1976e). As a consequence, the CVP was operated in 1976 as it was operated in any normal water year. That is, all contracted water supply deliveries were made, whether the water supply contract included the inflow stipulation or not, and one million ac-ft of interim water was also released. This operation left

3.9 million ac-ft, 61% of normal carryover storage, to begin the 1977 water year. Reduced carryover storage directly affected CVP water supply capability in 1977 and resulted in cutbacks of up to 75% in that year's deliveries.

Development of an operations plan which addresses decreased water deliveries and interim water supply management during droughts would appear to be appropriate for the CVP given their drought experience however this has not been done for two reasons. First, the Bureau is concerned over the marketability of water supply contracts which have a deficiency criterion clause such as the "arbitrary and capricious" clause in the SWP contracts. Therefore, although contracts containing the 3.2 MAF inflow to Lake Shasta as a cutback stipulation begin coming up for renewal in 1990 however, it is not clear how operationally restrictive the renewed contracts will be. Whether to include a stipulation or not and the form it might take if included is a current policy issue at the Bureau. As long as the Bureau adheres to its equality policy and because the contracts containing the stipulation are still in effect, the Bureau is prevented from using water supply delivery adjustments as a reservoir drought operation plan. The second reason is that CVP management views using decreases in the delivery of interim supply as providing CVP water contractors with a more "guaranteed" water supply than that for which they contracted.

In summary, CVP operations since the drought have generally improved with the development of the COA and one set of Delta water quality standards. No drought operation plan has been developed and an improved method for determining project delivery amounts during drought is prevented by legal, social, and economic concerns.

III.A.3. Corps-Operated Reservoirs

In 1980, the Corps began a program to develop drought operation plans for its reservoirs. These plans are referred to as "Drought Contingency Plans". Formulation of Drought Contingency Plans is to begin at the project level (U.S. Army Corps of Engineers, ER1110-2-1941). The water control manager (Corps' personnel which directs operation of the dam) is to assess his/her projects and develop a plan which could increase the projects' water supply capability. If the manager identifies an opportunity to increase water supply capability that lies outside of the manager's authority, a reconnaissance study is to be conducted. If after this study the opportunity remains promising, a detailed study is to be made. In 1982, seven multipurpose reservoirs were scheduled for reconnaissance-level studies however, they were dropped from that year's project starts due to budget cuts (Pace, 1982). They have yet to receive funding. As a result, development of Drought Contingency Plans remains at the water control managers' level.

A Drought Contingency Plan has been developed for Success Lake. It contains a method to increase water supply in anticipation of a dry year by allowing encroachment of water supply storage into flood control space. The amount of encroachment is dependent upon the precipitation for the day upon which the calculation is made and the previous day. This method accounts for the decreased runoff due to dry soil and allows storage of up to 3,200 ac-ft additional water supply. The Plan also mentions that pumping from the sediment pool may be done under extreme conditions. According to Success Lake's storage-elevation curve, this method would provide less than 50 ac-ft (U.S. Army Corps of Engineers, 1982). No mention is made regarding minimum pool release. Apparently, this operation is left to the Bureau and the water supply contractors.

One of the seven multipurpose reservoirs which have had their Drought Contingency Plan reconnaissance studies deferred is Black Butte Reservoir. This project currently has no Drought Contingency Plan. Roger Lundeen, Chief of the Corps' North Sacramento District reservoir operations, expects its Drought Contingency Plan to contain guidance for consolidation of storage within the Orland Project (Lundeen, 1985). Although it is scheduled for development, it is not known when the Drought Contingency Plan will be completed. Under present conditions, there is no documentation within the Corps or the Bureau that addresses the methods of minimum pool release or consolidation of storage as reservoir operations for the appropriate projects during droughts.

III.B. DELAWARE RIVER BASIN

As a direct result of the 1960's drought experience, the DRBC has developed a set of reservoir operation plans using reservoir storage as the drought indicator. The plans exemplify a water resources management scheme heavily influenced by political and social concerns and their analysis will shed light on the policital-engineering interface. Also presented here are methods of analysis used to develop various components of the plan.

The operation plans are based upon the timing of reservoir storage depletion in its Upper and Lower basins. The Upper Basin is defined as the drainage area above Montague, New Jersey. The Lower Basin lies below Montague and above Trenton, New Jersey. Current major reservoirs in the Basin are shown in Figure 19. A summary of the purposes and capacities of these reservoirs is given in Table 8.

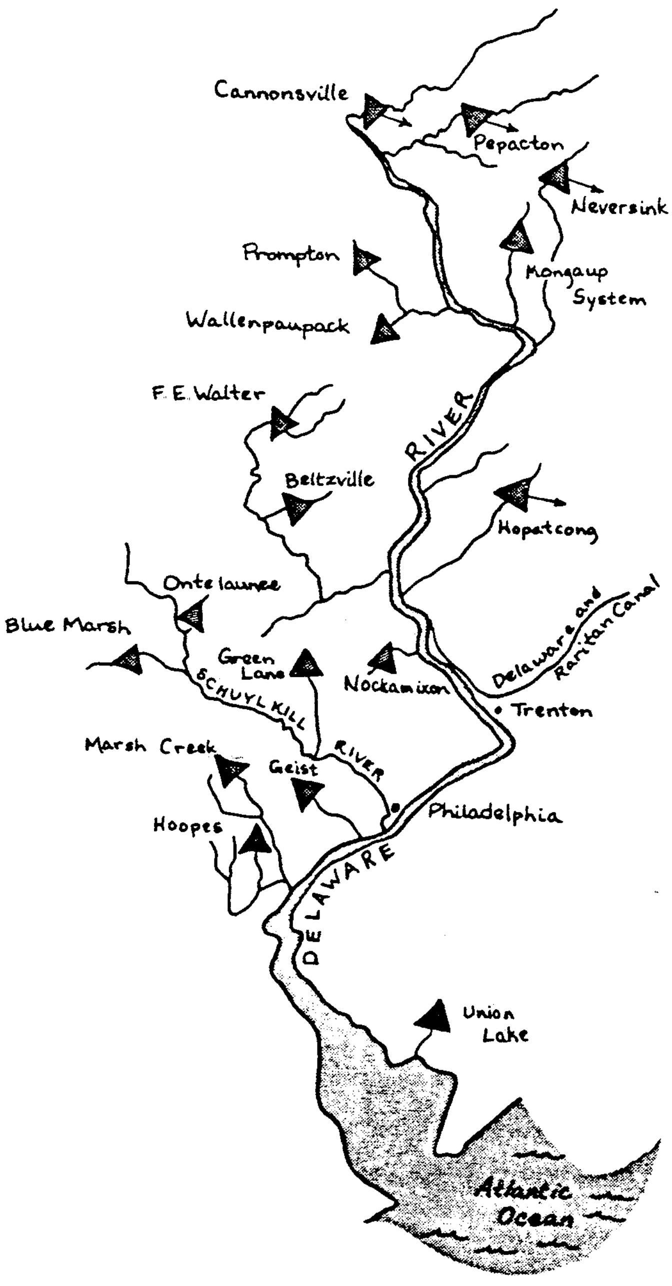


FIGURE 19 Major Reservoirs in the Delaware River Basin, 1985 (Delaware River Basin Commission, 1981)

TABLE 8: MAJOR RESERVOIRS IN THE DELAWARE RIVER BASIN

	Conservation Storage (acre-feet)	Flood Control Space (acre-feet)
Cannonsville (*)	302,000	--
Pepacton (*)	454,000	--
Neversink (*)	109,200	--
Mongaup System (*)	65,630	--
Wallenpaupack (*)	157,240	--
F.E. Walter (*)	--	108,000
Prompton (*)	5,600	203,000
Beltzville (*)	39,830	27,000
Blue Marsh (*)	14,600	32,390
Hopatcong	18,400	--
Nockamixon (*)	36,800	--
Ontelaunee	11,640	--
Green Lane	13,430	--
Geist	10,780	--
Marsh Creek	12,400	--
Hoopes	6,750	--

(*) Components of Drought Operations Plan

(Delaware River Basin Commission, 1981)

The following matrix will assist in the description of the plans.

Reservoir storage depletion occurs second in:	Reservoir storage depletion occurs first in: Upper Basin	Lower Basin
Lower Basin	1	3
Upper Basin	2	4

As indicated by the matrix, Condition 1 occurs when the Upper Basin reservoirs reach depletion levels and are followed by the Lower Basin reservoirs. Condition 2 is when only the Upper Basin reservoirs are depleted. Conditions 1 and 2 determine a Basin-wide Drought. Condition 3 defines a Lower-Basin Drought. Condition 4 is presently undefined. Upper Basin drought status is based upon the total reservoir storage in NYC's reservoirs (Cannonsville, Neversink, and Pepacton). Lower Basin drought status is based upon storage levels in Beltzville and Blue Marsh, both major reservoirs in the Lower Basin. The distinction between a Basin-wide Drought and a Lower Basin Drought is made because the management options available for each drought operation plan are very different. These options are defined by the reasoning that the basin (Upper or Lower) in which the drought originates will carry the primary burden of water supply shortage. Consequently, water stored in reservoirs of the drought stricken basin will be released first and, generally, diversions within that basin will be the first to be decreased.

III.B.1. Basin-wide Drought Operations

A Basin-wide drought is determined by the combined storages of the New York City (NYC) water supply reservoirs (Cannonsville, Pepacton, and

Neversink). Figure 20 is the rule curve which determines the Basin's drought status. If, for example, the combined storage of the reservoirs is 120 billion gallons (bg) on September 15, the Basin is in the upper level of the "Drought Warning" condition. Each condition: "Normal", "Drought Warning" (upper half or lower half), and "Drought" determines the allowable diversions by NYC and New Jersey (at their Raritan Canal) and the Montague and Trenton flow objectives.

Reservoirs other than the NYC reservoirs are called upon only during the "Drought" condition. At this time, the following steps are taken:

1) Prompton and F. E. Walters, flood control facilities, begin to retain water supply which may be used later in the year or during the next year;

2) Wallenpaupack and Mongaup System reservoirs (hydropower facilities) begin making water supply releases to assist in meeting the Montague flow objective;

3) The decreased Trenton flow objective is met by releases from the following reservoirs in the given priority

1. Prompton (if storage is available)
2. F. E. Walters (if storage is available)
3. Beltzville, Blue Marsh, and Lake Nockmixon

This operation plan is very similar to the actual reservoir operations which occurred during 1965, if one excludes the reservoirs which did not exist at that time (Beltzville, Blue Marsh, and Nockamixon). 1965 operations are refined in this plan by the specification of Lake Wallenpaupack's elevations during "Drought" conditions, an operations rule curve for Mongaup System reservoirs, and

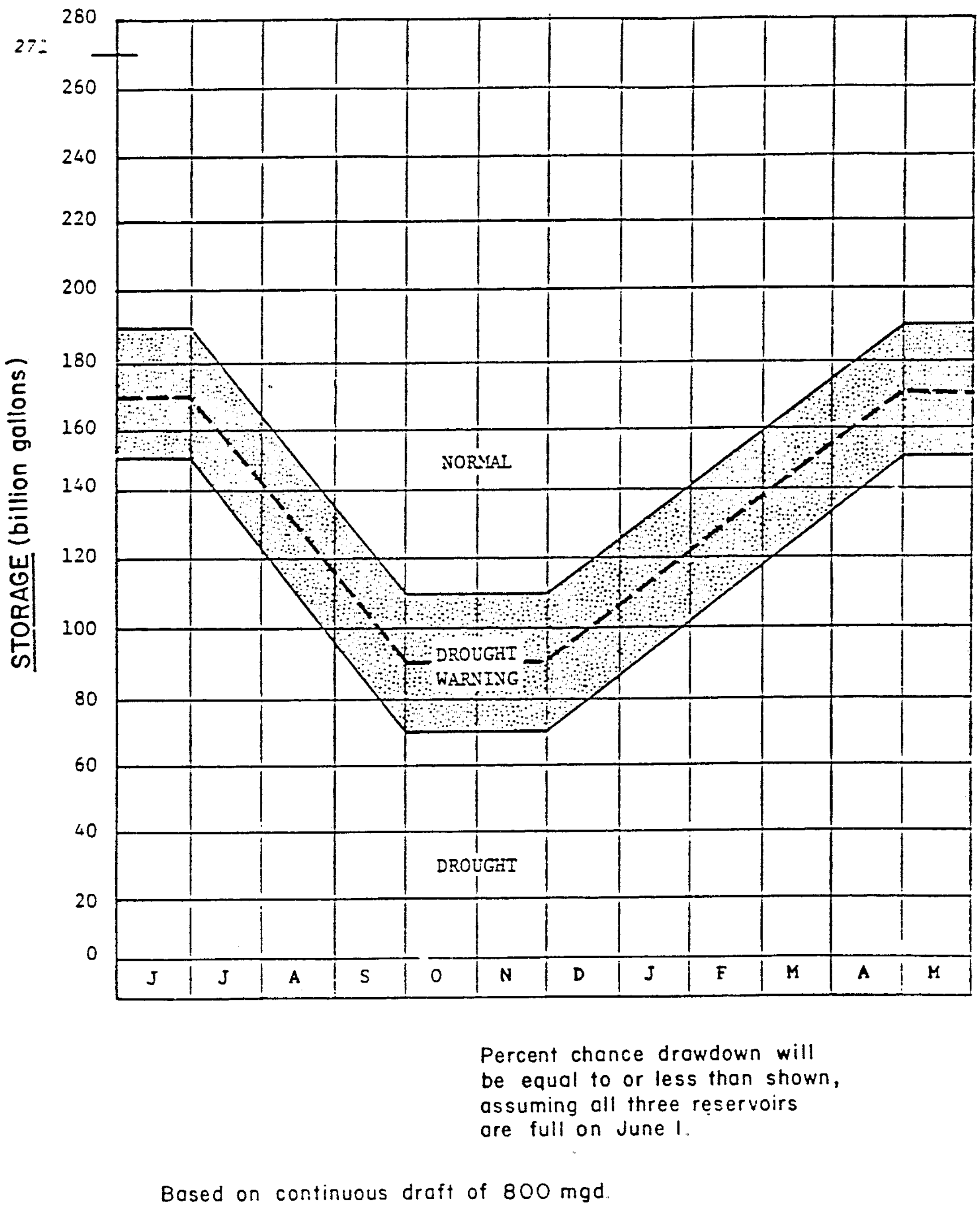


FIGURE 20: Rule Curve For Delaware River Basin Drought Conditions (McSparran, 1984a)

an operation which allows water supply stored behind F. E. Walters, which during a flood threat would have to be released, to be "saved" in the NYC reservoirs. This is done by lowering the Montague flow objective.

Beltzville and Blue Marsh reservoirs are normally operated for regional flow augmentation and for recreation. The releases specified under the operations plan are to be from storage below the normal minimum conservation pool level to augment Delaware River flow. Although releases from Blue Marsh enter downstream of Trenton, flow augmentation in Schuylkill River has roughly the same effect as equal augmentation in the Delaware River at Trenton. Lake Nockamixon is owned by Pennsylvania and is used for local water supply and recreation. Release priority from these reservoirs is based upon the amount of recreational use each provides (McSparren, 1984b). Beltzville and Blue Marsh provide almost the same amount of recreation and are, therefore, equally drawn upon. Lake Nockamixon is used heavily for recreation and is, consequently, drawn upon less often and later in time.

For a drought operation plan to be successful it must bring together the technical, legal, institutional, and social elements of the study area. A discussion of the technical analysis done to develop the drought operation rule curve follows because the methods used are of interest to water resources engineers and because it illustrates the interaction of technical engineering analysis with institutional, legal, and social elements. The information presented here is given in a Task Group Report titled Appraisal of Upper Basin Reservoir Systems, Drought Emergency Criteria and Conservation Measures (Delaware River Basin Commission, 1979).

The shape of the drought operations rule curve is based upon the shape of the annual drawdown curve developed by NYC for their reservoirs in the Basin. The annual drawdown curve uses a maximum allowable diversion of 800 mgd, a legal limitation set by the 1954 Supreme Court Decree. The curve represents a 67% chance that the drawdown will be less than indicated and was chosen because the initial storage (in June) equals the water year's end storage (Delaware River Basin Commission, 1979). The drawdown curve is shown as Figure 21. The curves for a 10% and 90% chance of greater storage are also included for comparison.

Once shape was determined, the storage levels of the curtailment curves were found. The initial storage levels were set by assuming a drought sequence which would initiate the "Drought Warning" and "Drought" conditions. For example, using annual drawdown curves, one model assumed the "Drought Warning" condition would be intercepted once every four years (ie. a 25% chance the drawdown will be exceeded in any year) and the "Drought" condition would be intercepted once every 50 years (a 2% chance the drawdown will be exceeded in any year). A second model assumed a 10-year drought would initialize "Drought Warning" and the "Drought" condition would be called by another 10-year drought following the first. The allowable diversions and Montague flow objectives were specified for each drought level, generally decreasing as "Drought Warning" approached "Drought". The values of the diversions and flow objectives were primarily determined by technical consideration also given the constraint of the 1954 Supreme Court Decree. Factors considered were system flexibility, NYC's ability to decrease demand via conservation (an assessment which requires assumptions about social response), and the possibility of NYC to recover the reduced diversions

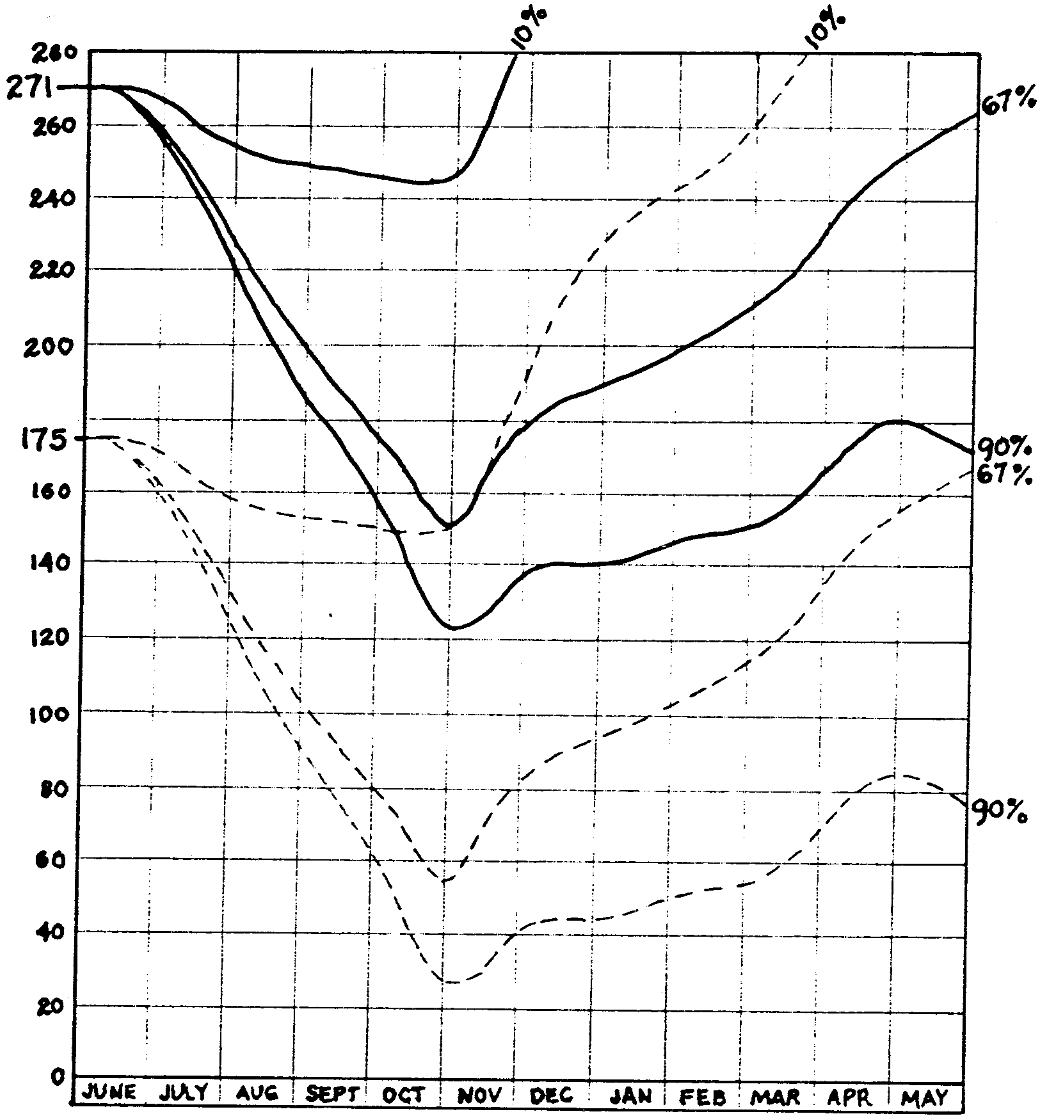


FIGURE 21 Annual Drawdown Curves for New York City Reservoirs
(Delaware River Basin Commission, 1981)

at a later time. The diversion and flow objective values were the same for each model therefore, the second model would initiate a "Drought Warning" or "Drought" condition more frequently than the first model.

The number of times each model would have triggered a "Drought Warning" or "Drought" condition was determined for the 1960's drought (the worst drought of record) by a graphical method. A mass curve for the second model is shown as Figure 22. In this curve, the cumulative net flow is shown twice, offset by the total maximum NYC reservoir capacity, 271 billion gallons. Within the 271 billion gallon offset, the storage levels corresponding to the various drought curves are drawn. Cumulative demands and diversions, adjusted for the defined limits, are added. The intersection of this line with the various drought operation zones indicates when a "Drought Warning" or "Drought" condition is called.

Knowledge of how often a "Drought Warning" or "Drought" condition is declared is important in determining its effectiveness. A balance between frequency of declaration and severity of the required curtailments must be made for an effective drought contingency plan. This is true because the impacts upon society of a drought contingency plan directly relate to the ability to decrease water consumption through conservation measures. Transition to any curtailment is costly and inconvenient. Requesting frequent, yet small, deviations from normal consumption decreases the willingness of society to respond. However, declaring a water emergency at the last possible moment may require curtailments which are impossible for society to meet. Institutional and social facets of the water resources system must be considered in making this decision. All members of the DRBC contributed

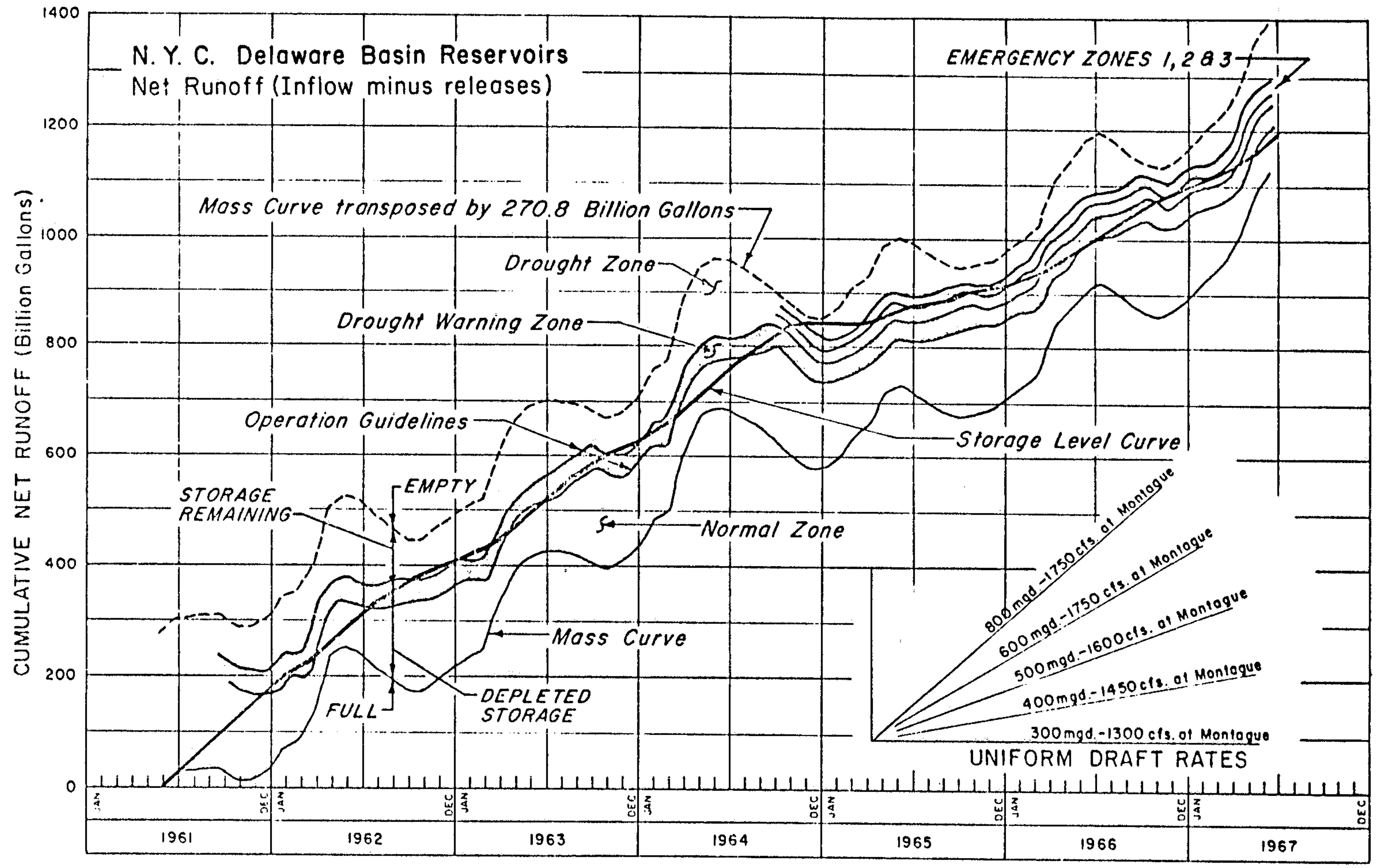


FIGURE 22 Model #2 Mass Curve Analysis of New York City Reservoirs in the Delaware River Basin (Delaware River Basin Commission, 1979)

to determining what they felt to be a reasonable number of declarations after reviewing the technical analyses.

The storage levels corresponding to "Drought Warning" and "Drought" conditions in the final operation curve are the same as the second model. Maximum allowable diversions and minimum allowable Montague flow objectives result from the interaction of the DRBC members given their knowledge of the legal constraints and the technical analyses of the operations. (Notice NYC and NJ diversions are proportionately reduced.) An analysis of the relation of estuary salinity levels and Delaware River outflow assisted in determining the required outflow during drought. The DRBC members resolved how much of this flow should come from the NYC reservoirs. Diversions and flow objectives for the Drought Operation Plan are summarized in Tables 9 and 10.

II.B.2. Lower Basin Drought Operations

The Draft Report on Alternative Lower Basin Drought Warning and Drought Operating Plans (Delaware River Basin Commission, 1985) bases a Lower Basin Drought upon the storage levels of Beltzville and Blue Marsh reservoirs. Supportive reasons for this criteria are 1) other conservation reservoirs are for local water supply and a correlation between their levels and drought would be very difficult; 2) Beltzville's and Blue Marsh's primary conservation purposes are regional flow augmentation; 3) Beltzville and Blue Marsh contain over 46% of the conservation capacity of all reservoirs affecting Delaware flow located between the Schuylkill-Delaware confluence and the Montague gage; 4) Beltzville and Blue Marsh releases are the primary releases made to augment Delaware River flow during Lower Basin "Drought-Warning" and "Drought" conditions.

TABLE 9: ALLOWABLE DIVERSIONS AND FLOW OBJECTIVES

	Diversions (mgd) NYC	NJ	Flow Objectives (cfs) Montague	Trenton
Normal (1)	800	100	1750	3000
Drought Warning				
-Upper Half	680	85	1655	2700
-Lower Half	560	70	1550	2700
Drought	520	65	(2)	(3)

(1) Governed by the 1954 Supreme Court Decree.
(2) Varies with time of year and location of the salinity front (250 parts per million isochlor).

(Delaware River Basin Commission, 1982a)

TABLE 10: FLOW OBJECTIVES FOR SALINITY CONTROL DURING DROUGHT PERIODS

7-day Average Location of "Salt Front" River-mile	Flow Objective, Cubic Feet per Second, at: Montague, NJ Dec-Apr	May-Aug	Sept-Nov	Trenton, NJ Dec-Apr	May-Aug	Sept-Nov
Upstream of R.M. 92.5	1600	1650	1650	2700	2900	2900
Between R.M. 87.0 & 92.5	1350	1600	1500	2700	2700	2700
Between R.M. 87.0 & 82.9	1350	1600	1500	2500	2500	2500
Downstream of R.M. 82.9	1100	1100	1100	2500	2500	2500

River mile measured in statute miles along the navigation channel from the mouth of Delaware Bay.

(McSparran, 1984a)

Beltzville and Blue Marsh elevations indicating drought status are specified below. Unlike the drought operations rule curve for a Basin-wide Drought, these elevations remain constant throughout the year.

Pool Elevation (feet m.s.l.)/% of storage capacity

	Drought-Warning	Drought
Beltzville	615/73.7%	590/38.0%
Blue Marsh	283/68.9%	273/36.8%

For Lower Basin "Drought-Warning" conditions, the diversion at the Raritan Canal is decreased along with the Trenton flow objective and balanced releases are made from Beltzvill and Blue Marsh. For "Drought" conditions, the diversion and flow objective are lowered again and reservoir operation depends upon NYC reservoir storage in the Basin. If the NYC reservoirs' storages are above their "Drought-Warning" condition by about 65 bg, then flow augmentation releases from these reservoirs contribute much to the Trenton objective. If the storage total is between 65 bg and 30 bg above their "Drought-Warning" condition, extra releases are considered only if the warning triggers after September 1. If total storage is below 30 bg above "Drought-Warning", additional releases to the River are not considered. The maximum allowable total increased release amount cannot be greater than 30 bg. Other flow augmentation releases may first come from Lake Nockamixon, secondly from the hydropower reservoirs, and thirdly from Lake Hopatcong (a privately-owned, recreation lake). The flood control reservoirs are also called upon to begin conserving storage.

The Lower Basin "Drought" operations are therefore to be decided by the DRBC. The Lower Basin drought contingency plan, 1) defines the "Drought Warning" and "Drought" conditions in the Basin, 2) requires a meeting between DRBC members within 30 days following a triggering of "Drought Warning" conditions, and 3) provides reservoir operation alternatives which have met DRBC member approval. This plan is designed to streamline the DRBC's response to water shortages. "Drought Warning" reservoir operations are well defined and can be implemented with little action by the DRBC. This gives the DRBC time to meet with the public and to evaluate the "Drought" operations alternatives. The pre-approved alternatives should help to decrease the amount of time taken for the DRBC's decision.

III.B.3. Recent Activities

Storage in the NYC reservoirs entered "Drought Warning" in mid-October, 1980 and, upon notification by the Delaware River Master, the DRBC declared a Basin-Wide "Drought Warning" condition. Over the two year drought period, the Basin entered "Drought Warning" three times. A "Drought" condition was declared once and, depending upon which agency's criteria is used, lasted 5 or 16 months. In 1981, double criteria existed regarding when a "Drought" condition should be ended. Regardless, the DRBC estimates a 60 bg savings in the NYC reservoirs is directly attributable to "Drought" reservoir management.

The Delaware River Master declared the "Drought" condition over on May 17, 1981. His decision was based upon the fact total NYC reservoir storage had remained over 15 bg above the "Drought Warning" zone for 5 consecutive days (Schaefer and Fish, 1982). As a result, allowable diversions and the Montague flow objective returned to their normal values on that date. The DRBC used criteria given in an "informal agreement" which declared a "Drought" condition over when NYC reservoir storage exceeded 40 bg above the "Drought Warning" zone for 30 consecutive days (Delaware River Basin Commission, 1982b). Their drought did not end until April, 1982.

During the period January through mid-March, 1981, 38 bg of storage was actually saved in the NYC reservoirs due to the decreased diversion amounts. If DRBC criteria had governed actual NYC reservoir operation, 127 bg would have been saved. As promising as the DRBC criteria appears for saving water supply, it is not an adequate method to determine the best time to end a "Drought Warning" or "Drought" condition. If the DRBC had held to its criteria during 1982, the Basin would have twice had "Drought Warning" status while experiencing flood flows at Trenton. During 1982, the DRBC used the River Master criteria to declare the shortage over. Even with this, one "Drought Warning" was ended in the midst of a flood scare. The River Master criteria is now specified as the criteria to use. Given the above, it appears other parameters should be used in addition to reservoir storage to determine when drought conditions are over.

The economics of the operation which temporarily uses flood control space in F. E. Walters and Prompton reservoirs for water supply storage is another component of the DCP which requires improvement. These projects are operated by the U.S. Army Corps of Engineers. Water supply was stored behind F. E. Walters in 1965 and 1981 (Delaware River Basin Commission, 1982b). Each time, the Corps paid the operation costs (Eiker, 1984). Because this operation is now a part of the formalized drought operations plan, a procedure should be developed for repayment of any drought operation costs to the Corps.

III.B.4. DCP and Basin Water Resources Planning

The DRBC has based its water supply Comprehensive Plan through the year 2000 upon the Basin-Wide DCP. The increased amount of Delaware River outflow required at Trenton for the year 2000 is determined as follows:

> The sustainable 4-month "summer flow" value at Trenton (obtained using the Montague flow objective for the Basin-Wide "Drought" condition, 1960's drought hydrologic conditions, reservoirs existing in 1981, and year 2000 depletive uses) less the flow value required to maintain the normal year salinity objective (3100 cfs) in the year 2000 (Delaware River Basin Commission, 1981).

The Comprehensive Plan is conservative in that, during drought operation, the salinity objective is allowed to move upstream during drought conditions and therefore decrease the Trenton flow objective (see Table 10). It also conservative because the 1960's drought has an estimated return interval of several hundred years for the Upper Basin and 100 years for the Lower Basin (Delaware River Basin Commission, 1981). Finally, the plan is conservative because the DCP contains other consumptive conservation restrictions not accounted for in the DRBC water supply plan. The projected depletive use in the year 2000 is not conservative. It contains an assumed 15% reduction in normal depletive uses which may or may not be achieved.

Several observations are warranted regarding the DRBC's Comprehensive Plan. First, it represents a shift in water resources management philosophy from complete avoidance of drought conditions through the development of physical systems to accepting the existence of drought and developing management plans to cope with the condition. These new plans inherently involve more public participation than the previous type of management. This aspect does not sit well in most engineers' minds because of its ambiguous and non-quantifiable nature. However, the people of the Delaware River Basin have prevented construction of traditional engineering solutions (Tock's Island, for example, a reservoir to store over 500,000 ac-ft of supply), therefore the water resources manager must develop more refined water supply system operation schemes and, given the reluctance of the public to develop new large storage projects, placing some of the management responsibility with the public sector appears justified. Secondly, including the Basin-Wide DCP as a cornerstone of the Comprehensive Plan has formally changed the functions of certain reservoir projects to include water supply/flow augmentation at the expense of their original purposes (hydropower or flood control). This is indicative of a trend in water supply system management. The current shift away from the construction of new facilities requires modification of the existing ones to better meet the water resources needs of the people. Water supply/flow augmentation is the primary need of the Delaware River Basin and, as such, marginal flood control benefits and relatively small amounts of energy generated by hydropower are lost as water supply/flow augmentation operation dominates.

III.B.5. Summary

The Delaware River Basin Drought Contingency Plans are comprehensive plans which affect the water resource systems of New York, Pennsylvania, New Jersey, Delaware, and New York City. As such, the plans are dominated by institutional interaction and legal constraints. These aspects along with the social and environmental affect the solutions deemed feasible by technical analysis. Examples of technical compromises which exist in the current plans are the equal percentage reductions for diversions by NYC and New Jersey and scheduling emergency flow augmentation releases based upon recreational use of the reservoirs.

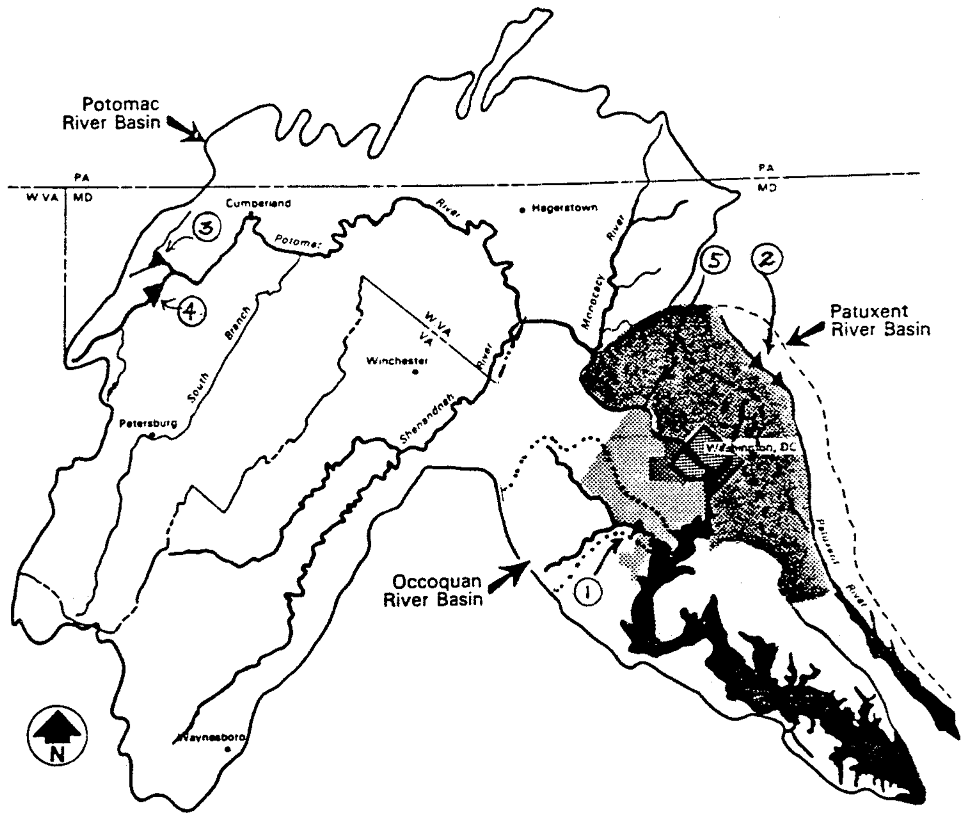
The main successes of the DCPs are its definition of water supply shortage, establishment of a procedure for convening all DRBC members to discuss the water supply situation, and providing automatic operation plans during the "Drought Warning" condition which allows DRBC members to devote their attention to the pending "Drought" condition.

III.C. POTOMAC RIVER BASIN

A previous section discusses how, in 1977, the Fairfax County Water Association (FCWA) used risk analysis to guide residential conservation measures. Since that time, the FCWA water supply system has added the Potomac River as source and radically changed its method of operation. FCWA water supply facility operation is now coordinated with two other water supply districts along with a large, multipurpose reservoir on the Potomac River. The following discussion describes the region's current water supply operation, illustrates how system operation during droughts can greatly increase water supply capability, and details certain aspects of the plan's development that are of particular importance to water resources planners and managers.

III.C.1. Current Operations

The three districts and reservoirs are illustrated on Figure 23. In addition to FCWA, there is the Washington Suburban Sanitation Commission (WSSC) which supplies aproximately 1.2 million people in the Maryland suburban area surrounding Washington D. C. (U.S. Army Corps of Engineers, 1983a). WSSC water supply sources are the Potomac and two reservoirs, Triadelphia and Rocky Gorge, on the Patuxent River. The third agency is the Washington Aqueduct Division, Corps of Engineers (WAD). It serves the District of Columbia and the County of Arlington



Reservoirs	Maximum Capacity (Million Gallons)
1. Occoquan	10,300
2. Patuxent	10,100
3. Savage	5,900
4. Bloomington	30,000
5. Little Seneca	4,020

Fairfax County Water Authority (FCWA)

Washington Suburban Sanitary Commission (WSSC)

Washington Aqueduct Division, Corps of Engineers (WAD)

FIGURE 23 Reservoirs and Water Agencies in the Washington D.C. Metropolitan Area.
(Adapted from Figure 1, U.S. Corps of Engineers, 1983a)

and City of Falls Church in Virginia (Sheer, 1983). The Potomac is its only source of water supply. Upstream reservoirs currently contributing to regulation of Potomac flows are Savage and Bloomington reservoirs. Savage Reservoir is a Federally constructed project primarily providing low flow augmentation for industrial use and water quality. Bloomington Reservoir is a Federal project which provides low flow augmentation for water supply and quality and flood protection. A third reservoir, Little Seneca, is constructed but not fully operational at this time. It provides flow augmentation for water supply.

Simply stated, the coordinated operation of the three water supply systems uses the Potomac as the primary source of supply during normal conditions, allowing the three reservoirs to maximize storage, and calls upon stored reservoir supply during low flows (see Figure 24). Because WAD obtains water solely from the Potomac, it is restricted to the river during low flow conditions but, its supply is more assured because FCWA and WSSC are drawing upon the river less.

During normal conditions, the operation of Occoquan and the Patuxent reservoirs is left to the individual project operators. This gives FCWA and WSSC operators flexibility in daily operations in order to minimize pumping costs, equalize system pressure, etc. Joint scheduling of releases from their reservoirs and withdrawals from the Potomac are done by the Interstate Commission on the Potomac River Basin (a commission established by Congress in 1940). It begins when drought conditions are expected. Drought conditions are defined in two ways: 1) flow in the Potomac is below 200% of expected FCWA, WSSC, and WAD withdrawals, or 2) the probability of meeting all water requirements and refilling all reservoirs by the following June is below 98% (Sheer,

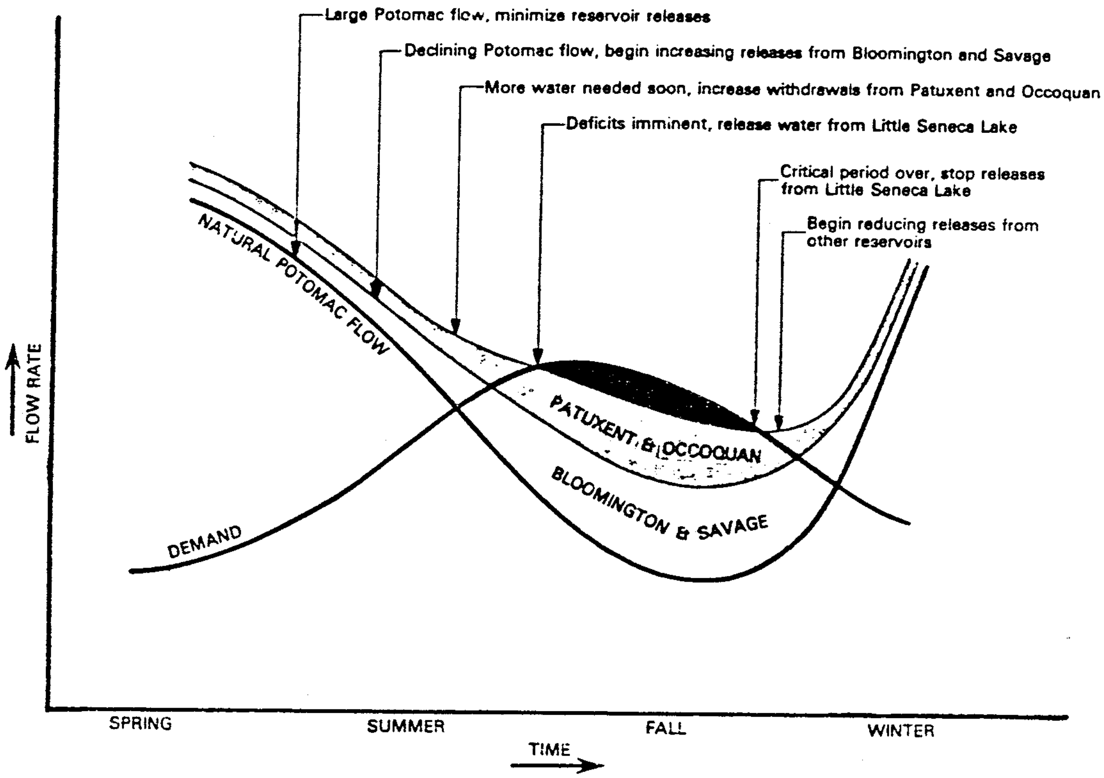


FIGURE 24 Schematic of the System Drought Operation of the Potomac River Basin Reservoirs. (U.S. Army Corps of Engineers, 1983a)

1983). The first condition is determined by routing river flow and accounting for FCWA, WSSC, and WAD river withdrawals. The second condition is determined by risk analysis. A position analysis is conducted using a runoff simulation model, predicted demands, and a given system operation. This type of analysis was first conducted for the Occoquan Reservoir in 1977. (See Sec II.B.3).

If a drought condition is identified, releases from Bloomington Reservoir are re-scheduled using a difference rule. This difference rule is explained by Sheer (1983) as follows:

> "To determine upstream releases under this rule, the natural flow in the Potomac at Washington (D. C.) on the date of the release is subtracted from the total demand (including required instream flow) from all sources expected on the day the release will arrive. This is equivalent to assuming (or forecasting) that the flow will remain unchanged over the time of travel. The difference (hence "difference rule") represents the total additional water which will be needed if the natural flow remains constant. The difference is adjusted by subtracting the amount desired to be taken from the local reservoirs and adding a safety factor."

A demand model is used to forecast the three districts' demand. The withdrawals from the Occoquan and Patuxent reservoirs are set at their joint-operation safe yields. The safety factor is 100 mgd which, when Little Seneca Reservoir becomes operational, will be reduced. The operation endeavors to maintain balanced storage in the local reservoirs by setting target withdrawals from the Potomac for WSSC and FCWA in the morning and adjusting these withdrawals in the afternoon, if necessary.

III.C.2. Evolution of the Solution

a. From A Structural to A Non-structural Approach.

Serious analysis of the Potomac River Basin's water resources began in 1955 when Congress directed the Corps to prepare a long range development plan. In 1963, the Corps' Baltimore District published a plan which included 16 major reservoirs and over 400 smaller reservoirs providing water supply, water quality improvements, recreation, and flood control (Potomac River Basin Study, February, 1963). At this time, wastewater was being released into the Potomac with very little treatment. As a result, most of the proposed water storage was for upgrading water quality by dilution. This plan created great controversy and was not submitted to Congress. A less controversial Corps' project, Bloomington Lake on the North Branch of the Potomac, was authorized by Congress in 1962.

When pollution standards were set for wastewater discharge in 1972 (Federal Water Pollution Control Act), the Corps re-evaluated the Potomac River Basin. Solutions investigated were high flow skimming operations using the Occoquan and Patuxent reservoirs, Potomac Estuary water treatment, pumping from other rivers, new reservoir storage, and water use restrictions. All except water use restrictions involve new, constructed facilities. By 1976, studies remained in progress and a regional solution to the water supply problem had not been found.

In 1977, the method of formulating a solution to the regional problem changed from emphasizing physical solutions to emphasizing operational solutions. The change began when the Interstate Commission on the Potomac River Basin (ICPRB) while studying water quality management, realized operations of existing water supply facilities had not been fully considered. Although operations of this type would require considerable cooperation between water supply agencies, the deduction appeared promising. Regional cooperation between these agencies had been developing since the early 1970's and FCWA, WAD, and WSSC were approaching the finalization of a low flow allocation agreement. Therefore, at the request of the Federal, Interstate, State Regional Advisory Commmittee, an advisory committee to the Corps' study, the Corps began to investigate ways of increasing yield through operation of existing facilities.

b. Safe Yield vs Volume Analysis.

Scrutiny of the different methods of analysis used by the Corps and ICPRB will illustrate the impact founding assumptions had upon conclusions regarding MWA's water supply situation. In Corps' studies prior to 1977, estimations of water supply system capability are based upon safe yield analysis. The ICPRB conducted a volume analysis involving the reservoirs within the basin.

The values obtained by the Corps for the capability of the Potomac water supply system using the independently-operated reservoir safe yield are summarized in Table 11. They amount to 513 mgd. By the year 2000, Potomac River withdrawals were expected to be up to 815 mgd (Army U.S. Corps of Engineers, 1977b) indicating a deficit of 292 mgd (388 mgd + 135 mgd - 815 mgd) for Potomac water users.

The ICPRB conducted a very simple volume analysis on the existing Potomac water supply system. The analysis began with the identification of the drought which produced the largest deficit, given year 2000 water demands. This drought had a recurrence interval of 50 years and a duration of 90 days. The Potomac low flow for the drought was 580 mgd, giving a total volume of 52.5 billion gallons (580 mgd x 90 days). The demand (WSSC, FCWA, WAD, and required instream flow) amounted to 750 mgd, giving a required volume of 67.5 billion gallons (750 mgd x 90 days). This produces a deficit of 15 billion gallons. The sum of the Occoquan and Patuxent reservoirs is 20 billion gallons. The volume

TABLE 11: SAFE YIELDS OF METROPOLITAN WASHINGTON SUPPLIES

Potomac River (including Savage Reservoir)	388 mgd
Bloomington Lake	135 mgd
Patuxent Reservoirs (net water supply)	35 mgd
Occoquan Reservoir	55 mgd
Total	613 mgd
Less Minimum Flowby	-100 mgd
Total of Independently Operated Supplies	513 mgd

(Sheer, 1983)

analysis indicated the water supply already existed. It only required an efficient management scheme.

Safe yield analysis of the local reservoirs assumed that the reservoirs would be operated independently of the Potomac. Therefore, Occoquan Reservoir's safe yield was determined upon Occoquan River's behavior only. This is a very conservative assumption. For example, if Occoquan River's worst low flow condition occurred over a period of nine months, the safe yield would be as shown by the top sketch in Figure 25. If the reservoir were operated in conjunction with the Potomac, to provide supply when flow in the Potomac were low, its safe yield would be increased because the period over which Occoquan Reservoir would be drawn upon is less (Figure 25, bottom sketch). Diversity in the deterministic (physical) and stochastic (statistical) characteristics of the Potomac and Occoquan flows account for the withdrawal period decrease. Hirsch, et al (1977) defines the increase in water supply capability due to this type of joint operation a synergistic gain. The constraint to capturing a synergistic gain is system operation flexibility. The volume analysis done by ICPRB resulted in the minimum volume (15 billion gallons) required to meet the year 2000 demands because it assumes completely unrestrained interactive operation of the Potomac with the Occoquan and Patuxent reservoirs. The task remaining for the Corps was to devise a way to capture the largest possible synergistic gain through an operations scheme.

c. The Corps' Redirected Study

The Corps' redirected study is its Metropolitan Washington Area Water Supply Study (MWA Study) and was completed in 1983. It contains a new approach to water supply planning. Inovative objectives of the MWA

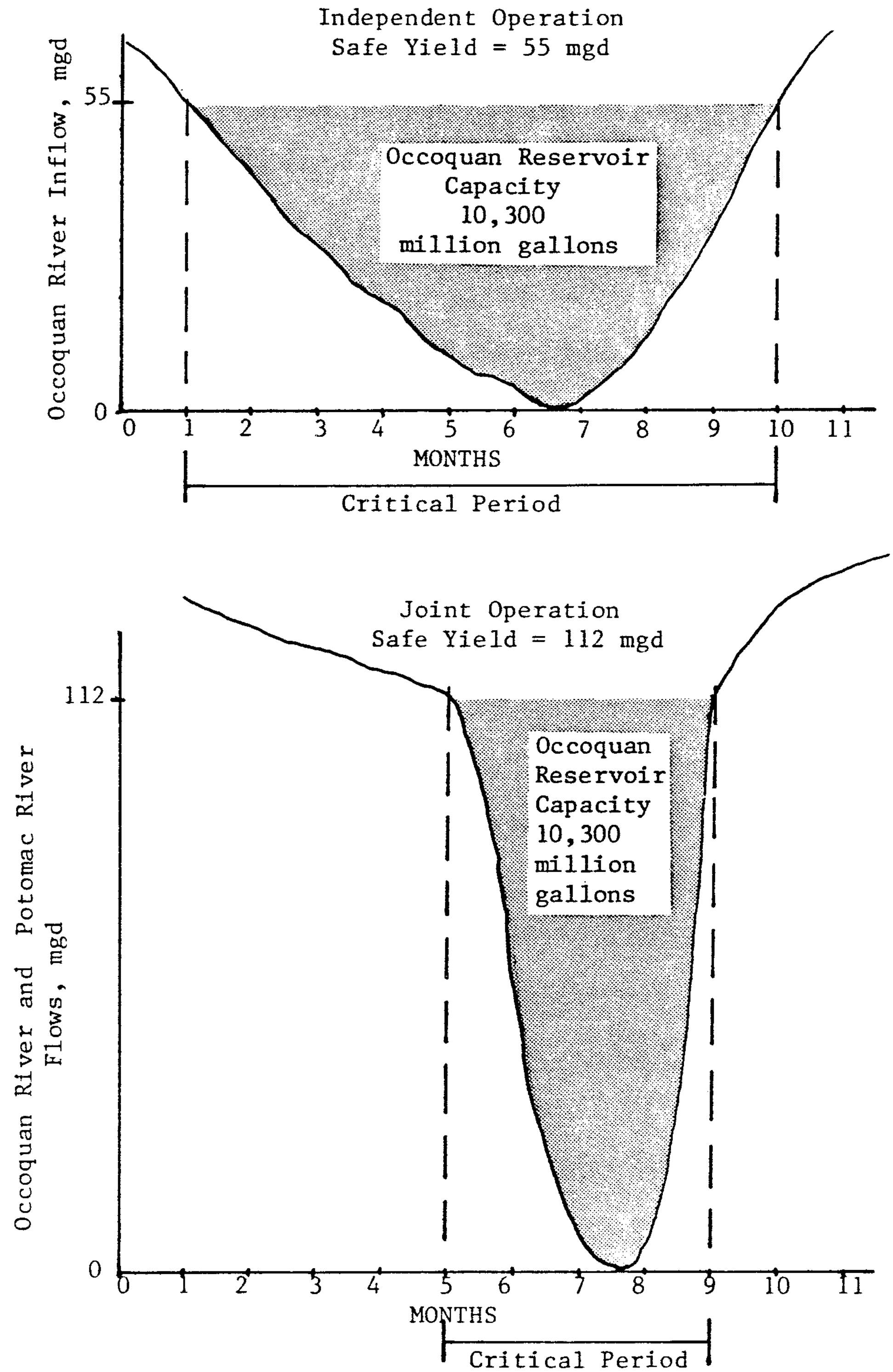


FIGURE 25 Reservoir Safe Yield of Independent and Joint Operations.

study include:

- using all existing water supply sources and facilities to the maximum extent practicable;

- providing solutions within the study area before constructing new projects outside of the study area;

- using drought management techniques aimed at demand reduction rather than increased supply to overcome short-term peak deficits;

- minimizing the use of structural measures;

- providing an institutional framework to promote cooperative management of all MWA water supply sources as a single, regional resource;

- developing a scheme to equitably distribute the costs and benefits of the new water supply plan.
(U.S. Army Corps of Engineers, 1983a)

During the study, the Corps changed its method of analyzing water supply capability (from safe yield to operations analysis), developed a refined method of quantifying projected water supply demands, developed a method for quantifying consumption reduction measures, and implemented an analysis process based upon the level of institutional interaction required for plan implementation (i.e. local, subregional, or regional). In addition, the Corps developed an extensive public involvement program. Public is defined here as any affected or interested non-Corps entity. Components of the program are listed in Table 12.

Scrutiny of the objectives listed above leads to the conclusion that information transmission between the public and the Corps was an important component to formulating a solution. It was essential. In fact, the public involvement program began at the study's inception in order to determine the study objectives. It continued throughout the study to devise the desired management scheme. For example, the

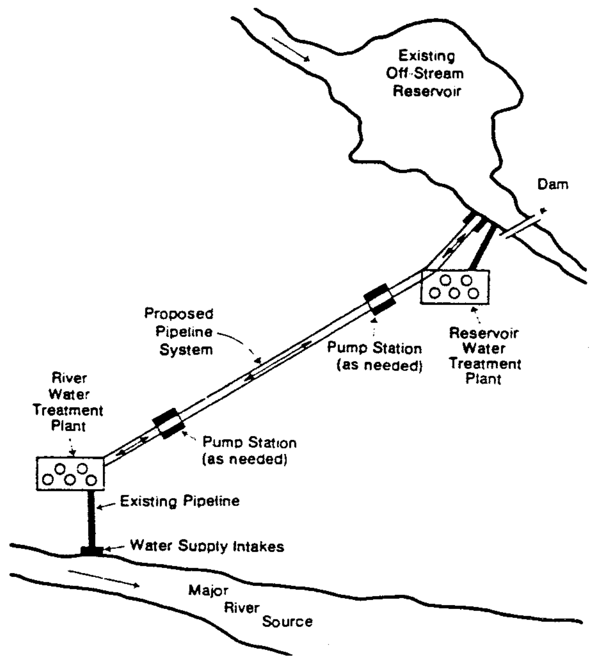
TABLE 12: METROPOLITAN WASHINGTON AREA WATER SUPPLY STUDY PUBLIC INVOLVEMENT PROGRAM.

General Information:	used to distribute information about the MWA study's progress and results to as many people as possible. Mechanisms: - Water Forum Notes (nine newsletters describing the study's status) - Newspaper articles - Communications media releases
Interaction-Dialogue:	to provide two-way communication between planners and public. Mechanisms: - Public workshops - Educational programs - Speeches to organized groups - Opinion surveys
Review-Reaction:	to obtain responses of those most directly involved with the study. Mechanisms: - Formation of special committees and advisory groups. MWA examples are a Federal-Interstate-State-Regional Advisory Committee and a Citizens' Task Group. - Responses were obtained from these groups via: Committee meetings Formal public meetings Review of the study's progress, interim, draft, and final reports

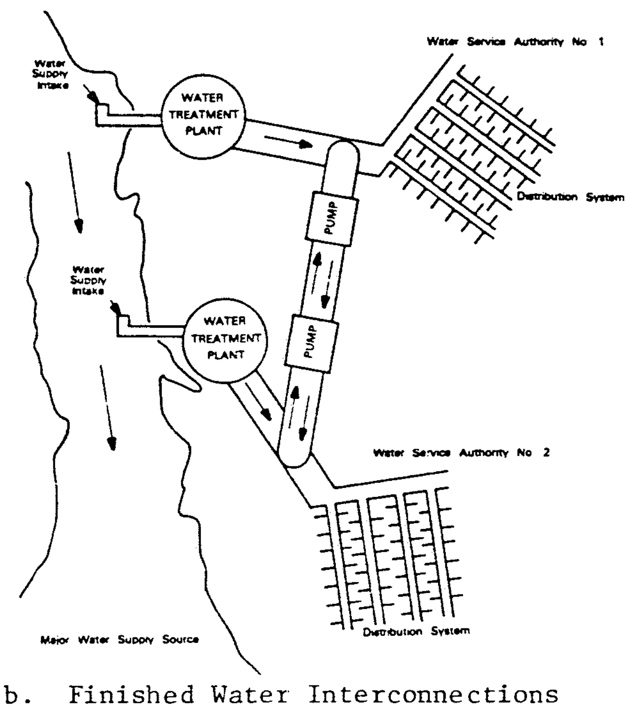
(Summarized from U. S. Army Corps of Engineers, 1983a) acceptable drought risk and accompanying consumption reduction measures were determined by the public after viewing Corps' projected water shortages and surpluses. These values were based upon the allocation formula devised by the local water agencies and specified in their Low Flow Allocation Agreement (January, 1978). In addition, the public was given the shortage-surplus values for five different demand reduction programs plus a baseline containing no conservation measures. These "scenarios" analyzed the cost and effectiveness of each program. The public, therefore, was given information directed toward public understanding of the conditions and, as a result, felt informed and involved in the study. This situation contributed to keeping the "regional view" of the solution process and the public's confidence that the study would be productive.

d. Surprising Conclusions Regarding System Flexibility

The Corps analyzed various system interconnections as means of increasing the local distribution systems' flexibility. The connections were of two types, raw-water interconnections and finished-water interconnections. Raw-water interconnections connected the sources to several water treatment plants. Finished-water interconnections allowed treated water to be taken to different distribution locations (Figure 26). The connections were analyzed by modeling the distribution systems. The analyses concluded that the ability to increase yield by altering system operation could not be improved by constructing new distribution lines. They showed that existing distribution systems, with proposed improvements for normal water supply operations, would be able to accomodate the capacities required for drought operation (Sheer, 1983). Sheer (1983) gives the reasons for this surprising result.



a. Raw Water Interconnections



b. Finished Water Interconnections

FIGURE 26 Metropolitan Washington Area Local Water Supply System Interconnections.
(U.S. Army Corps of Engineers, 1983a)

First, major parts of the system are designed to handle infrequent peak demands and smaller parts of the system are designed to handle flows required for fighting fire. Peak demand flows are 160% of the Washington area average and fire flows are proportionately higher (Sheer, 1983). Secondly, the probability the occurrence of peak demands and drought operation will happen during the same period of time is very small. Therefore, the normal-operation system possesses the capability, granted a small risk, to accomodate drought operations.

Simulation of the water supply system operation includes a prediction of the hydrologic behavior of the drainage area between the upstream reservoirs, Bloomington and Savage, and the Potomac water supply intakes. The travel time of their release to the intakes is 5-7 days. Simulations must make assumptions regarding weather and runoff during this period. The larger the period, the greater the assumptions and the more inaccurate the prediction. To account for this inaccuracy, a 100 mgd safety margin was included in the upstream reservoir release. Simulation showed most of the release was never used and, as a result, the study area demands would be met only to the year 2000. In addition, because the local reservoirs were rarely called upon to make compensating releases, the local reservoirs remained full while the storage in the upstream reservoirs dropped.

Little Seneca Reservoir was added to the system to overcome this operation inefficiency. Travel time for a release from Little Seneca is one day (U.S. Army Corps of Engineers, 1983a). With Little Seneca in operation, the 100 mgd safety margin is reduced significantly, the percent of unused release drops from 70% to 10%, and local reservoir storage is fully used (Sheer, 1983). The effect of this increased efficiency is to extend by 30 years (through the year 2030) the water supply system's capability to meet demands.

Little Seneca represents a new way to view the role of reservoirs in water supply systems. Because of the inaccuracy of predictions, reservoirs close to a point requiring specific flows (for example, a river intake or estuary outflow) have additional value to operations than those further upstream. The benefits obtained to downstream users of re-regulating an existing reservoir close to a river flow control point for increased operation efficiency may be much greater than its potential losses to, say, recreation or flood control. Simulation of operation under various operation rules will determine the trade-offs.

III.C.3. Summary

The solution to the Metropolitan Washington area's water supply problem includes many recent advances in water resources management techniques. These advances include linear programming, synthetic hydrology, hydrologic modeling, statistical analysis, and computer simulation of operations. Table 13 lists examples of how these techniques are used in the analysis. In addition to these methods of analysis, MWA's experience emphasizes the importance of public and local agency involvement, beginning with the study's inception and continuing throughout its development, to produce a successful water supply system operation plan.

Current drought operation of the Potomac River Basin water supply system was made possible by eight separate agreements among agencies. These agreements were signed on July 22, 1982 and address low flow allocation, sharing of Little Seneca Reservoir's construction and operation and maintenance costs, and repayment of water supply storage

TABLE 13: SOLUTION TECHNIQUES AND EXAMPLES OF THEIR APPLICATION.

Solution Technique	Application Example
Linear Programming	Local distribution system operations modeling.
Synthetic Hydrology	NWSRFM (*) model to develop streamflow from precipitation and soil moisture data.
Hydrologic Modeling	Routing flow and reservoir releases to Potomac water supply intakes.
Statistical Analysis	Determination of drought risk.
Computer Simulation	Simulation of proposed operations. "Games" used to fine-tune operations and show success of cooperative operation to individual water supply agencies.

* National Weather Service River Flow Simulation

in Bloomington Reservoir (Sheer, 1983). In addition, the Water Supply Coordination Agreement binds all parties to joint operations during drought and assigns the responsibility for scheduling release withdrawals to a coordinating group established by the ICPRB consisting of members representing the District of Columbia, Maryland, Virginia, and West Virginia plus technical advisors from FCWA, WSSC, and WAD. A great deal of time and energy was spent constructing them however, the negotiators were motivated by the conviction that cooperative operation would provide the solution which had been sought for 30 years. Other water supply agencies should not be dissuaded from conducting similar studies by these required negotiations because, as shown by the Potomac, the benefits may be very large.

IV. CONCLUSION

Assessment of the past and current operations of the reservoir systems of the Potomac River Basin, Delaware River Basin, and California points to their lack of similarity. This is surprising given that they are all multi-reservoir systems serving large water supply demands and, to varying degrees, flood control and recreation, and that they have a common concern over salinity intrusion. Yet, it comes as no surprise at all if one considers the facilities of each basin, its politics, and hydrological characteristics.

Each region made operational changes after their drought experiences. Out of the three regions, two developed drought operation plans which include specified reservoir operations. As a result of these plans, both the Potomac River Basin and the Delaware River Basin are more capable of managing drought, and their managers have discovered that, with their plans and the addition of relatively small storage facilities, their water supply capability is greatly increased. Their experiences prove that other reservoir systems will benefit from developing their own drought operation plans.

The following two sections discuss the value of the historical drought operations as general drought operations for the nation, define the characteristics of a drought operation plan, and specify applicable analyses for development of such a plan. These sections are provided to assist other water supply systems in developing their drought operation plan. The final section makes observations regarding the drought preparedness of the study regions and includes recommendations for improvement.

IV.A. Potential of Specific Drought Operations

Section II, Past Drought Operations, describes methods used in the study regions to increase water supply during droughts. It illustrates the site-specific nature of operational responses to drought because no particular operation described in the section was used in more than one study region. In other words, minimum pool releases were not made in the Delaware River Basin and the purpose of the reservoirs in the Potomac Basin was not changed from flood control to water supply. These operations, however, could be used in other areas during drought. For example, many reservoirs in the western U.S. contain minimum pools which are subject to the same constraints to operation as those in California, those of fish habitat and recreation. These reservoirs could use releases from their minimum pools as a drought operation if these constraints were relaxed. Consolidation of reservoir storage in the reservoir nearest the demand point is a potential drought operation in areas where seepage and evaporation losses are large and the majority of water supply demands are downstream of the reservoir system.

Operating a reservoir during drought for a purpose other than the one for which it is authorized offers much potential. Such a change of purposes will be specific to the reservoir or system of reservoirs. The extensive power of the DRBC makes operating hydropower projects for water supply possible in their basin. It is unlikely that private hydropower project owners in other areas would be ameanable to operating solely for water supply during drought. This is true in California. For California, a water supply shortage can mean an energy shortage as well. The drought in 1976 and 1977 extended into western Canada and made California's usual additional energy source, that of imported energy from the Pacific Northwest, unavailable. Operating flood control projects for water supply is a valuable drought operation for any reservoir which receives inflow during the drought. It is unlikely that arid areas would qualify because of their seasonal hydrology and high seasonal demands. Most flood control reservoirs are operated by the Corps and, therefore, this operation should be included in the project Drought Contingency Plan (as discussed in Section III.A.3) of reservoirs for which it is beneficial.

Loaning water supply has the most potential for contributing to drought operations because of its broad applicability. Since their drought experience, the CVP and SWP have extended water supply loans as a means of meeting Delta water quality standards. The Delaware River's Basin-Wide Drought operation plan includes a variation to water supply loans. It is more accurately described as a storage space loan. If during a Basin-Wide Drought, F.E. Walters Reservoir is required to release its stored water supply to increase flood control space, the Montague flow objective is decreased. This lower requirement allows NYC reservoirs to decrease their releases to the Delaware River and, consequently, retain the storage lost from F.E. Walters. Both types of loans show much potential for increasing water supply during drought. Given their general applicability to reservoir systems, they should be considered for any reservoir system's drought operation plan.

These historical drought opertions provide options to be considered by reservoir system managers and planners in the development of their own drought operation plans. Their applicability or contribution to a plan is specific to the water supply system. Their value as general drought operations can be measured by their potential for increasing water supply and the size of the region to which they apply. Minimum pool release and conservation of storage provide relatively small increases to supply and are limited to the West and arid areas respectively. Their value as drought operations is not high when compared to the remaining two. Water supply loans and project purpose changes are not limited to particular regions and show more potential for increasing supply. Their value as drought operations measures for the nation is high.

IV.B. Drought Operation Plan Characteristics and Applicable Analyses

Analysis of the drought operation plans of the Delaware and Potomac river basins and California's SWP has identified three components to drought operation plans in general. The first component defines the drought indicator; the second specifies coordinated operation of the reservoir or reservoir system; the third identifies when normal operations resume.

The analyzed drought operation plans use different indicators for drought. The Delaware River Basin uses the combined storage levels of either its upper or lower basins' major reservoirs. The Potomac River basin's plan declares drought using one of two indicators. The first is based upon predicted estuary outflow. The second indicator is the risk of the systems' reservoirs not refilling within a given period of time. California's SWP bases drought operation upon forecasted inflow to four northern California river basins and the amount of carryover storage in their major water supply reservoir.

As stated previously, the reservoir operations specified in the drought operation plans of the study regions are individually complex with specific operations applicable to only the area for which the plan was developed. Hence, the second component of a drought operation plan can take many forms. Reservoir operations specified in the drought operation plans of the Delaware and Potomac river basins do have a general similarity. It is the fact that each plan is founded upon the coordinated operation of normally independent reservoir systems. This is evident in the Potomac's plan in which FCWA and WSSC river and reservoir withdrawals are scheduled by the ICPRB. In the Delaware plan, the type of drought, Lower-Basin or Basin-Wide, defines the amount of coordination between flood control reservoirs, private hydropower facilities, water supply reservoirs, and federal and state multipurpose reservoirs. Although the CVP and SWP do not have a formal drought operation plan coordinating their systems, their coordinated operation during and since the 1976-1977 drought also supports the trend to coordinated operations for more efficient management of water supply systems. With these three regions choosing coordinated system operation, the prospect for increasing the capability of most surface water supply systems during drought appears promising.

All three regions have similar methods for indicating the resumption of normal operations. Normal operations begin when the drought indicator was no longer defining a drought condition. This component must identify when the risk of reverting to a drought condition is negligible. The Delaware River Basin's experience in 1981-82 illustrates the problem of declaring an end to drought conditions too late. Determining when to leave a drought operation condition is critical to the efficiency and credibility of a drought operation plan and invloves the same analysis techniques used to determine the timing of drought declaration.

Information presented in this report will assist others in developing drought operation plans regardless of the emphasis placed upon coordinating operations. The four methods of increasing water supply during drought provide a reservoir manager or water supply planner with drought operation options. The discussions of drought operation impacts upon project purposes and the interaction of the legal, political, and engineering facets of water supply management during droughts gives insight to drought operation issues. The analyses in this report will also help in the development of drought operation plans. These analyses are the Delaware River Basin's development of a drought rule curve using historical drawdown data; their mass-curve analysis used to determine the frequency of drought declaration; FCWA's position analysis to determine the risk of running out of supply; the Potomac's use of linear programming, synthetic hydrology, hydrologic modeling, statistical anaylsis, and computer simulation.

IV.C. Drought Preparedness of the Study Regions

Having experienced drought and had the time to develop operational plans for future droughts, how prepared are the study regions? The following discussion addresses the status of each study region's ability to mitigate drought impacts should drought recur and makes recommendations for increasing preparedness.

IV.C.1. California

California's drought preparedness is fragmented. The Corps' operated reservoirs have yet to receive Drought Contingency Plans defining the methods of minimum pool release or consolidation of storage. The CVP has developed no drought operation plan and uses the same drought declaration criteria as before the drought. The SWP has a plan which maintains carryover storage assuming the following year will be dry by decreasing deliveries during the current year. What follows is a discussion of the current status of CVP and SWP operations and how they relate to drought operation and recommendations for improving drought preparedness for the CVP, SWP, and Corps' operated reservoirs.

The CVP and SWP are better prepared for drought now than in 1976-1977 because their operations have become more coordinated in general. During the drought, the issue of which Delta water quality standards each project would strive to maintain was not fully resolved. This created an atmosphere which did not support efficient coordination of the two projects. This issue has been resolved and both projects operate to maintain the Delta water quality requirements specified in Decision 1485. Resolution of the Delta water quality issue and finalization of their COA has created an atmosphere of cooperation between the CVP and SWP systems. The water accounting system allows water from one system to be easily used by the other for Delta water quality. For example, if Delta water quality deteriorates rapidly, the CVP's Folsom Reservoir could be used to meet both CVP and SWP release requirements until acceptable quality resumes. This operation is actually done on occasion because water released from Folsom reaches the Delta one to two days faster than releases from the SWP's Oroville Reservoir. The value of the amount of water which SWP would have released (but did not) from Oroville is kept on record and is returned to the CVP by extra releases from Oroville at a later date.

In addition to making coordination of the projects easier, Decision 1485 determines the drought parameter for the Delta because its standards vary depending upon the water-year type. Water-year type is based upon forecasted cumulative runoff for the Sacramento, Yuba, American, and Feather rivers. This value is called the Four-Basin Index and is the same value the SWP uses to determine water delivery capability using its rule curve. The CVP is therefore operating to two drought parameters. One, the Four-Basin Index, determining Delta water quality releases and the other, predicted inflow to Lake Shasta, determining when deliveries can be decreased. The CVP could find itself operating for drought because inflow to Lake Shasta is low yet meeting normal-year standards in the Delta. In addition, the CVP and SWP could be declaring drought and non-drought conditions for the same water year.

Ultimately the CVP and SWP should develop a drought operation plan for their coordinated operation. Development of the plan whould help quantify the impacts a proposed operation would have upon each project's delivery capability and produce a plan agreeable to both. In addition, a single method of determining drought should be used to simplify drought declaration. This is especially important if the SWP succeeds in contracting for the interim water of the CVP. If this were to occur and two drought indicators remained, both projects would be operating with two drought indicators which would only confuse drought operations and the public further.

For the interim, the CVP should develop an individual drought operation plan. Operations included in the CVP plan could involve coordination with upstream hydropower reservoirs and major divertors along the Sacramento River. The plan could identify operation options involving the SWP, and define the method of determining decreased deliveries for their various types of water supply contracts. It also might include operations for fish habitat such as increasing the proportion of releases from the Trinity River system to the Sacramento River as a means of maintaining cooler river temperatures. In addition to guiding drought operation, CVP's drought operation plan would also provide a foundation to the CVP-SWP drought operation plan because operation concerns and constraints during drought would be identified.

The content of the Drought Contingency Plans and expected time of their inclusion in the Corps' reservoir operation manuals is unknown. It would be appropriate that the manuals include the following subjects. A section describing minimum pool releases for the southern San Joaquin reservoirs should primarily address institutional and legal issues of the release and also discuss recreational concerns at the project, their validity, and means of mitigation, if any. A report of this type would shorten and ease the process of obtaining release approval. A report on the Orland Project's consolidation of storage would be primarily technical in nature and provide direction for maximizing the water supply increase potential of the operation. It should describe the conditions under which consolidation of supply should be done and how it should be conducted.

To summarize, two milestones have been passed for CVP and SWP operation since the drought. They are the agreement of both projects to operate for the same Delta water quality standards and, second, a formal agreement to coordinate reservoir system operations. Drought operations for the two projects remain unspecified except for the standards to be met in the Delta. Further, different drought definitions are used by each project. Although CVP and SWP operations have improved considerably since the drought, a drought operation plan which addresses coordination of the projects has not yet been approached. Corps' operated reservoirs have Drought Contingency Plans pending. It would be appropriate that the CVP develop an individual drought operation plan as soon as possible with the ultimate goal being a CVP-SWP drought operation plan. It would also be fitting that the Corps include technical, institutional, and legal concerns of drought operation in their projects' Drought Contingency Plans and finish the plans as soon as possible.

IV.C.2. The Delaware River Basin

Of the three regions studied, the Delaware River Basin is the most susceptible to drought. In the past five years, a Basin-Wide drought-warning has been declared three times (October, 1980; November, 1981; and May, 1985) and a drought-emergency has been declared twice (January, 1981 and May, 1985). The following discussion points out the basin's dependency upon interagency and public cooperation during drought operations and how that cooperation has weakened since the development of the Basin-wide Drought Operation Plan.

The Delaware River Basin's drought operation plan is complex. It contains two levels of operation for two types of droughts. These levels, Drought-warning and Drought-emergency, designate stricter and more extensive operations as water storage within the basin becomes more depleted. Drought types, Basin-wide and Lower-basin, are defined as a means of placing the burden of drought operation upon the drought's area of origin. This intricate plan is dependent upon the cooperation of the DRBC members (the states of New Jersey, New York, Pennsylvania, and Delaware, and the federal government) because the DRBC members declare drought conditions and they specify the operations. The plan is also dependent upon the cooperation of New York City's water supply agency because its out-of-basin diversions are reduced during drought operation. Finally, the plan is dependent upon the willingness of the public within the Delaware River basin to reduce consumption during drought because decreases in river diversions river for water supply within the basin are implemented during drought operations.

Public support of water use restrictions is difficult to predict and hard to maintain without constant effort. Consumption reduction programs attempt to combine aspects of engineering, sociology, and psychology regarding public response to produce an effective plan. The Basin-wide drought operation plan's required decreases in river diversions illustrate how psychology is involved in the development of a convervation plan. Municipal water purveyors in Philadelphia using the Delaware River for supply must restrict river withdrawals during drought-emergency conditions even though they are not consumptive and, therefore, do not decrease river flow to the estuary. The theory behind this consumption restriction is to make the drought management plan appear fair to the public and to convey the seriousness of the water supply condition. During a Basin-wide drought-emergency, New York City must decrease its usage because the out-of-basin diversions supplying it are depleting the Delaware River's water supply. It is believed New York City residents would be less willing to conserve if Philadelphia residents were not required to conserve also. Although it is not rational, the plan appears to work. McSparran (1984a) observed public cooperation in restricting water use during the declared emergencies has been good.

From Pennsylvania's example one can conclude that for the consumption reduction program to work, a sense of unity must exist with the public. This unity is fostered by the perceived fairness of the program. The unity is also reinforced by the impression that water management agencies of the basin are cooperating via a well-developed plan to manage water supplies during drought efficiently and fairly for the benefit of all affected. In other words, the public's confidence in its water supply managers is high.

Events which occurred during the most recent drought-emergency (1985) indicate the drought operation plan is weakening and cooperation between agencies is decreasing. When the DRBC, of which New York City is not a member, declared a drought-emergency, they expected New York City to decrease its diversions from the basin by 40 mgd (from 560 mgd to 520 mgd) as specified in the drought operation plan. New York City, however, refused because a formula to which they and the DRBC agreed in 1982 regarding allowable diversions permitted New York City to continue its 560 mgd withdrawal. Now it appears there are two criteria for determining allowable diversions from the basin. This situation detracts from the effectivness of the drought operation plan for two reasons: 1) it lengthens the time required for plan implementation and 2) it creates uncertainty regarding the drought operations specified by the plan. This uncertainty can cause the public to lose confidence in the plan or to fail to perceive the seriousness of the drought condition. A lack of public cooperation will only weaken the plan further.

Given that the Delaware River Basin's Comprehensive Plan for water supply development incorporates the drought operation plans and the frequency with which drought operation is implemented, the DRBC must resolve the New York City diversion discrepancy. In addition, bickering amongst the agencies should be minimized. These actions would help the drought operation plans to regain the ability to minimize drought impacts. If the drought plans do not give strong direction for drought operation, the Comprehensive Plan will have to be revised to contain more water supply source facilities.

IV.C.3. The Potomac River Basin

The Potomac River Basin is well prepared for drought. So well prepared that drought conditions for the worst drought of record could recur today without the public's notice. This is one of the strengths of the drought operation plan. It uses water supply system operations to minimize drought impacts. Water use decreases are used only during emergencies such as facility outages or if a drought more severe than the worst drought of record occurs.

Potomac River Basin's drought operation plan illustrates the large increases available to water supply systems if operations can coordinate better with each other or their water supply sources. The Potomac's success is founded upon the simplicity of its water supply system. This system is not complicated by other purposes, primarily recreational, which reservoirs may serve. Salinity control is met simply by maintaining specified values for "environmental flow-by". Other, more constrained systems may not achieve such large increases in supply.

The Potomac Basin is not institutionally simple. Acceptance of the drought operation plan required eight separate agreements involving a total of seven agencies. As a way of avoiding situations such as the Delaware River Basin experienced in 1985, drought operation is done by the ICPRB. The ICPRB contains all agencies affected by drought operation. For the plan to succeed, these members must cooperate during drought operation because they are determining daily operation schedules. Cooperation between the agencies is good because the drought operation plan has already incorporated their concerns or constraints through the computer operation simulations. When drought operation is done, there should be no surprises.

V. REFERENCES

California Department of Water Resources, Lake Oroville, Phamphlet R-2-75, Sacramento, 1975.

California Department of Water Resources, State Water Project Annual Report of Operations, Sacramento, 1976.

California Department of Water Resources, The California State Water Project - 1976 Activities and Future Management Plans, Bull. 132-77, Sacramento, 1977a.

California Department of Water Resources, State Water Project Annual Report of Operations, Sacramento, 1977b.

California Department of Water Resources, Operational Criteria for the State Water Project, December 1, 1977 - December 31, 1978, Sacramento, December, 1977c.

California Department of Water Resources, The 1976-1977 California Drought: A Review, Sacramento, May, 1978a.

California Department of Water Resources, The California State Water Project - 1977 Activities and Future Management Plans, Bull. 132-78, Sacramento, 1978b.

California Department of Water Resources, The California State Water Project - 1978 Activities and Future Management Plans, Bull. 132-79, Sacramento, 1979.

California Department of Water Resources, State Water Project Water Delivery Rule Curve and Criteria for 1984, Sacramento, January, 1984.

Countryman, J., U.S. Army Corps of Engineers, Sacramento District, personal communication with author on August 23, 1984.

Delaware River Basin Commission, Delaware River Basin Compact, Trenton, NJ, January, 1967.

Delaware River Basin Commission, Appraisal of Upper Basin Reservoir Systems, Drought Emergency Criteria and Conservation Measures, Task Group Report DRBC Docket No. D-77-20, Trenton, NJ, March, 1979.

Delaware River Basin Commission, The Delaware River Basin - The Final Report and Environmental Impact Statement of the Level B Study, Trenton, NJ, May, 1981.

Delaware River Basin Commission, Recommendations of the Parties to the U.S. Supreme Court Decree of 1954 to the Delaware River Basin Commission, (the "Good Faith Agreement"), Trenton, NJ, November, 1982a.

Delaware River Basin Commission, Annual Report - 1982, Trenton, NJ, 1982b.

Delaware River Basin Commission, Draft Report on Alternative Lower Basin Drought Warning and Drought Operation Plans, Trenton, NJ, January 31, 1985.

Eiker, Earl, Chief Water Control/Quality Branch, Office of the Chief of Engineers, U.S. Corps of Engineers, Personal discussion with author, Washington, D.C., December, 1984.

Green, D., Attorney representing Chowchilla Water District, Letter to B. E. Martin and Colonel F. G. Rockwell, March 1, 1977.

Henkel, K., "Special Drought Operations of Oroville Reservoir", Water For Resource Development, Proceedings of ASCE Conference, Irrigation and Drainage Division, Coeur d'Alene, ID, pps 859-863, August 14-17, 1984.

Hirsch, R.M., et al, "Gains from Joint Operation of Multiple Reservoir Systems", Water Resources Research, Vol. 13, No. 2, 239-245, 1977.

Hogarth, R.A., The Delaware River Drought Emergency, Inter-University Case Program No. 107, Bobbs-Merrill Co., Inc., Syracuse, NY, 1970.

Hunt, R., Orland Unit Water Users Association Manager, Conversation with author, March 11, 1985.

Hydrologic Engineering Center, Potential for Increasing the Output of Existing Hydroelectric Plants, National Hydroelectric Power Resources Study, Vol IX, Davis, CA., July, 1981.

Link, George, U.S. Bureau of Reclamation, Central Valley Coordinating Office, Hydraulic Engineer, Conversation with author, Sacramento, CA, November 12, 1984.

Lundeen, R., North Sacramento District Reservoir Operations, U.S. Corps of Engineers, Conversation with author, Sacramento, CA, May 6, 1985.

Martin, B.E., Memo to the U.S. Bureau of Reclamation Commissioner regarding Dry Year Operation of the Central Valley Project, Sacramento Regional Director of U.S. Bureau of Reclamation, Mid-Pacific Region, May, 1976.

Martin, B.E., Letter to R. Robie, Director or the California Department of Water Resources, Sacramento Regional Director of U.S. Bureau of Reclamation, Mid-Pacific Region, August 16, 1977a.

Martin, B.E., Letter to U.S. Bureau Commissioner regarding Current Update on Drought Condition in Central Valley Basin and Operation of the Central Valley Project during 1977, Sacramento Regional Director of U.S. Bureau of Reclamation, Mid-Pacific Region, Washington, D.C., February 15, 1977b.

McSparran, J.E., "Impacts of Drought Management Policies and Programs in Pennsylvania", American Society of Civil Engineers, Urban Water '84 Specialty Conference, Baltimore, MD, May 28-31, 1984a.

McSparrran, J.E., Director, Bureau of Water Resources Management, Pennsylvania Department of Environmental Resources, Conversation with author, Harrisburg, PA, December, 1984b.

Pace, R.S., A Review of the Potential for the Expanded Use of Corps Multipurpose Reservoirs for Water Supply, U.S. Corps of Engineers, Baltimore District, January, 1982.

Schaefer, F.T. and Fish, R. E., Report of the River Master of the Delaware River for the Period December 1, 1980-November 30, 1981, U.S. Geol. Surv. Open-File Report 82-341, Washington, D.C., 1982.

Sheer, Daniel P., "Analyzing the Risk of Drought: The Occoquan Experience", American Water Works Association Journal, pps 246-253, May, 1980.

Sheer, Daniel P., Assured Water Supply for the Washington Metropolitan Area, Interstate Commission on the Potomac River Basin, Rockville, MD, January, 1983.

Thompson, D., Public Information Officer, Delaware River Basin Commission, Trenton, NJ, Conversation with author, February 4, 1985.

U.S. Bureau of Reclamation, Mid-Pacific Region, Daily Operation Records for Stony Gorge Reservoir and East Park Reservoir, Sacramento, California, January-June, 1976a.

U.S. Bureau of Reclamation, Mid-Pacific Region, Drought - Current Status Report, Sacramento, CA, October 15, 1976b.

U.S. Bureau of Reclamation, Mid-Pacific Region, Drought - Current Status Report, Sacramento, CA, October 29, 1976c.

U.S. Bureau of Reclamation, Mid-Pacific Region, Fact Sheet: Shasta Dam - Shasta Powerplant - Shasta Lake, Central Valley Project, Sacramento, CA, June, 1976d.

U.S. Bureau of Reclamation, Mid-Pacific Region, Central Valley Project Operation in 1976 - A Dry Year, Sacramento, CA, 1976e.

U.S. Bureau of Reclamation, Mid-Pacific Region, Dry Year Operations Policy, 1977, Central Valley Project, 1976f.

U.S. Bureau of Reclamation, Mid-Pacific Region, Central Valley Project Water Operation In 1977 - The Second Dry Year, U.S. Department of Interior, Washington, D. C., December, 1977a.

U.S. Bureau of Reclamation, Mid-Pacific Region, Daily Operation Records for Stony Gorge Reservoir and East Park Reservoir, Sacramento, California, January-June, 1977b.

U.S. Bureau of Reclamation, Engineering and Research Center, Director of Design and Construction, Letter to M.A. Catino regarding minimum power pool releases, August, 1977c.

U.S. Bureau of Reclamation, Mid-Pacific Region, Drought - Current Status Report, Sacramento, CA, September 1, 1977d.

U.S. Bureau of Reclamation, Mid-Pacific Region, Factual Data on the Orland Project, U.S. Department of Interior, Washington, D.C., October, 1978.

U.S. Bureau of Reclamation, Mid-Pacific Region, Fact Sheet: Trinity River Division, Central Valley Project, Sacramento , CA, November, 1980.

U.S. Bureau of Reclamation, Mid-Pacific Region, Central Valley Project, Its Historical Background and Economic Impacts, U.S. Department of Interior, Washington, D.C., July, 1981.

U.S. Bureau of Reclamation, Mid-Pacific Region, Agreement between the United States of America and the State Of California for the Coordinated Operation of the Central Valley Project and the State Water Project, Sacramento, Revision dated January 3, 1985.

U.S. Corps of Engineers, South Pacific Division, Water Recources Development by the U.S. Army Corps of Engineers in California, Los Angeles, California, January, 1973.

U.S. Corps of Engineers, Reservoir Control Section, Office Report - New Hogan Water Rights and Water Usage, Sacramento, California, June, 1977a.

U.S. Corps of Engineers, Northeastern United States Water Supply Study, Summary Report, North Atlantic Division, July, 1977b.

U.S. Corps of Engineers, Sacramento District, Success Lake, Tule River, California, Water Control Manual, Sacramento, California, January, 1982.

U.S. Corps of Engineers, Baltimore District, Metropolitan Washington Area Water Supply Study, Main Report, Baltimore, MD, September, 1983a.

Weddell, G. C., Chief, Inter-office letter to Technical Engineering Branch regarding Minimum Pool storage, Engineering Division, U. S. Corps of Engineers, Sacramento District, March 25, 1977a.

Weddell, G. C., Letter to the U.S. Bureau of Reclamation Regional Director regarding Success Lake, Chief, Engineering Division, U.S. Corps of Engineers, Sacramento District, April 28, 1977b.

Wells, J.V.B. and Fish, R.E., Report of the River Master of the Delaware River for the Period December 1, 1964-November 30, 1965, U.S. Geol. Surv., Washington, D.C., November, 1966.

Wells, J.V.B. and Fish, R.E., Report of the River Master of the Delaware River for the Period December 1, 1965-November 30, 1966, U.S. Geol. Surv., Washington, D.C., September, 1967.

Wells, J.V.B. and Fish, R.E., Report of the River Master of the Delaware River for the Period December 1, 1966-November 30, 1967, U.S. Geol. Surv., Washington, D.C., June, 1968.