1967

Derivation of Reservoir Operating Rules by Economic Analysis

Digital Object Identifier: https://doi.org/10.13023/kwrri.rr.06

Charles O. Dowell
University of Kentucky

Repository Citation
Dowell, Charles O., "Derivation of Reservoir Operating Rules by Economic Analysis" (1967). *KWRRI Research Reports*. 187.
https://uknowledge.uky.edu/kwrri_reports/187

RESEARCH REPORT NO. 6

DERIVATION OF RESERVOIR OPERATING RULES BY ECONOMIC ANALYSIS

Charles O. Dowell

1967

UNIVERSITY OF KENTUCKY
WATER RESOURCES INSTITUTE
LEXINGTON, KENTUCKY

United States Department of Interior
Contract No. 14-01-0001-787
P.L. 88-379

Research Report No. 6

DERIVATION OF RESERVOIR OPERATING RULES BY ECONOMIC ANALYSIS

Charles O. Dowell

University of Kentucky Water Resources Institute
Lexington, Kentucky

Project Number A-006-KY
Dr. L. Douglas James, Principal Investigator

1967

INTRODUCTION

"Derivation of Reservoir Operating Rules by Economic Analysis" is based on research performed as part of a project entitled "The Economic Impact of Flood Control Reservoirs" (OWRR Project No. A-006-KY) sponsored by the University of Kentucky Water Resources Institute and supported in part by funds provided by the United States Department of Interior as authorized under the Water Resources Research Act of 1964, Public Law 88-379. The Division and District offices of the U.S. Army Corps of Engineers have assisted by providing much of the necessary data.

The overall project is examining the economic consequences which resulted from the construction of four existing reservoirs in the hope of being able to suggest improved economic evaluation techniques. This is the fifth in a series of reports on the project and deals with the development of a methodology for determining an optimum set of reservoir operating rules specifying the monthly allocation of storage space which will maximize the sum of resulting flood control, recreation, and water supply benefits. Based on the physical and hydrologic characteristics of Rough River Reservoir, Kentucky, the derived operating rules are presented in curves showing how optimum operation varies with the marginal value of water for water supply and with recreation visitation.

Reader comments on the research problem, the approach described in this report, or the findings presented are encouraged and should be directed to L. Douglas James, Project Director.

ABSTRACT

The purpose of this study was to develop a methodology for determining an optimum set of reservoir operating rules specifying the monthly allocation of storage space based on the example of Rough River Reservoir, a Corps of Engineers project in Breckinridge and Grayson Counties, Kentucky, and assuming this multipurpose reservoir provides flood control, water supply, and recreation. The operating rules were derived by the method of marginal analysis which uses as its criteria achievement of maximum net benefits from the available storage capacity.

Benefit relationships were derived for each use. The variation of flood control benefits with available flood storage was determined from Corps of Engineers stage-damage curves and statistical analysis of the historical storms in the area. The variation of water supply yield with the allowable water surface fluctuation within the reservoir was determined by using statistical properties of past streamflow to synthesize a month-by-month operation of the reservoir. Recreation benefits as they varied with available storage were determined for five levels of annual visitation (up to twice the present value) by subdividing use among three activity types and estimating how each type of use would be affected by a fluctuation of water level.

The three benefit curves were combined by the method of marginal analysis, and the derived operating rules were expressed as curves which vary with the marginal value of an acre-foot of water for water supply.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

Chapter Page

V. RECREATION

VI. DERIVATION OF OPERATING RULES

VII. SUMMARY AND CONCLUSIONS

LIST OF TABLES

LIST OF TABLES
(Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
(Continued)

Chapter I

OPERATING PROCEDURE OPTIMIZATION

INTRODUCTION

The economic analysis of the alternatives in water resources management should not end with reservoir construction. The manner in which a reservoir is operated can substantially alter the benefits received. Just as marginal economic analysis should be used during initial planning to help determine whether, to what size, at what location, and when a reservoir should be built; it should also be used as a guide to those in charge of reservoir operation to help them decide how much water should be stored in the reservoir under varying conditions. However, while abundant literature (1, 2, 4, and 6) can be found on the application of benefit-cost analysis to reservoir planning for the guidance of water resources development agencies, the techniques of applying benefit-cost analysis to reservoir operation are scarcely mentioned in the literature and thus can be only applied in the most general way by the agencies.

The purpose of this study is to demonstrate by example how marginal economic analysis can be applied to determine the best way to operate an existing reservoir. The question of what way should an existing reservoir be operated to maximize the resulting benefits immediately introduces the issue of what types of operating questions must be resolved. The six basic operating questions are:

1. Whether storage space should be filled to provide water for future beneficial use and to provide space for recreation or reserved to provide space for potential floods;
2. Whether storing the current inflow to reduce the immediate flood peak would minimize flood damages more effectively than increasing releases to provide additional storage space for possible larger future inflows;
3. Whether water held for beneficial use should be released for present use or held longer for future beneficial use in the event of a possible future drought;
4. How much water should be released from each individual reservoir when a group of reservoirs is used to provide the yield;
5. How the water which is released should be divided among possible beneficial uses;
6. Whether warm water should be released from the surface of the reservoir or colder water should be released from some depth within the reservoir.

The application of economic criteria to answering each of the six operating questions requires a rather complex analysis, and so only the first will be attempted in this study. Rough River Reservoir, the reservoir to be studied in detail in the subsequent analysis, has as its primary purposes flood control and recreation, but it is also used to a lesser degree for water supply for low flow augmentation.

The question to be analyzed is how much water should be kept in the reservoir each month of the year in order to maximize the net benefit realized from these three purposes.

NECESSITY FOR MONTHLY RULES

Operating rules depend on the purposes for which the reservoir is constructed and the current demand each purpose places on reservoir storage. Recreation benefits increase with a fuller reservoir. Flood control requires freedom to store additional water during periods of high runoff and freedom to draw the reservoir down during low flow periods. The conflict among the demands placed on storage space by the various purposes must be resolved in operating rule selection.

The magnitude of the storage needs by purpose vary with the seasons of the year. In Kentucky, flood threats are greater in the spring than any other season, and recreation demand is greater in the summer. Although water supply demands are greatest in the summer, the storage required to produce a given yield must be filled the preceding spring.

Operating rules, or the amount of water to be kept in the reservoir, specified by month seem to fit the needs of reservoir operation more adequately than those specified by season or by week for several reasons. Most climatological and demand data are found in a monthly form and may be used directly to develop monthly operating rules. The more responsive operating rules are to changing conditions, the better able they are to produce the maximum benefits from the reservoir; a daily or weekly schedule would be too tedious to control and does not appear to increase benefits enough to warrant the additional computational complexity. A seasonal procedure could not adequately cover changes which come within the season.

The ideal operating procedure must compromise the conflict between an emptier reservoir which would increase certain benefits and a fuller reservoir which increase others. Drawdown, or available storage, when increased reduces current recreation benefits, reduces yield (releases water which could be used later), and reduces the chance of later filling for the recreation season. However, further drawdown reduces the expected value of flood damages. Recreation may also conflict with reservoir yield because storage cannot be retained for recreation while water is being released for beneficial use.

MARGINAL ANALYSIS

The recommended procedure in determining the optimum multipurpose reservoir size is to determine the marginal benefits and costs for varying degrees of development of each project purpose and to include those elements whose marginal benefits exceed their marginal cost. In this study, the capacity is fixed by the size of the existing reservoir and the problem remaining to be solved is what allocation of the fixed storage space among the various project purposes will maximize the net benefit. The optimum allocation varies by time of year according to the seasonal distribution of flood control, recreation, and water supply demand.

Marginal analysis uses as its basis the value of a marginal change. If, in the case of reservoir operation, the best use of an additional acre-foot of storage space is unknown, marginal analysis will consider all alternatives; and the alternative creating the greatest net benefit will be used. If an acre-foot of storage kept empty for flood control has a greater value than if kept full for recreation, each additional acre-foot of storage should be used for flood control until the marginal value of additional storage decreases to the value of that used for recreation. This is the type of analysis to be used to derive operating rules for Rough River Reservoir; and for the analysis, marginal benefits by month with respect to storage are needed for each purpose.

The allocation of space within a multipurpose reservoir requires a marginal tradeoff among uses. In a wet season, flood control may require a considerable drawdown for storage purposes; but water supply may require filling with water significantly above the minimum drawdown requirements for flood control. Obviously, maximum benefits cannot be received from both purposes because of the conflict for space between the two. Resolution of the conflict requires a relationship between the portion of the total needed space which is available and the portion of the potential benefits which can still be realized. Four sets of such curves will be developed for this analysis:

1. Recreation benefits as a function of water currently stored in the reservoir;
2. Flood control benefits as a function of available empty

storage space in the reservoir;

3. Water supply benefits as a function of how much drawdown is allowed during extended dry periods;
4. Water supply benefits as a function of how full the reservoir is allowed to get during peak inflow periods.

After the sets of curves are developed (one curve of each type by month), the space whose use is in conflict between two or more purposes in each month can be allocated to realize the greatest net benefits. As each additional increment of space is allotted to a particular use, it can be determined from the curves whether the allocation has resulted in increasing the benefits from that use more than the reduction in benefits for another use. If they do not, the space should be allotted to the other use. In this way, month-by-month rules can be derived.

METHODOLOGY OF THE ANALYSIS

The basic approach applied in this study is that of a case study based on determining the optimum operating policy for Rough River Reservoir, 50 miles southwest of Louisville, Kentucky. While the end product will be the optimum operating policy for this reservoir, the techniques used in its derivation have much more widespread applicability. The relationship established between recreation benefit and reservoir storage and the monthly marginal tradeoffs are unique. Thus, while the particular operating rules produced apply specifically only to the reservoir described in detail in Chapter II, the methodology used in their derivation may be used for other reservoirs to devise other operating rules which will increase the benefits derived.

The value of a water supply increases with the certainty that it will be available when needed. A consistent yield of X acre-feet per year is worth much more than a yield of Y acre-feet (Y greater than X) if no water were available during the summer months. Due to differences in reservoir size and local climate, every reservoir has a unique consistent, or firm, yield if it is used for only the one purpose. If in order to change to a multipurpose use, restrictions were placed on the operating procedure (reducing maximum drawdown allowed because of recreational needs or reducing the maximum allowable water level to allow more room for flood storage) the firm yield would be lessened. Methods, procedures, and results for estimating firm yield and determining how much it is reduced by various restrictions for Rough River Reservoir are presented in detail in Chapter III.

Flood damages prevented by flood storage are known as flood control benefits. A reservoir reducing flood peaks will reduce flood damages downstream, and the more room allowed for flood storage the greater the reduction. An analysis of flood peak reductions and the resulting benefits is discussed in Chapter IV.

Recreation opportunities will increase with storage because of a greater water surface area and more shoreline miles. An important part of this analysis is determining the variance of visitor capacity as the storage varies. Chapter V includes an analysis on recreational benefits and explains one method of determining visitor capacity.

After the benefit curves are derived for each purpose, they can be combined by marginal analysis to determine suitable operating rules for each month. A resulting month rule might be: keep at least X acre feet of water in the reservoir for recreation, reserve at least Y acre feet of storage for flood control, and fluctuate between these two levels as needed for yield. Chapter VI of this report discusses the combining of results from Chapters III, IV, and V to derive operating rules to produce maximum benefits from Rough River Reservoir.

Chapter II

DESCRIPTION OF ROUGH RIVER RESERVOIR

INTRODUCTION

Rough River Reservoir is located mainly in Breckinridge and Grayson Counties, Kentucky, on Rough River, a tributary of Green River. The dam, located on the county line 89.3 miles upstream from the mouth of Rough River, controls a drainage area of 454 square miles. The surrounding country is primarily second rate woodland, rolling hills, and farmland.

The Rough River project was authorized for flood control as part of a multi-reservoir plan for the Ohio River Basin by the Act of Congress (Public Law No. 761, 75th Congress, 3rd Session) approved June 28, 1938 (Flood Control Act of 1938). Construction of the project began in November, 1955, and was completed in June, 1961. The reservoir began affecting downstream flows in October, 1959. It provides flood control along the Rough and Green Rivers and also forms an integral part of the flood control system for the Ohio and Mississippi Rivers.

Access to the reservoir is provided by Kentucky state routes leading from U.S. Route 60 running east-west ten miles north of the damsite and the Western Kentucky Parkway and U.S. Route 62 running east-west about the same distance to the south. Figure 1 shows the location relative to nearby towns and rivers, and Figure 2 shows the location relative to important cities and reservoirs within the state. The site is 40 air miles north of Bowling Green, Kentucky, 30 air miles northwest of Mammouth Cave, 60 miles southeast of Evansville, Indiana (1960 population, 142000), and about 50 miles southwest of Louisville, Kentucky. Metropolitan Louisville, with a population of 770000 contributes about 40 percent of the present recreational use of the reservoir.

PRESENT OPERATION

Rough River Reservoir is operated for flood control, recreation, and low flow augmentation. Table 1 shows the operating pools. The reservoir is only drawn down to the minimum pool level during the flood season. The minimum pool is the minimum water level to which the reservoir will be lowered unless additional water is required for flow augmentation or other project purposes, and its level is established to provide a basic recreation facility and silt storage. The

TABLE 1

OPERATING POOLS OF ROUGH RIVER RESERVOIR*

Pool	Elevation of Pool	Capacity (Acre-Ft.)	Area (Acres)	Backwater (Miles)
Minimum	465	20170	1700	27
Seasonal	465-495	99840	5100	27-39
Flood Control	465-524	314210	10260	27-45
Total Storage	524	334380	10260	45

*Source (18, p. 26)

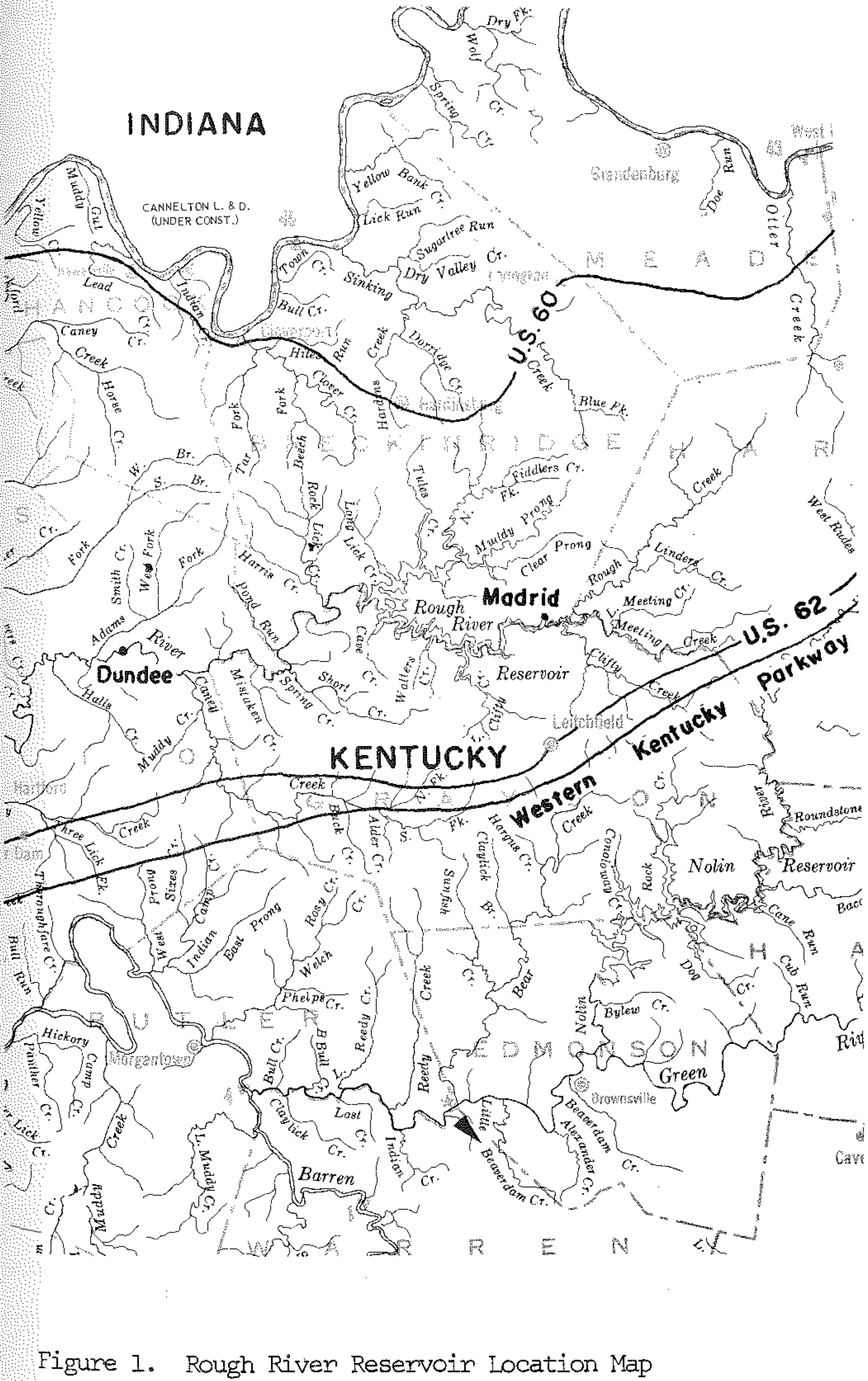


Figure 1. Rough River Reservoir Location Map

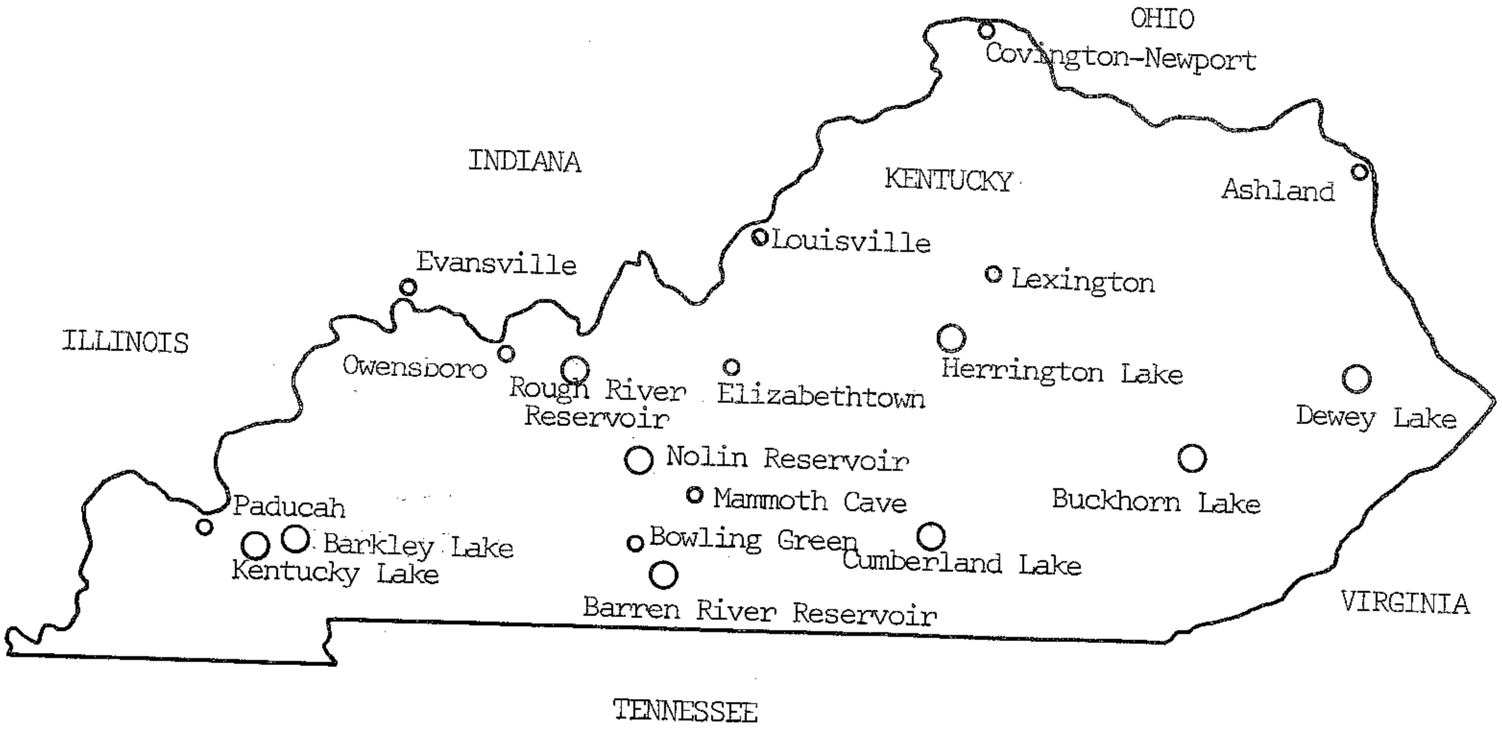


Figure 2. Areas of Importance in Kentucky

seasonal pool is the target pool for the summer months when more water is desirable for recreation and less storage is required for flood control. The flood control pool is storage filled only by flood events and makes up the greater part of the total capacity. After a flood, the pool is emptied as rapidly as is consistent with downstream channel capacity. The seasonal pool level in the summer and the minimum pool level in the winter are maintained whenever flood storage is not being used for the passage of floods or droughts do not cause additional drawdown.

The timing of the present operating policy at Rough River Reservoir is relatively simply stated. Beginning about April 1, the reservoir pool is raised from the minimum level by limiting outflow until the seasonal pool is reached. The seasonal pool will be maintained until Labor Day except for variation caused by flooding and low flow augmentation. The pool is lowered during the fall to minimum pool by December 1 to be ready for winter flooding (18). Table 2 provides a comparison between the target operating rules and the degree to which the minimum and seasonal pools are actually maintained.

The beginning-of-month storages for Rough River Reservoir given on Table 2 indicate that the December 1 target is relatively easy to reach. Because October and November are among the drier months of the year, flooding does not usually interfere with the drawdown rate necessary to reach the target. The late winter and early spring rains and subsequent drawdowns to restore minimum pool between storms cause the water level to fluctuate widely during the flooding season. The

TABLE 2

ACTUAL BEGINNING OF MONTH STORAGES (ACRE-FEET)
AT ROUGH RIVER RESERVOIR*

Water Year	1962	1963	1964	1965
Oct.	87880	86770	86730	85970
Nov.	53510	52840	52390	53570
Dec.	20440	20480	20480	21980
Jan.	20140	21680	19780	26980
Feb.	71750	20260	20190	17460
Mar.	111250	20220	20290	50290
Apr.	126510	99670	205000	66390
May	111750	66240	125000	96080
Jun.	118060	73470	121500	97870
Jul.	120010	73740	118400	97550
Aug.	118620	83730	119000	98010
Sep.	112300	94050	115500	94840

*Source (20)

prescribed seasonal pool is not consistently kept full during the summer months. In drier years enough water is not available during April and May to reach the seasonal pool level. In two of the four years shown on Table 2, the 120010 acre-feet in the full seasonal pool was not approached during the summer.

PRESENT RESERVOIR USES

The present uses of Rough River Reservoir are flood control, recreation, and low flow augmentation. Even though flood control received priority in the initial planning stages, the Corps of Engineers did consider recreation in planning Rough River Reservoir. Eleven recreation sites were planned, and those developed have the facilities shown on Table 3.

Flood control will probably remain the major purpose at Rough River, but recreation is growing in importance. The Department of Parks of Kentucky holds 50-year leases on land and facilities at sites 1 and 8 with the exception of lands retained by the Corps for dam operation. All other sites remain in the operation of the Corps (11). As a result of the leases Rough River became a part of the growing Kentucky State Park system. The development was done at a cost to the state of $1,465,000, and the Corps through the same period has invested $816,200. Still more state funds have been allocated for a

TABLE 3

ROUGH RIVER RESERVOIR RECREATION SITE
FACILITY INVENTORY*

	Recreation Sites	Parking Area	Boating Ramp	Water Supply	Rest Rooms	Shelter	Picnic Facilities	Camp Sites	Swimming Area	Lodging Facilities	Air Strip
1	Main Entrance	X	X	X	X	X	X		X	X	X
2	Laurel Branch	X	X	X	X		X	X			
3	Cave Creek	X	X	X	X		X				
4	Axtel	X	X		X	X	X	X			
5	North Fork	X	X		X		X	X			
6	Everleigh	X	X								
7	Calvert		Future Development								
8	Below Dam	X			X						
9	Panther Creek		Future Development								
10	Little Clifty		Future Development								
11	Peter Cave	X	X		X		X				

*Source (17)

TABLE 4

BENEFITS ATTRIBUTED TO ROUGH RIVER RESERVOIR IN DOLLARS PER YEAR

	Flood Control Benefits[1]	Recreational Benefits[2]
1959	195900	11264
1960	256000	40259
1961	1760200	106934
1962	1070500	336550
1963	548000	703984
1964	307000	883031
1965	360000	987425
1966	895000	1046734

[1] For fiscal year from source (15)

[2] For calendar year from source (16; 10, p. 148)

golf course and improvements to the air strip. Recreational benefits, as well as flood control benefits, attributable to Rough River Reservoir year by year since completion are shown on Table 4.

Low flow augmentation at present is only necessary in the summer and early fall months. Streamflow records since 1959 indicate a minimum allowed streamflow averaging about 70 cubic feet per second (20). This minimum flow requires a relatively small amount of low flow augmentation water because all months have an average streamflow at the damsite greater than 70 cubic feet per second. The required yield is too small in the light of normal inflows to cause prolonged drawdown.

Use of the reservoir for water supply, other than for incidental park uses and for low flow augmentation, has not been planned. Quantities large enough to support a municipality could be developed but would require some revision in operating procedure. The detailed derivation of marginal water supply benefits in Chapter III serves primarily to present a method of analysis and is not meant to imply that water supply is expected to become a major project purpose.

Chapter III

WATER SUPPLY

INTRODUCTION

At the present time, water supply has a very small effect on the overall operation of Rough River Reservoir. A small system provides water for facilities in the immediate vicinity, and low flow augmentation in the summer months requires an annual yield of perhaps 4000 acre-feet, but both quantities are completely overshadowed by the potential yield found in this analysis.

While water volumes currently supplied by the reservoir are quite small, they may substantially increase in the future. It is not inconceivable that a larger water supply may be needed by a nearby municipality. Although Evansville, Indiana, is located on the Ohio River, various factors might require the city to look for a new supply. Other cities might be forced into a similar situation by future growth. With increasing population and industrial development, water quality control may require additional water for low flow augmentation. Although Kentucky farmers have not irrigated much in the past, supplemental irrigation may become profitable.

However, the primary purpose for including water supply in the analysis is methodological. Even if water supply never becomes a significant factor in the operation of Rough River Reservoir, it is in many other reservoirs; and a method of analysis is needed.

OPERATION STUDY DATA

The analysis of water supply demand was predicated on the annual demand pattern for municipal water supply. In order to determine the volume of firm yield which could be developed at the site as a function of operating procedure a month-by-month tabular operation study (3, pp. 292-7) was run on the digital computer. The operation study amounts to a month-by-month tabulation of inflow from the upstream watershed, precipitation, evaporation, current release for low flow augmentation, water supplied to satisfy the municipal demand, and any spills that would occur. Alternate demands are evaluated to find the maximum which can be satisfied without the reservoir running dry. The monthly data for the operation study were obtained in the manner described below.

Stream Inflow: The Geological Survey maintains a streamgage 6.5 miles downstream from the Rough River Reservoir dam. Published records (20) were used to obtain the 26 years of historical monthly streamflows from water year 1940 through water year 1965. Before October, 1952, the streamgage was in the vicinity of the present location of the dam. Because this previous location was more indicative of the flows into Rough River Reservoir and because the watershed tributary to this gage was 449 square miles (nearly the same as the 454 square miles tributary to the dam) rather than the 504 square miles above the present gage, all flows since 1952 were corrected to a value appropriate to the damsite area.

The correction was based on a comparison of the monthly flows at the two gage sites with flows at a gage upstream at Madrid, Kentucky, having a tributary area of 225 square miles (Figure 1). Streamflow for a seven-year period before 1952 was found to average 2.008 times that at the Madrid site. Streamflow for the seven years after 1952 was found to average 2.057 times that at the Madrid site. The ratio of the two numbers is 0.977, or the monthly flows at the damsite are approximately 97.7 percent of those at the downstream gage.

The 26 years of adjusted historical flows were used to synthesize a 500-year record for determining yield. The advantage of the long synthesized record based on the statistical parameters of the historical record is that it allows examination of many more possible combinations of low flows so that yield may more realistically be determined on a probability basis. The streamflows were synthesized using the formula:

$$Q_{i+1} = \bar{Q}_{j+1} + b_j(Q_i - \bar{Q}_j) + t_i\sigma_{j+1}\,(1 - r_j^2)^{\frac{1}{2}} \qquad (1)$$

where j refers to the month of the year, i refers to the month in the synthesized flow sequence, b_j is the regression coefficient of Q_{j+1} on Q_j, σ is the standard deviation, r is the coefficient of determination of Q_{j+1} on Q_j, $\bar{Q}$ is the mean historical flow, and Q is the synthesized flow (9, pp. 459-477). Q_{i+1} is the synthesized flow for the current month in the sequence, and Q_i is the generated flow for the previous month. The generated flow is made up from three terms:

1. The average streamflow in that month,
2. The expected effect of departures from average flow in the past month on current flows,
3. A random term based on the degree of variance of the streamflows within that calendar month.

The third term is made random by selecting the value t_i at random from a statistical distribution. For this analysis, the distribution used was defined by the distribution of historical flows (normalized by division by their mean) in that month around their mean. For the operation study, 500 years of monthly streamflow were synthesized from the 26 years of corrected historical flows.

Precipitation: The raingage nearest the damsite is at Dundee, Kentucky, approximately 15 air miles to the west (Figure 1). It was assumed that this rainfall data (19) applied to the damsite area. In order to obtain 500 years of rainfall data commensurate with the synthesized streamflows, a least squares analysis was run between the 26 years of monthly streamflows and 26 years of monthly rainfall.

Evaporation: Because evaporation data is not as abundant as other data, it was necessary to use data from Lexington, about 110 miles to the east. It was thought that the two areas did not sufficiently differ in climatological characteristics to make the use of these data inappropriate. Average values by month of the year were calculated from pan evaporation data (21) and representative pan coefficients

(3, p. 107) and were used in the operation study as shown on Table 5.

Release: The maximum yield for water supply requires the storing of all streamflow not required by downstream users. Most water-right laws require the release of all streamflow which was put to a beneficial use by those downstream prior to the construction of the reservoir as long as that much streamflow occurs. If the natural streamflow is less than that required, only that streamflow that actually comes into the reservoir has to be released.

However, in the case of Rough River Reservoir, water is currently released for low flow augmentation. The practice, which would doubtless continue were water for a hypothetical municipal water supply required from the reservoir, requires maintenance of a minimum flow downstream regardless of the flow upstream. After studying streamflow records downstream from the dam since the reservoir went into operation, it was found that approximately 4000 acre feet of water per month is the minimum maintained streamflow (20). It was decided to use this amount in this analysis.

Area-Capacity Curves: The Corps of Engineers provided tables of surface area of the reservoir in acres and storage in acre-feet as these vary with the elevation of the water surface. These data were needed in calculating the evaporation from and the net additional precipitation into the reservoir, both of which depend on the surface area of the body of water. The curve of storage versus surface area shown in Figure 3 was derived from these other two curves and broken into two parts (a straight line for larger values of storage and a parabola for the smaller values) so that the data could be converted to equation form to be used in the computer program.

Demand: Some data was needed on the relative demand for water by month so that an assumed yearly demand could be subdivided by month. Because the analysis was done with a municipal water supply in mind, 1966 figures of water use by month in Lexington, Kentucky, were obtained from the Lexington Water Company and from these figures the fractional use by month was calculated to produce the figures shown on Table 5.

Runoff Coefficients: Streamflow comes from the portion of precipitation that runs off the land, and the portion of runoff varies with the condition of the watershed surface, primarily dryness and use. Only part of the rainfall falling on the land surface runs off, while all the precipitation falling on the reservoir would contribute to its filling. Thus, an amount of precipitation equal to the product of (1.0 - runoff coefficient), (surface area of the lake), and (inches of precipitation) must be added to the water entering the reservoir through streamflow. It is for this reason that the runoff coefficients by month are needed.

The precipitation gage at Dundee, Kentucky and the recorded streamflows adjusted to the damsite were used for this purpose. Monthly precipitation at Dundee (19) was converted to acre-feet of water over the Rough River Reservoir watershed. Monthly streamflow for the watershed for the same period of time (1941 through 1959) was also converted

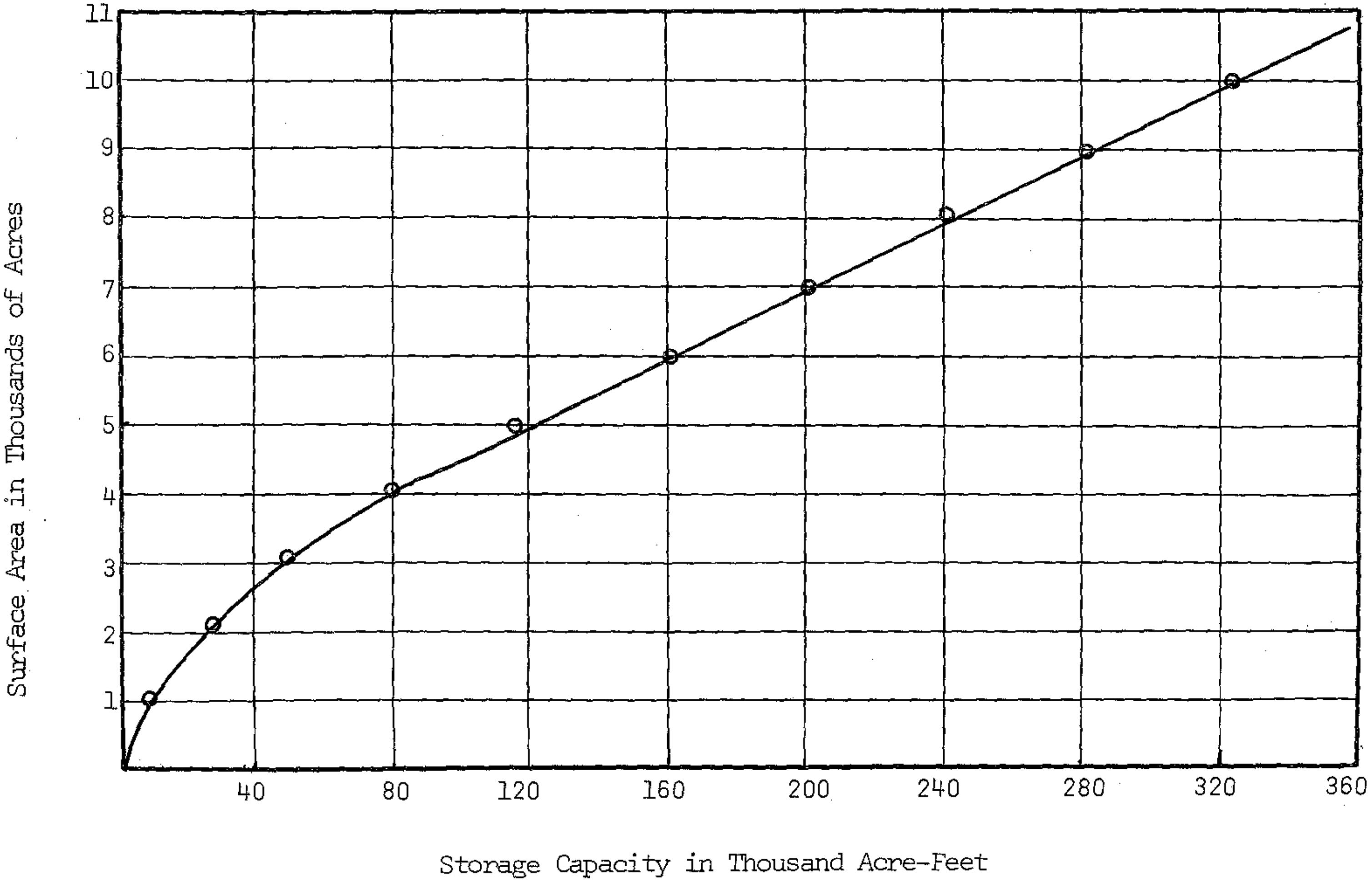


Figure 3. Surface Area-Capacity Curve for Rough River Reservoir

TABLE 5

MONTHLY VALUES USED IN OPERATION STUDY

	Runoff Coefficients	Lexington Demand	Lake Evaporation in./mo.
January	0.63	0.071	0.63
February	0.84	0.073	0.66
March	0.70	0.079	0.73
April	0.56	0.077	2.17
May	0.36	0.080	4.21
June	0.23	0.101	5.34
July	0.16	0.099	5.75
August	0.14	0.095	6.25
September	0.11	0.095	5.02
October	0.05	0.081	3.15
November	0.26	0.073	1.65
December	0.48	0.076	0.79
Annual	0.41	1.000	36.35

to acre-feet. The latter value for any given month divided by the precipitation for the same month gives the monthly runoff coefficient. In this way, average values of coefficients by month as shown on Table 5 were found for the watershed. An average annual runoff coefficient for the wooded and cropland area around the watershed was found to be 0.410 by this method. This value is in good agreement with other annual coefficients for the Kentucky area.

OPERATION STUDY PROCEDURE

Using the data described, a monthly accounting of the fluctuation of the reservoir level was developed for the 500 years of simulated streamflow. Precipitation directly on the lake surface and streamflow contributed to the filling of the lake. Evaporation from the surface of the lake, downstream release requirements (4000 acre-feet per month), demand (or water use), and any spills contributed to the lowering of the level. As the storage in the lake was calculated, the surface area could then be calculated from the area-capacity equations. The full 334380 acre-foot capacity to the spillway crest of the present reservoir was utilized.

From the 500 years of simulated operation, the fifth worst drought was chosen to be the 100-year drought, as this is the drought severity often implicitly used in water supply design. Only the years defining the drawdown and recovery period of this fifth worst drought were used in the further analysis to save computer time.

Using the same procedure with the nine-year drought a firm yield was evaluated by a trial and error process incorporated into the computer program. A fairly low yield was assumed for the first run through the period. As long as the reservoir did not completely empty, the yield estimate was increased by a constant percentage until the reservoir ran dry. The firm yield for the present capacity of the reservoir was found to be 269100 acre-feet per year. In other words, with no restrictions set on how the level fluctuated and utilizing the full capacity, the reservoir could supply 269100 acre-feet of water per year right through the 100-year drought.

The operator of a multipurpose reservoir should not allow the level of the reservoir to fluctuate as determined by the single purpose of water supply when the other purposes would achieve a greater overall benefit by maintaining a different level. Certain restrictions on the maximum and minimum allowable levels by month must be supplied by the operator. The next logical step in the analysis is thus to find how such restrictions would affect the yield from the reservoir.

The maximum storage required to get the firm yield was found for each month of the year in the critical nine-year dry period. As long as this maximum storage is allowed, the full yield could be realized, but reducing the maximum allowable storage in a given month of the year for a purpose such as to provide room for flood control would reduce the available water and thus reduce the firm yield. To get an idea of how much the yield would be reduced, the operation study was repeated with a limit of 0.8 of the maximum storage in the month. This same procedure was followed using 0.6, 0.4, and 0.2 of the maximum storage. From the firm yield for each procedure, a curve was developed of the variation of the yield with allowable maximum storage by month.

Using the same argument, if a maximum limit was put on the amount of drawdown (i.e., a minimum amount of water to be kept in the reservoir) the restriction would also reduce the obtainable firm yield. For each month of the critical drawdown period, the maximum drawdown required for the firm yield was noted in acre-feet of drawdown. Then restrictions were put on these drawdowns, reducing the allowable drawdowns in 0.2 increments, to obtain monthly curves of yield verses drawdown allowed.

Table 6 lists the maximum drawdown required in each calendar month of the critical drawdown period and the maximum storage required in each month if the full potential firm yield is to be developed. Figure 4 contains the curves of yield as a fraction of 269100 versus the required maximum storage as a fraction of the appropriate monthly value from Table 6. Figure 5 contains curves of yield as a fraction of 269100 versus the required maximum drawdown as found on Table 6.

ANALYSIS OF THE DERIVED CURVES

The information contained on Table 6 and Figures 4 and 5 summarizes the findings of the determination of water supply yield as a function of monthly operating restrictions. If the entire 334380 acre-feet capacity is used for water supply, an annual yield of 269100 acre-feet can be obtained. As long as flood control does not restrict

TABLE 6

STORAGES REQUIRED FOR MAXIMUM FIRM YIELD

	Maximum Drawdown Required	Maximum Storage Required
Jan.	266100	188580
Feb.	246600	267587
Mar.	258200	334380
Apr.	232610	316160
May	241000	317180
Jun.	239900	298920
Jul.	256650	273480
Aug.	275000	249715
Sep.	296000	233050
Oct.	315600	211530
Nov.	334380	192580
Dec.	258300	174115

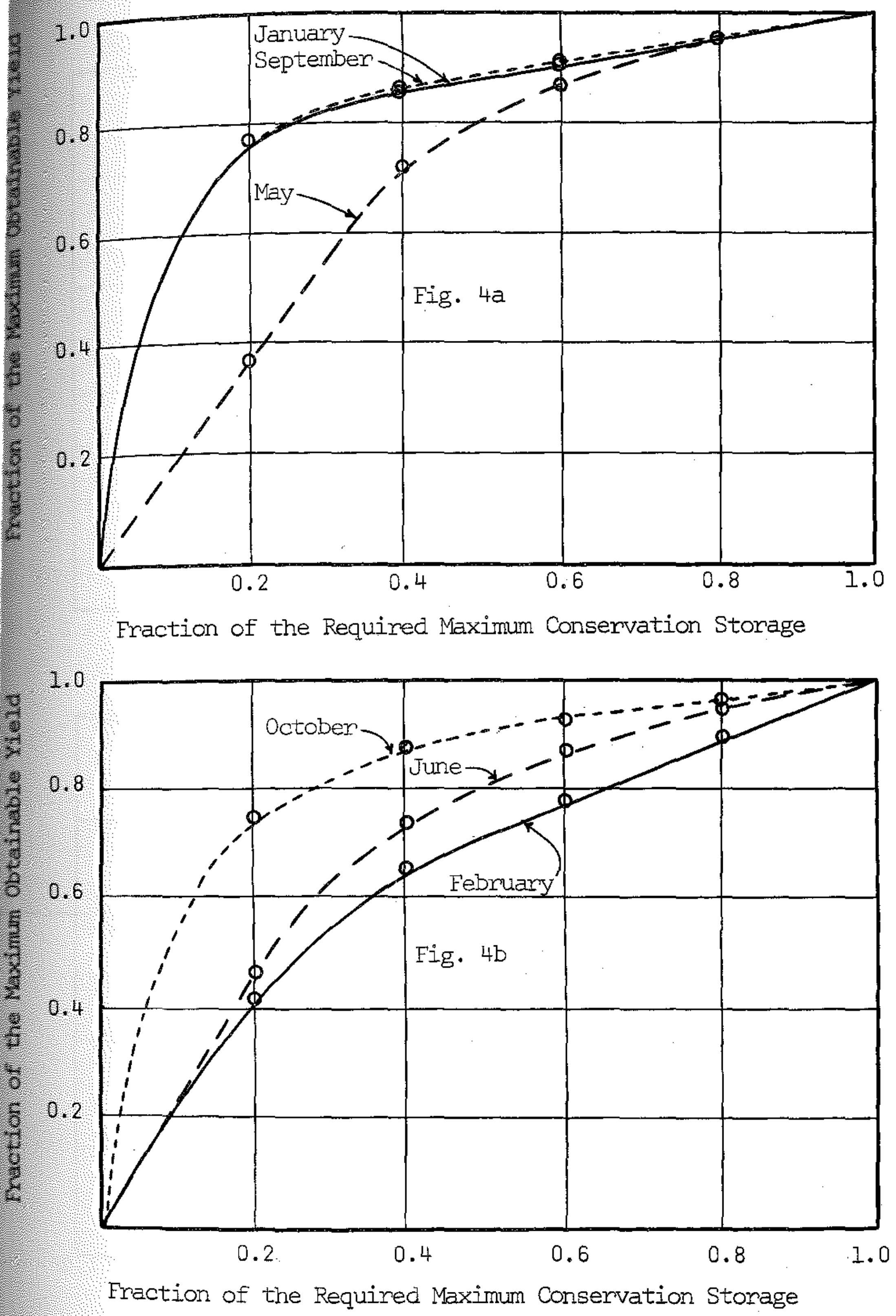
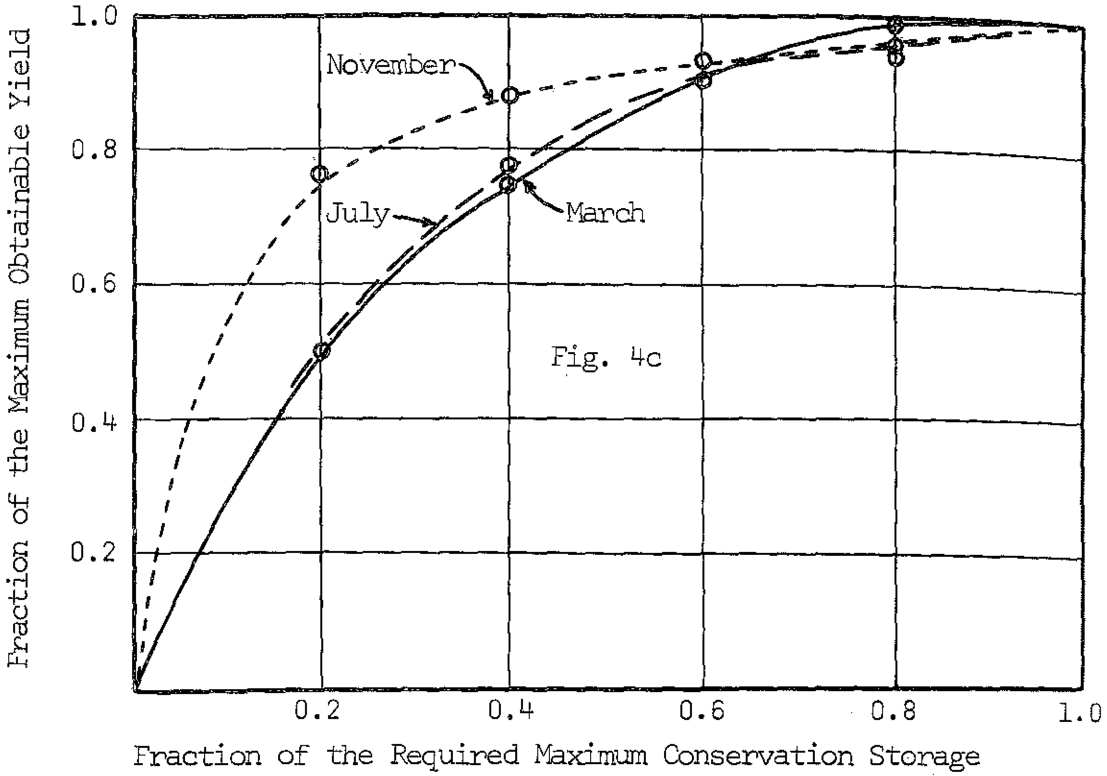


Figure 4. Variation of Reservoir Yield with Maximum Allowable Conservation Storage



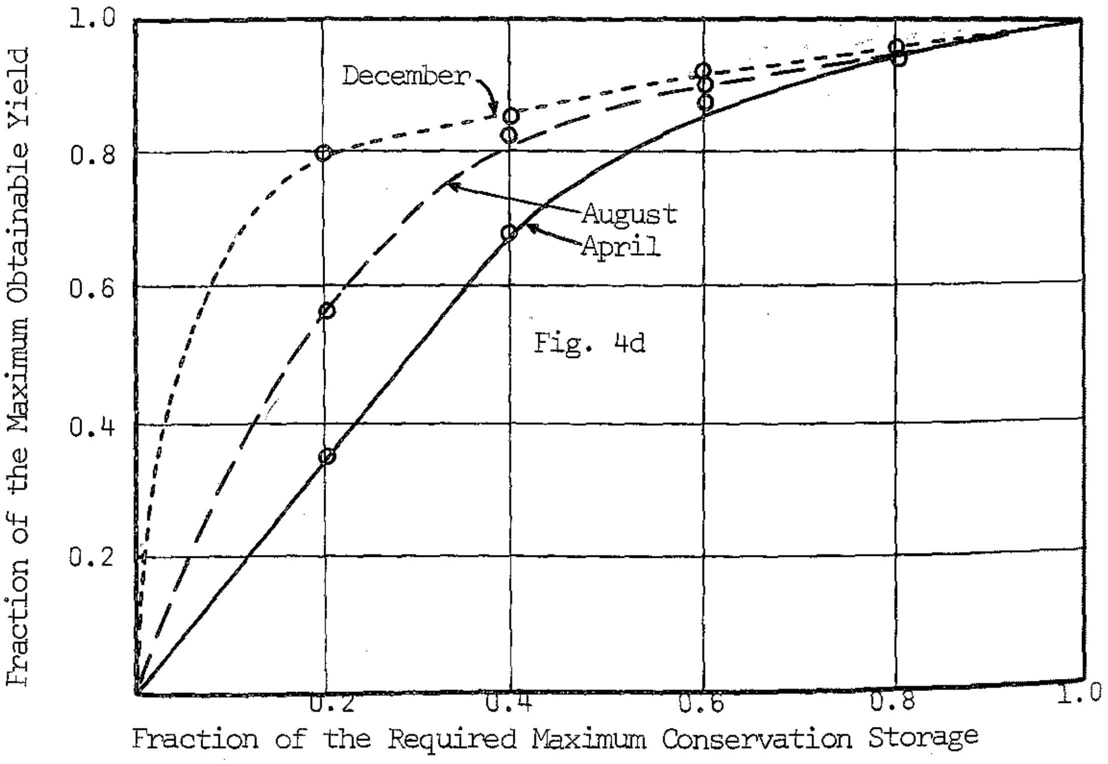


Figure 4.--Continued

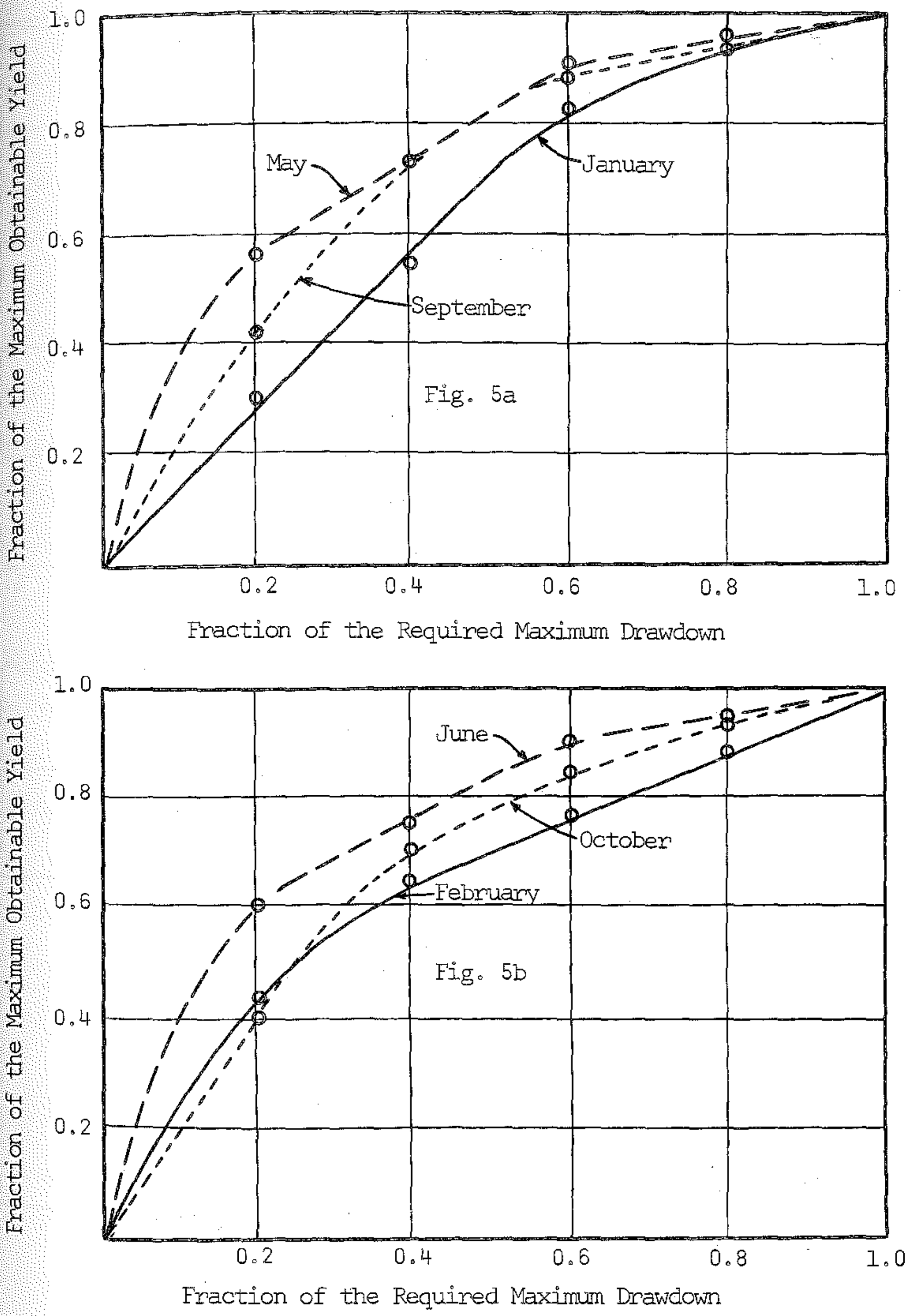


Figure 5. Variation of Reservoir Yield with Maximum Allowable Drawdown

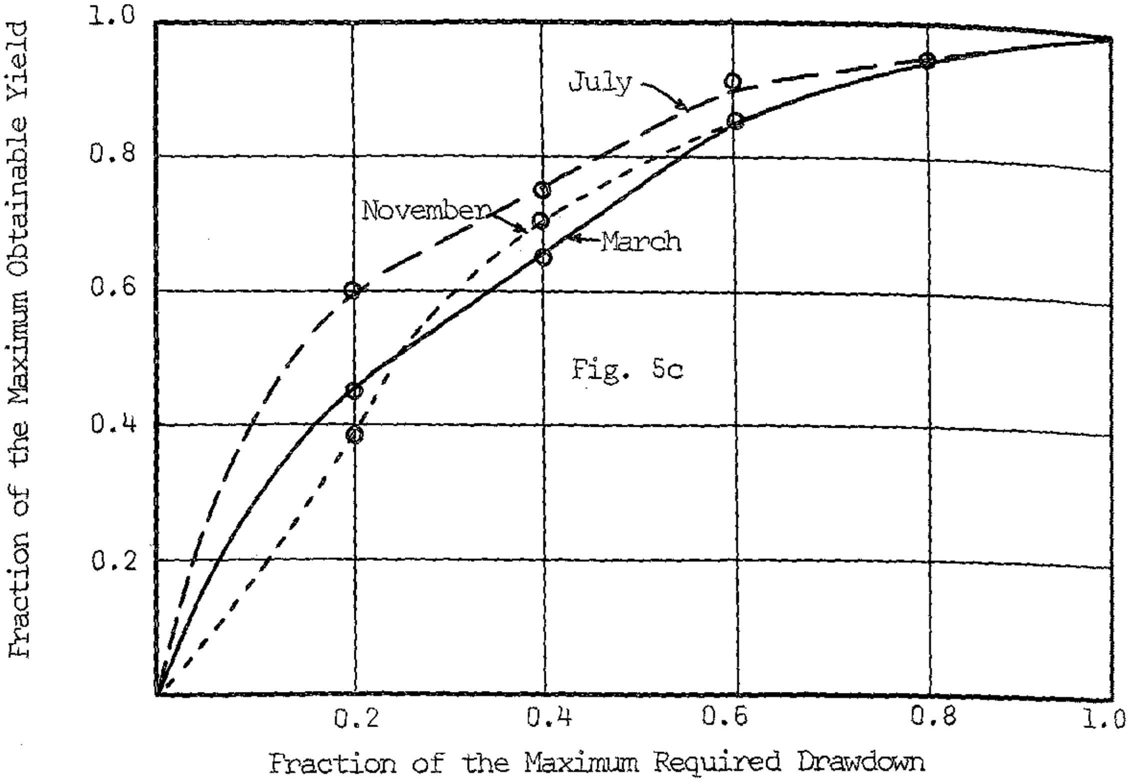


Fig. 5c

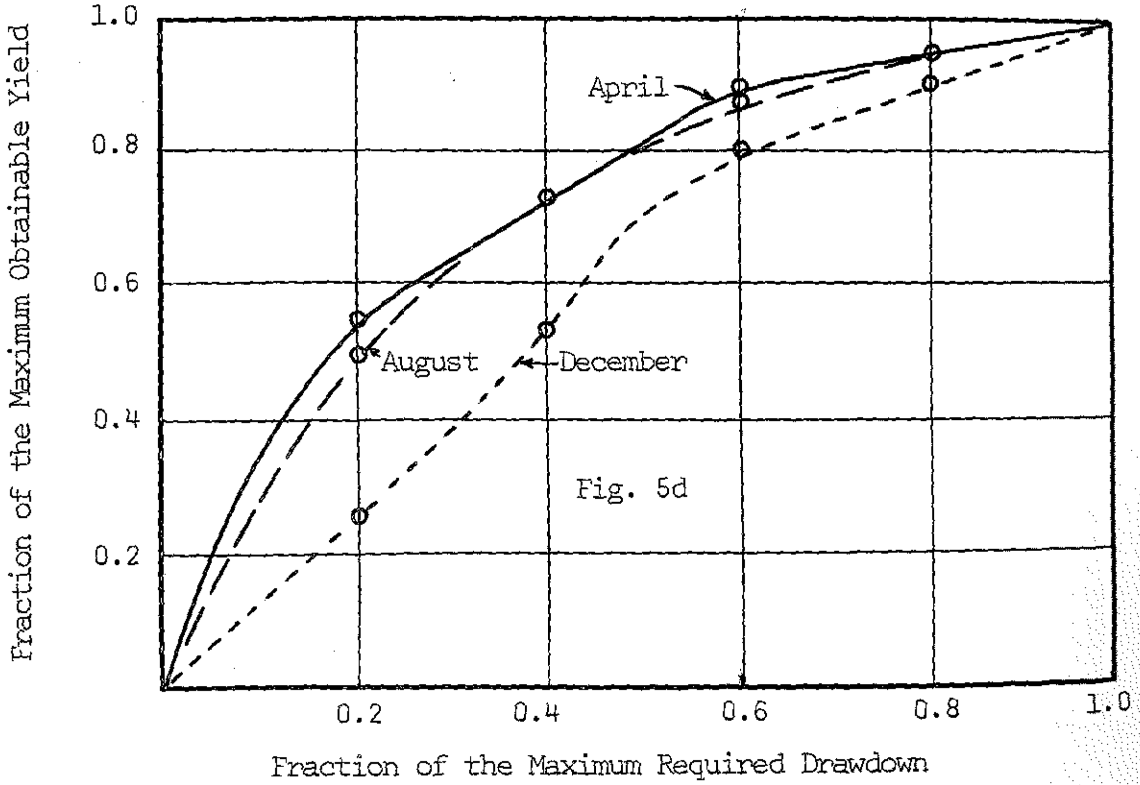


Fig. 5d

Figure 5.---Continued

the maximum storages or recreation does not restrict the maximum drawdowns shown on Table 6, the maximum annual yield of 269100 acre-feet can still be obtained. The reduction in yield which would result from various degrees of the two types of restrictions is shown on Figures 4 and 5 respectively.

Table 6 shows the greatest storage for maximum yield to be required in March. Figure 4c shows March to be one of the months where restrictions on maximum storage causes yield to drop fairly sharply. Since March is one of the months of major flood threat, the potential for significant competition between the two uses for the same storage space is indicated.

A review of Figure 4 reveals that the curves for the spring months exhibit a greater responsiveness to changes in the maximum allowable storage than do the curves for the fall months (i.e., they plot below and to the right). Summer and winter months tend to fall in between. Because most runoff occurs in the spring months, these are the months in which the reservoir must save most of the water for subsequent summer and fall use. Thus, any restrictions on the maximum storage within these months will cause the greatest reduction in firm yield.

Table 6 also shows the greatest required drawdown for maximum yield to be in November at the end of a series of increasing values through the late summer and fall. However, the required recreation pool is dropping during this same period as visitation decreases. The curves in Figure 5 exhibit a trend toward greater responsiveness to restrictions in allowable drawdown as one progresses from summer into fall and winter by plotting further below and to the right. The marginal loss in yield which would be caused by restricting the maximum drawdown below the values on Table 6 is greatest in winter when water must still be withdrawn for municipal purposes but just before the bulk of the spring runoff. Fortunately, recreational use is minimal during this period.

Chapter IV

FLOOD CONTROL

INTRODUCTION

In contrast to water supply, Rough River Reservoir at the present time achieves major flood control benefits. The reservoir is operated during flood periods to store as much of the runoff as is needed to prevent downstream flooding or, for larger storms, to reduce downstream flood peaks as much as possible. As part of the economic evaluation of a reservoir for flood control, a thorough analysis is made of past floods and resulting damages; and predictions are made as to future flood plain development. The flood control analysis for this report was also begun by gathering data for the Rough River area to determine the relative magnitudes of expected floods.

Rough River Reservoir has some influence on flooding all the way to the Gulf of Mexico (13). For this analysis, it only seemed feasible to consider effects on flood damage from alternative operation schemes on Rough River Reservoir downstream to the mouth of the Ohio River at Cairo, Illinois. The Corps of Engineers divides all streams into reaches for the purpose of collecting and presenting flood damage data. There are six of these reaches between the damsite and the Mississippi River. Proceding upstream from the mouth of the Ohio River (Figure 6), they are in order:

1. The Ohio River from the Mississippi River to the mouth of the Cumberland River,
2. The Ohio River from the mouth of the Cumberland River to the mouth of the Wabash River,
3. The Ohio River from the mouth of the Wabash River to below Owensboro, Kentucky,
4. The Green River from 26.0 miles upstream from its mouth to the mouth of the Rough River at mile 72.0 (mile 0.0 to mile 26.0 on Green River is included in the adjacent Ohio River reach because of backwater effects),
5. The Rough River from mile 0.0 to mile 14.0,
6. The Rough River from mile 14.0 to mile 89.3 (the damsite).

EXPECTED FLOOD PEAKS

In order to develop monthly operating rules for Rough River Reservoir, it was necessary to determine the flood frequency relationship for each calendar month. The data required for the analysis of flooding in each of these reaches were taken at a representative streamgage in each reach. The Gumbel method of flood frequency analysis (3, pp. 250-252) was thought to be suitable for the needs of this study. The Geological Survey (20) publishes mean daily flows, monthly streamflows, and all instantaneous peak flows above a certain base. The data needed for the Gumbel analysis was the instantaneous peak flow for every month of every year during the period of analysis. Peak mean daily flows were taken when available, and the instantaneous peak flow was determined as a multiple of the mean flow for that day for each

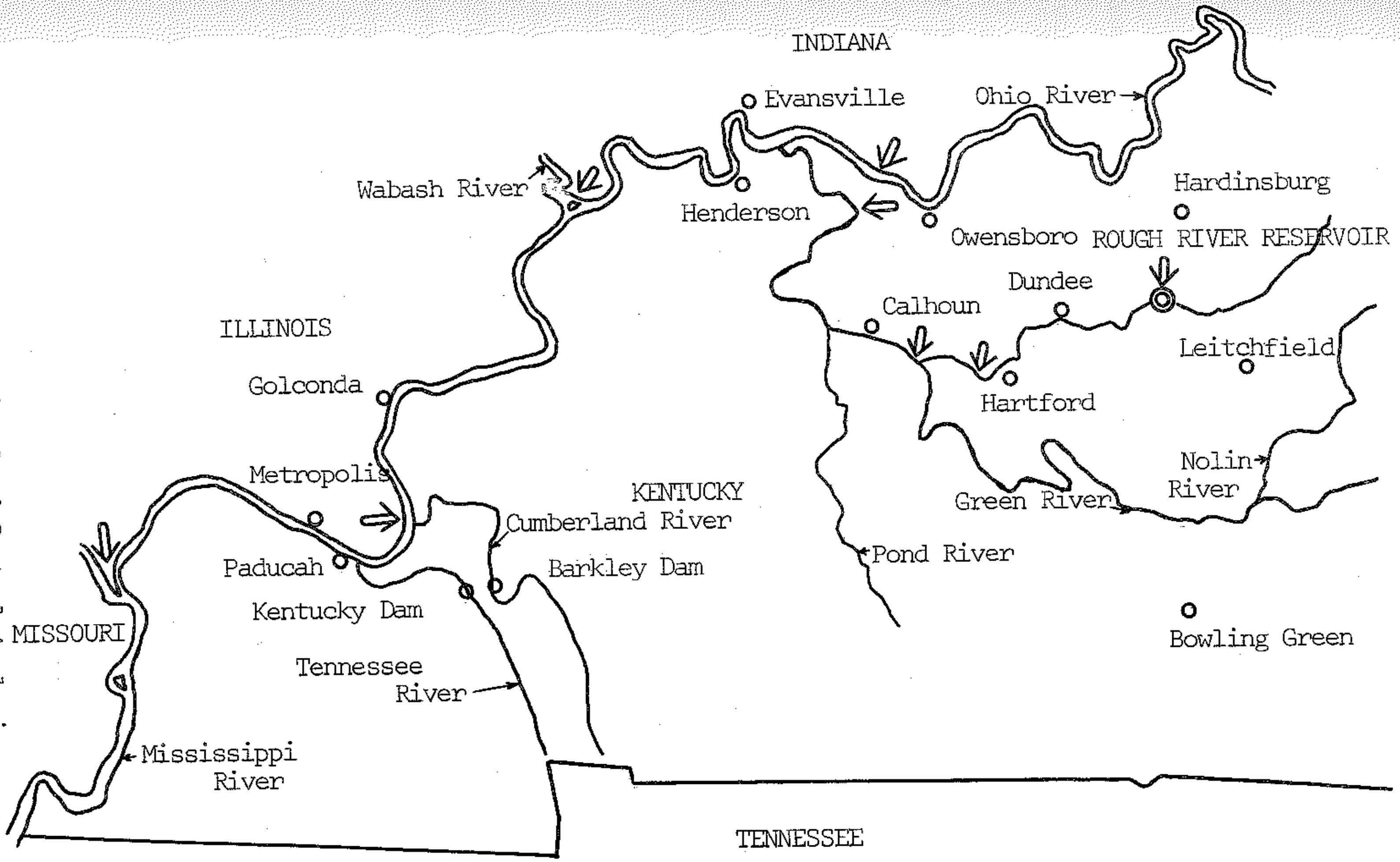


Figure 6. River Reaches Used in Flood Control Analysis

reach. These relationships were assumed good for all storms, were applied to those data where mean daily but not instantaneous peak flows were given, and are shown in Table 7 along with the city for which the data was taken in each reach. For example, for a given monthly flood at Calhoun, Kentucky, the peak flow during the flood will be 1.014 times greater than the mean daily flow on the day in which the peak flow occurred. Using these relationships the peak mean daily flow for each month could be converted to the instantaneous peak flow for the month, the data required for the Gumbel analysis. Peak flows for every month for water years 1939 through 1958 for all six reaches were thus derived.

The Gumbel method of analysis predicts flood peaks by return period by making use of the theoretical distribution of extreme values (3, p. 327). A computer program was written to apply this method; and

TABLE 7

RELATIONSHIP BETWEEN THE PEAK INSTANTANEOUS FLOW IN A FLOOD AND THE MEAN DAILY FLOW

Reach	Stream Gage	Qpeak/Qday
1	Metropolis, Ill.	1.005
2	Golconda, Ill.	1.005
3	Evansville, Ind.	1.004
4	Calhoun, Ky.	1.014
5	Dundee, Ky.	1.023
6	Dundee, Ky.	1.023
Damsite	Falls of Rough (Adj)	1.059

expected floods were calculated by the program for every month of the year, for each reach, and for the following return periods: 200-year, 100-year, 25-year, 6.7-year, and 2.33-year. Table 8 shows the results of the analysis.

It can be seen that the September floods for Dundee, Kentucky (to a lesser extent, also those for the adjacent gages) seem too large in comparison to the other months. An extremely unusual, or at least unseasonal, storm occurred near Dundee in September, 1950, in which the streamflow was well over ten times the average peak for the other 19 years studied. The short period of record underestimated the return period for this rare storm and caused the Gumbel analysis to overestimate the magnitude of rare floods for September. For comparison purposes, a flood of about average magnitude was substituted for the original data, and the analysis was repeated. The expected 200-year flood fell from 11651 cfs to 2917. The historical data was used in the remainder of the analysis, however, and did increase the flood control benefits for September significantly. Nevertheless, flood storage requirements were not a significant factor in determining September operating policy even with these larger floods.

ROUTING OF FLOODS THROUGH THE RESERVOIR

The next step in the analysis was to determine what effects the existence of varying amounts of storage space in Rough River Reservoir will have on downstream flood peaks of varying sizes. The effect at the reservoir site was determined by routing flood hydrographs through the reservoir to determine the resulting reduction in the peak. The

TABLE 8

EXPECTED MAGNITUDE OF FLOODS OF SPECIFIED FREQUENCY

DAMSITE

FREQ.	0.5%	1.0%	4.0%	15%	43%
Jan.	20978	18598	13810	9056	4845
Feb.	23315	20688	15405	10159	5514
Mar.	17023	15162	11417	7699	4407
Apr.	17531	15611	11749	7915	4519
May	14683	12985	9569	6178	3174
Jun.	10060	8876	6495	4130	2036
Jul.	5199	4632	3491	2358	1355
Aug.	5447	4801	3502	2212	1070
Sep.	5649	4930	3482	2045	773
Oct.	1226	1084	797	512	259
Nov.	13297	11623	8255	4911	1949
Dec.	18018	15868	11543	7248	3445

DUNDEE (Reach 6 and 5)

FREQ.	0.5%	1.0%	4.0%	15%	43%
Jan.	27512	24397	18132	11911	6402
Feb.	25425	22688	17182	11716	6875
Mar.	23243	20853	16045	11272	7045
Apr.	21691	19429	14879	10362	6361
May	19446	17168	12587	8039	4011
Jun.	10579	9364	6919	4492	2342
Jul.	7439	6597	4904	3223	1734
Aug.	7088	6236	4524	2823	1317
Sep.	11651	10098	6975	3874	1128
Oct.	2011	1770	1285	803	376
Nov.	15818	13837	9851	5894	2389
Dec.	22318	19634	14235	8875	4128

CALHOUN (Reach 4)

FREQ.	0.5%	1.0%	4.0%	15%	43%
Jan.	119244	107333	83375	59587	38520
Feb.	132404	119289	92908	66716	43520
Mar.	130373	117650	92060	66653	44152
Apr.	97276	88747	71591	54558	39473
May	80595	72207	55335	38583	23748
Jun.	66042	58674	43853	29138	16106
Jul.	41484	36829	27466	18169	9935
Aug.	55368	48580	34924	21367	9360
Sep.	59929	52287	36915	21654	8138
Oct.	19550	17212	12507	7837	3701
Nov.	76570	67116	48100	29219	12498
Dec.	101584	89966	66596	43394	22845

TABLE 8--Continued

EVANSVILLE (Reach 3)

FREQ.	0.5%	1.0%	4.0%	15%	43%
Jan.	1151646	1032113	791670	552945	341528
Feb.	1171413	1060891	838576	617848	422369
Mar.	1259416	1138578	895214	653686	439787
Apr.	1001006	914744	741228	568952	416382
May	663280	606453	492146	378656	278147
Jun.	511286	465650	373853	282713	201997
Jul.	279616	257328	212498	167988	128569
Aug.	329144	295228	227006	159271	99284
Sep.	315804	280702	210095	139993	77910
Oct.	337877	300008	224078	148610	81775
Nov.	457301	409395	313032	217357	132626
Dec.	868012	773543	583521	394855	227771

GOLCONDA (Reach 2)

FREQ.	0.5%	1.0%	4.0%	15%	43%
Jan.	1474965	1316576	997976	681652	401512
Feb.	1381369	1250176	986283	724274	492236
Mar.	1495812	1352390	1063896	777462	523793
Apr.	1323886	1207327	972871	740090	533936
May	1093430	988126	776307	566001	379752
Jun.	732110	662979	523921	385857	263585
Jul.	553476	497319	384358	272205	172880
Aug.	515962	458917	344171	230245	129351
Sep.	364030	324295	244368	165012	94733
Oct.	380847	337197	249394	162219	85015
Nov.	598140	531361	397034	263667	145556
Dec.	1017793	903712	674238	446404	244631

METROPOLIS (Reach 1)

FREQ.	0.5%	1.0%	4.0%	15%	43%
Jan.	2020063	1805228	1373089	944036	564062
Feb.	2107455	1903870	1494362	1087778	727703
Mar.	1800311	1640543	1319172	1000096	717519
Apr.	1759037	1597498	1272563	949949	664239
May	1330199	1200613	939953	681155	451960
Jun.	888694	804163	634131	465313	315806
Jul.	527316	480436	386136	292510	209594
Aug.	439345	397224	312931	229240	155122
Sep.	493345	439310	330618	222702	127131
Oct.	899283	790137	570591	352613	159570
Nov.	1121984	991905	730253	470253	240402
Dec.	1347515	1198310	898185	600204	336308

flood routing procedure was quickly and easily handled by programming the flood routing for the digital computer. The program used the relationship that the difference between the streamflow into the reservoir and the streamflow out must equal the change in storage over the elapsed time interval (3, p. 224). Known inflows and storage-outflow relationships were then used for the routing.

The data required for the routing program included: an array of elevations of water surface with corresponding arrays of water surface area and reservoir storages (the program interpolates to find intermediate values); data on the spillway, such as width, discharge coefficient, and elevation of the crest; data on the outflow ducts within the dam (it was assumed that these ducts are closed throughout the flooding period in order to achieve the maximum possible reduction in flood peak); the storage within the reservoir at the beginning of the flood; and a flood hydrograph typical of the damsite.

The hydrograph must be carefully selected by peak and volume. A unit hydrograph for a six hour rainfall duration was obtained from the Corps of Engineers, but it was found that floods of sufficient volume to require use of significant storage capacity would be caused by much longer rainfall than six hours. The longer hydrographs would have the same peak but greater volumes. However, if the hydrograph duration is extended too long the flows at its extremities become too small to have a significant effect on flood hydrology. By routing hydrographs of varying duration through the reservoir, a 12-day hydrograph was found to be about the most critical.

The volume of the 12-day hydrograph was based on cumulative runoff data. Runoff over peak flow periods lasting from one to twelve days was tabulated for a number of years and averaged to get average annual amounts. The hydrograph was developed so the flow volumes reflected these average values while the shape of the peak cresting at the magnitude of the mean annual flood was based on the six-hour unit hydrograph. The peak was placed toward the end of the hydrograph because this condition would be more critical than an earlier peak. The resulting 12-day hydrograph with each ordinate expanded by a constant multiple to reflect the 200-year values is shown in Figure 7.

A total of 44 storms were routed through the reservoir with the varying conditions being the size of the storm and the available storage at the storm beginning. A 200-year storm for the damsite (peak found by the Gumbel analysis to be 23315 cfs.) was the largest storm routed through the reservoir. Then storms whose each ordinate was 0.75, 0.50, and 0.25 of those for the 200-year storm were used. The initial amount of water stored in the reservoir was varied from zero to the full capacity of 334380 acre-feet.

The major purpose of the routing was to determine the reduction caused by the reservoir in the flood peak as a function of flood size and available storage. Figure 8 summarizes the results and shows the change in flood peak for available storages. It is seen that an available storage of 265680 acre-feet is large enough to completely absorb anything as large as a 200-year storm.

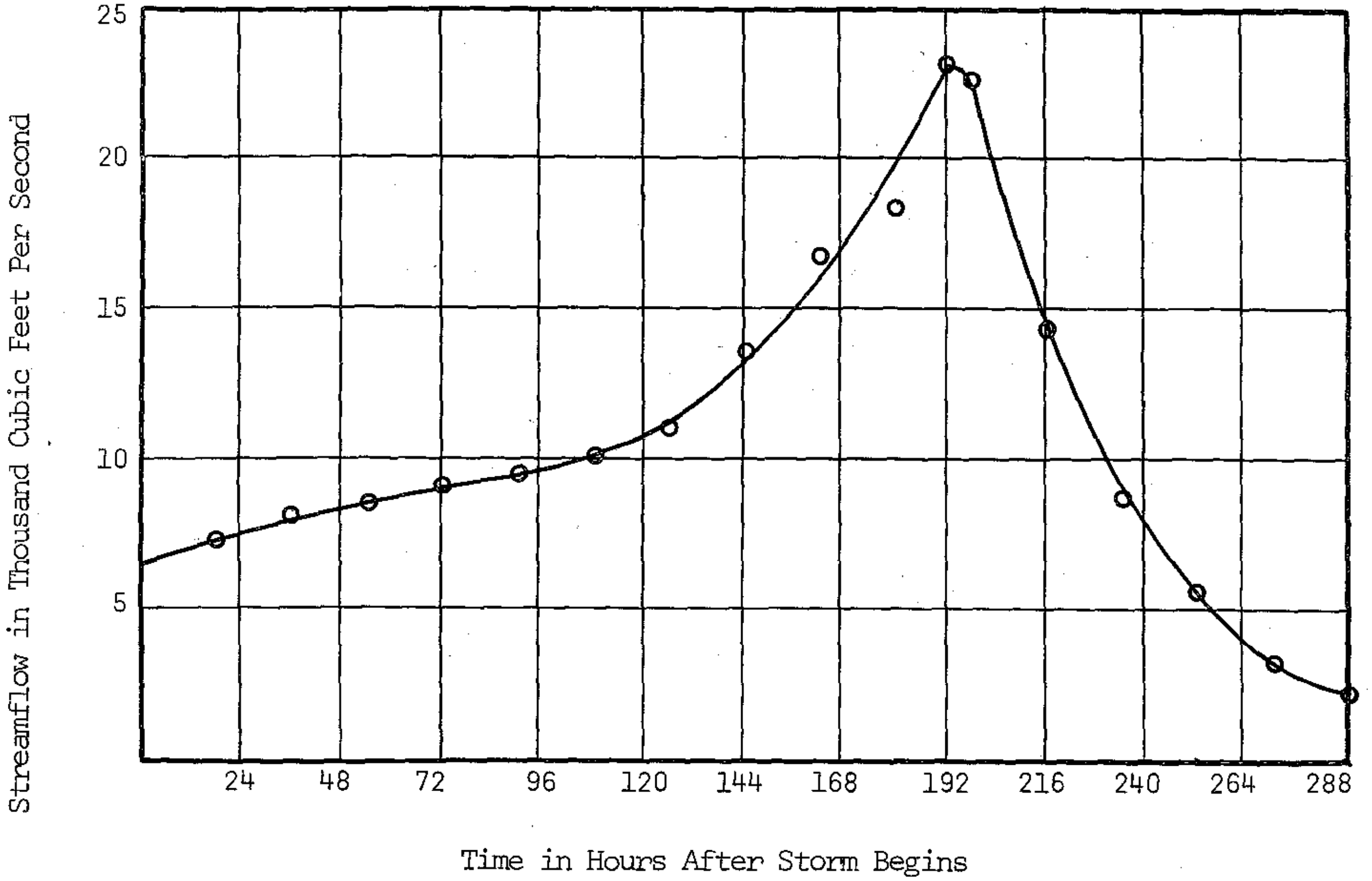


Figure 7. Rough River Reservoir Inflow Hydrograph, 200-year, 12-day

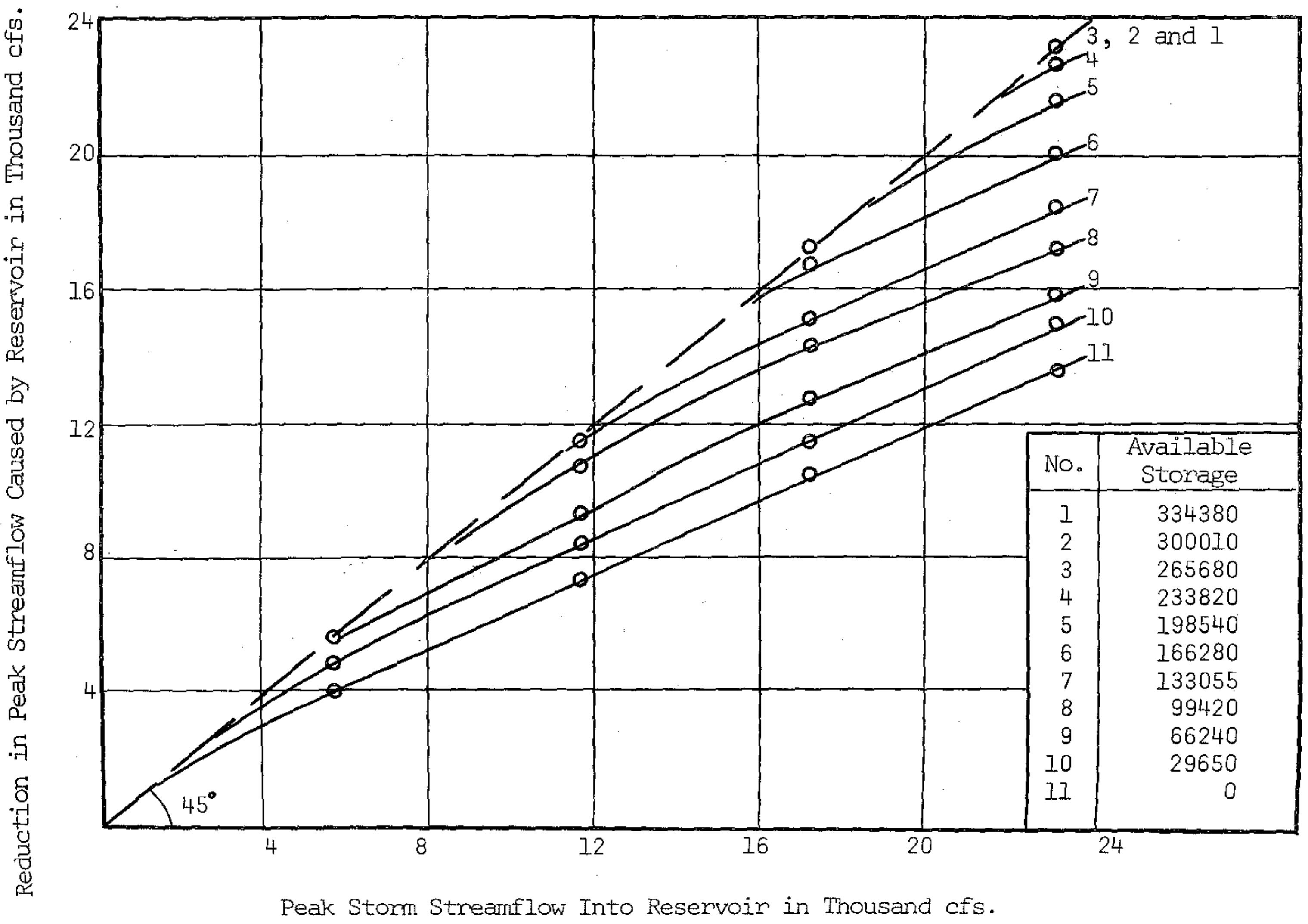
EFFECT OF THE RESERVOIR DOWNSTREAM

As the flow proceeds downstream and joins with flows from other and sometimes larger streams, the reduction achieved by the reservoir will be steadily dampened. Just how this dampening effect varies as the watershed area increases is a sizeable analysis in itself.

Rosenbaum (8) did extensive work on the benefits attributable to Dewey Reservoir and determined the flood control benefits it achieved in various reaches downstream. Because Rough River Reservoir and Dewey Reservoir are separated by only 250 miles, both drain to the Ohio River, both are in the same climate, and benefit data of this type was not directly available for Rough River, it was decided to use a relationship developed from the Dewey study in the manner described below. This procedure was followed as a method to determine the reduction in flood peak achieved (expressed as a fraction of the reduction achieved at the damsite) as a function of the fraction of the watershed controlled by the reservoir.

U. S. Geological Survey maintains streamgages at Van Lear, Kentucky, 0.7 mile downstream from the Dewey damsite, and at Meta, Kentucky, approximately 20 air miles upstream from the damsite as shown in Figure 9. It was necessary to find relationships between flows at these two locations to determine the potential streamflow at the damsite if the dam did not exist. Through the study of several years of flood peaks before the reservoir was built, it was found that on the average the flood peak at Van Lear was 1.93 times the flood peak at Meta.

The following example will illustrate how this relationship was



No.	Available Storage
1	334380
2	300010
3	265680
4	233820
5	198540
6	166280
7	133055
8	99420
9	66240
10	29650
11	0

Figure 8. Reduction in Flood Peak Downstream Caused By Storage in Rough River Reservoir

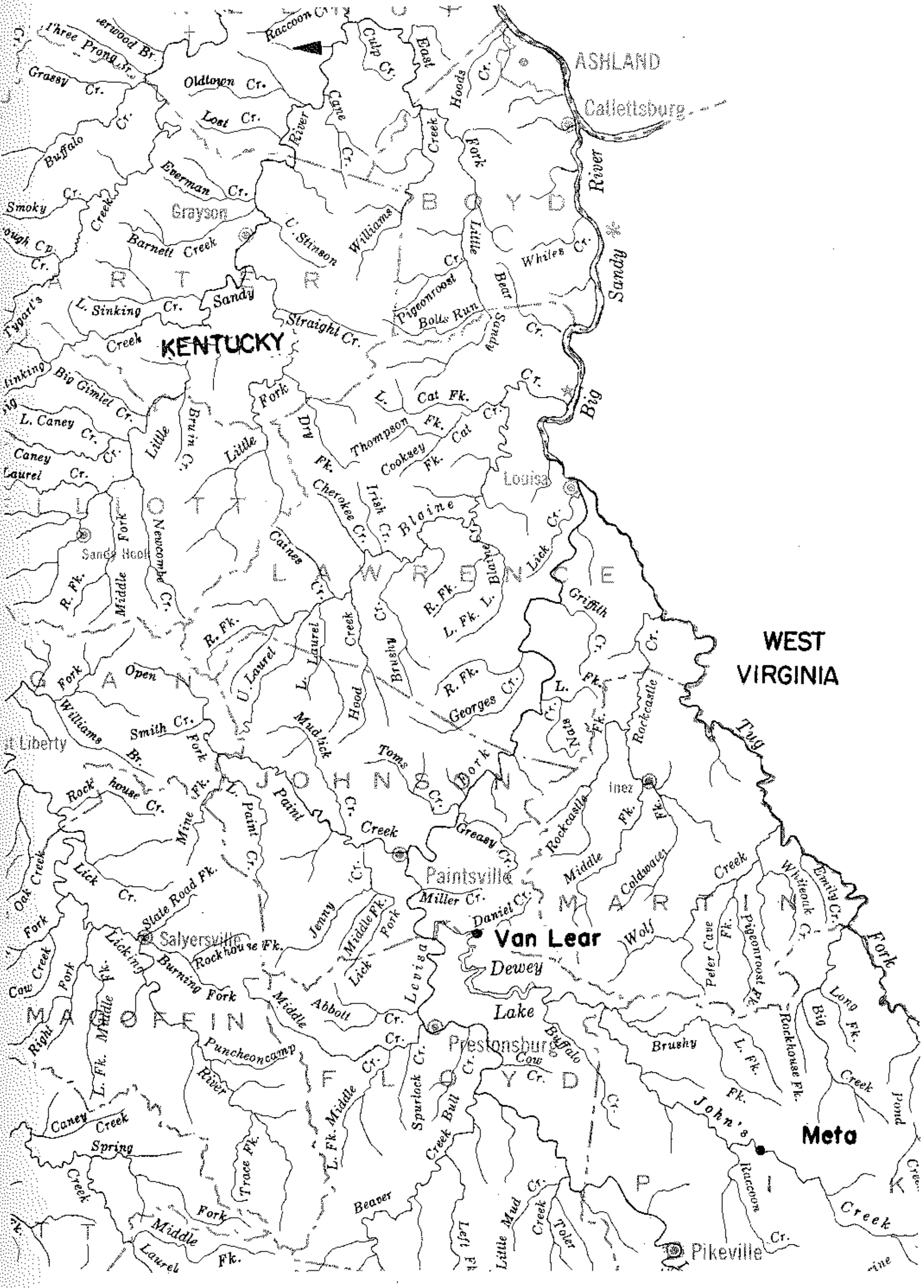
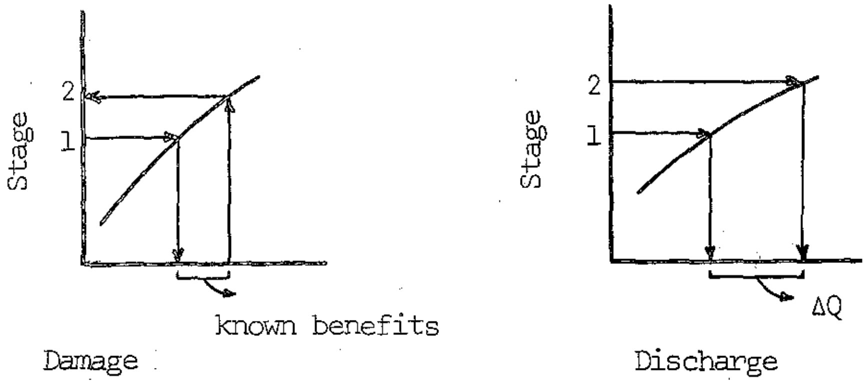


Figure 9. Dewey Reservoir Location Map

used. The storm of February 27, 1962, produced a peak streamflow of 4420 cfs at Meta and 3610 cfs at Van Lear. Had the reservoir not been built the expected peak at Van Lear would have been 1.93 x 4420 or 8530 cfs. Therefore, the dam reduced the flood by 8530 - 3610 or 4920 cfs. The remainder of this part of the analysis will determine how the flood peak reduction varied in the downstream reaches.

Rosenbaum listed benefits by years attributed to Dewey Reservoir for 17 reaches from the damsite to the Mississippi River (8, p. 64). By assuming that one storm each year was the major contributor to damage, the reduction in the annual flood peak at the reservoir site could be found by the procedure given above. The procedure to find the dampening of this reduction downstream was:

1. Find the maximum yearly flood for a year since the reservoir was constructed (5),
2. Find the stage reached by this flood in every reach downstream (5),
3. Find the damage caused by this stage from stage-damage curves supplied by the Corps of Engineers for each of the reaches,
4. Add the benefits for the year for that reach to the actual damage to obtain the damage that would have occurred had the reservoir not existed,
5. From this new damage obtain the corresponding stage from the appropriate stage-damage curve,
6. From the stage-discharge curve (5 and 20) find the discharge that would have occurred for this higher stage.



stage-damage curve stage-discharge curve

Figure 10. Illustrated Determination of Reduction in Peak Flow (ΔQ) Due to Reservoir.

7. The achieved reach flood peak reduction equals the difference between the discharge of step 6 and the recorded peak discharge.

Figure 10 illustrates the above six-step procedure as used for each reach for each year. The end product is the resulting discharge reduction at each point, achieved by the reservoir.

The stage-damage curves for some reaches are based on the stage at a location that does not also have a streamgage. At any time when this was the case, the nearest streamgage location in the reach was used to estimate the streamflow at the base location.

The procedure illustrated above was followed using the same yearly storm for each reach to find how the reduction in flow brought about by the reservoir diminished as the distance downstream increased. By analyzing several years of storms, the relationship was derived as shown in Figure 11 and expressed as the ratio of the reduction in flood peak for the reach to the reduction in flood peak at the damsite

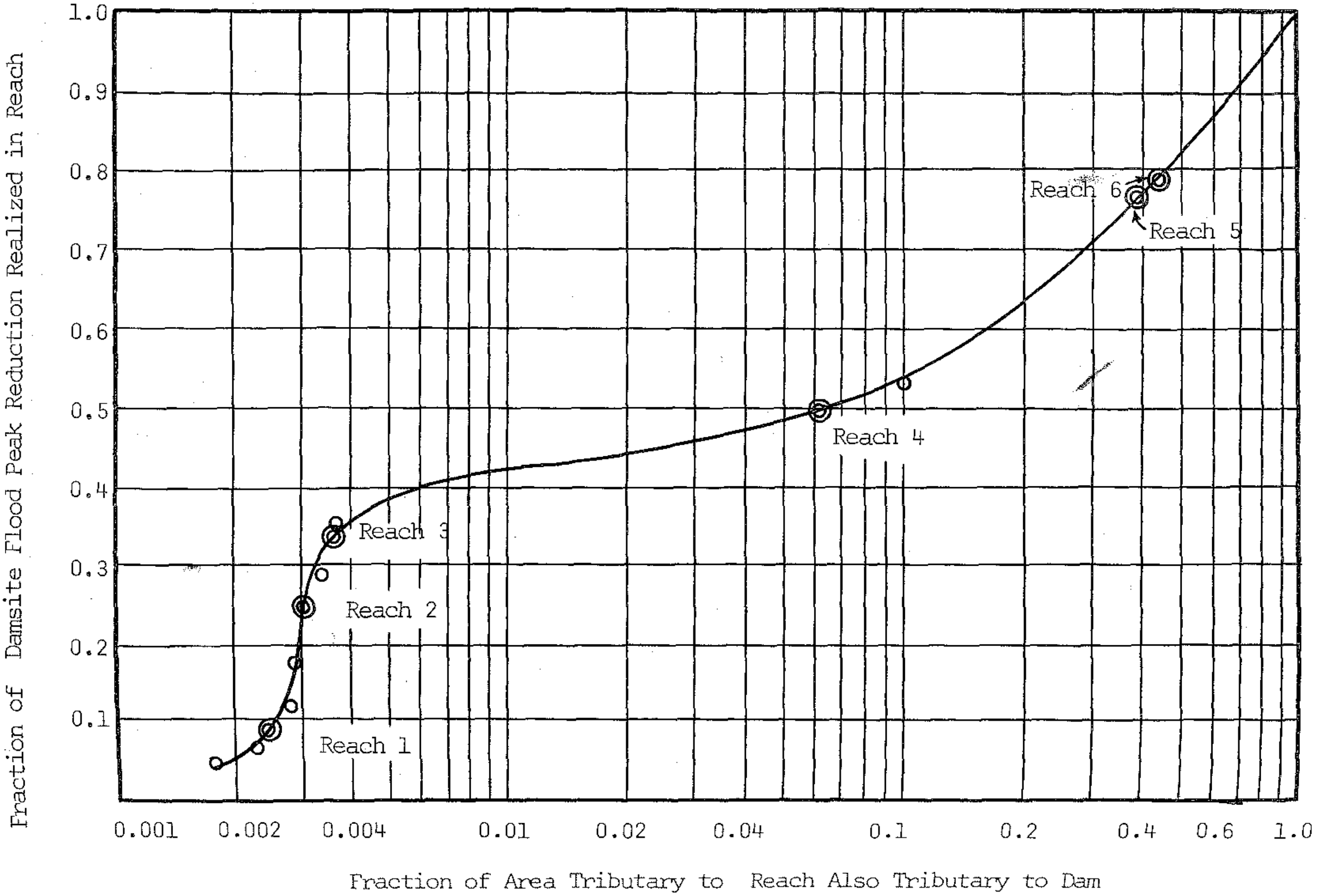


Figure 11. Reduction in the Effects of the Reservoir Downstream

as a function of the fraction of the area tributary to the reach also tributary to the reservoir. Assuming this curve derived from an analysis of Dewey Reservoir to be applicable to Rough River Reservoir, one can find for a given reduction in flood peak adjacent to the damsite, how this reduction is dampened further downstream with the area fractions applying to the six Rough River reaches shown on Figure 11.

CALCULATION OF MONTHLY FLOOD CONTROL BENEFITS FOR ROUGH RIVER

In order to determine average annual flood control benefits by month as a function of available reservoir storage, flood control benefits were calculated for each reach for the five different magnitudes of storms found by the Gumbel analysis with the reservoir in varying degrees of fullness. The available storage was varied from zero to the volume of the 200-year flood for the month, shown on Table 9 and found by taking the area under the hydrograph (Figure 7) whose each ordinate was adjusted proportional to the monthly flood peak. Storage increments used were 0.2 times the maximum value.

The tabulation shown on Table 10 is an example of the calculation of benefits for reach six near Dundee for the month of January and for the case where the available storage is large enough to absorb the entire inflow to the reservoir. The procedure was as follows:

1. Row 1 is the storage in the reservoir available for flood storage at the beginning of the storm (Table 9),
2. Row 2 is the frequency of the storm being studied,
3. Row 3 is the reduction in streamflow immediately downstream

TABLE 9

VOLUME IN ACRE-FEET OF THE EXPECTED 200-YEAR FLOOD BY MONTH AT THE ROUGH RIVER RESERVOIR DAMSITE

January	231500	July	59600
February	257600	August	60100
March	188000	September	62400
April	193500	October	13500
May	162000	November	147000
June	110700	December	198800

from the damsite and can be found from Figure 8. In this example, the values are identical to those tabulated for the damsite on Table 8 because the storage is large enough to completely absorb the flow into the reservoir. For a smaller storage, one would enter Figure 8 with the inflow of Table 8 and read a reduction which would be less than the total value.

4. Row 4 is found from entering Figure 11 with the fraction of the area tributary to the reach being controlled by the reservoir and is the fraction of the flood reduction at the damsite that is realized in the reach being studied,
5. Row 5 is Row 4 multiplied by Row 3 and is the reduction in the flood peak in the reach brought about by the reservoir,
6. Row 6 is the flood peak that would occur at the frequency in Row 2 if the reservoir did not exist and is found on Table 8,

TABLE 10

SAMPLE CALCULATION OF EXPECTED FLOOD CONTROL BENEFITS FROM ROUGH RIVER RESERVOIR[1]

Row						
1	Available Storage (A-Ft)	231500	231500	231500	231500	231500
2	Flood Freq. (%)	0.5	1.0	4.0	15.	43.
3	ΔQ (cfs) at Reservoir	20978	18598	13810	9056	4845
4	$\frac{\Delta Q \text{ reach}}{\Delta Q \text{ reservoir}}$	0.785	0.785	0.785	0.785	0.785
5	ΔQ reach (cfs)	16468	14599	10841	7109	3803
6	Q-before (cfs)	27512	24400	18130	11910	6400
7	Q-after (cfs)	11044	9801	7289	4801	2597
8	S-before (ft.)[2]	29.4	29.2	28.8	27.9	23.1
9	S-after (ft.)[2]	27.9	27.3	24.8	20.6	15.7
10	Damages Saved ($)	135500	148000	220000	181000	1000

[1] Example is the calculation of benefits for reach number six near Dundee in the month of January

[2] Stage in feet above datum in Dundee, Ky.

7. Row 7 is Row 5 subtracted from Row 6 and is the expected peak flow with the reservoir storage in effect,
8. Row 8 is the maximum stage that would occur with the peak flow in Row 6 and is found from Figure 12 which is the stage-discharge curve for Dundee,

9. Row 9 is the actual peak stage that will occur from the actual streamflow in Row 7 and is also found from Figure 12,

10. Row 10 is the damages saved in the reach for the frequency of storm in Row 2 because the maximum stage that will be reached has been reduced by the reservoir and is found as the difference in damages between the two stages on the stage-damage curve for the reach (Figure 13).

The stage-discharge curves mentioned above were derived from listings of recent flood peak streamflows and the corresponding peak stages (5 and 20). One of these curves was derived for a location in each of the six reaches. Figure 12 is the stage-discharge curve for Dundee. The stage-damage curves were supplied by the Corps of Engineers, one for each reach, and the curve for the reach immediately downstream from Rough River Reservoir is reproduced in Figure 13.

As was expected for the reaches further downstream, flood-peak reductions became so small that differences in stages and damages were impossible to read directly from the stage-damage and stage-discharge curves. It then became necessary to use calculated marginal damages and marginal flows (slope of the curve at a given point) in terms of dollars or cfs, respectively, per foot of stage reduction.

The procedure summarized on Table 10 followed for five storms and six degrees of available storages for each reach for each month of the year. When all these calculations were made, the damages were summed for a given month at one available storage and flood frequency

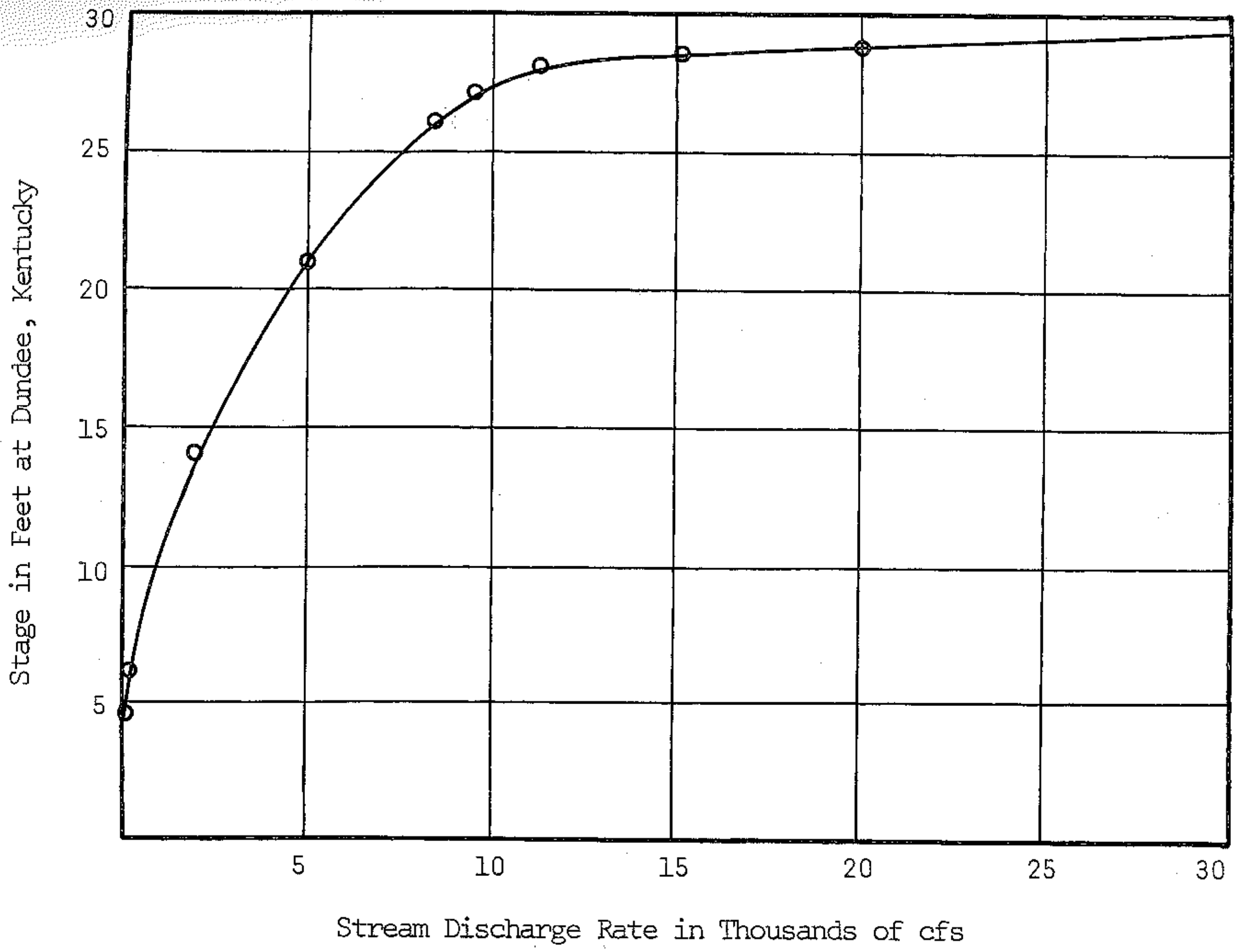
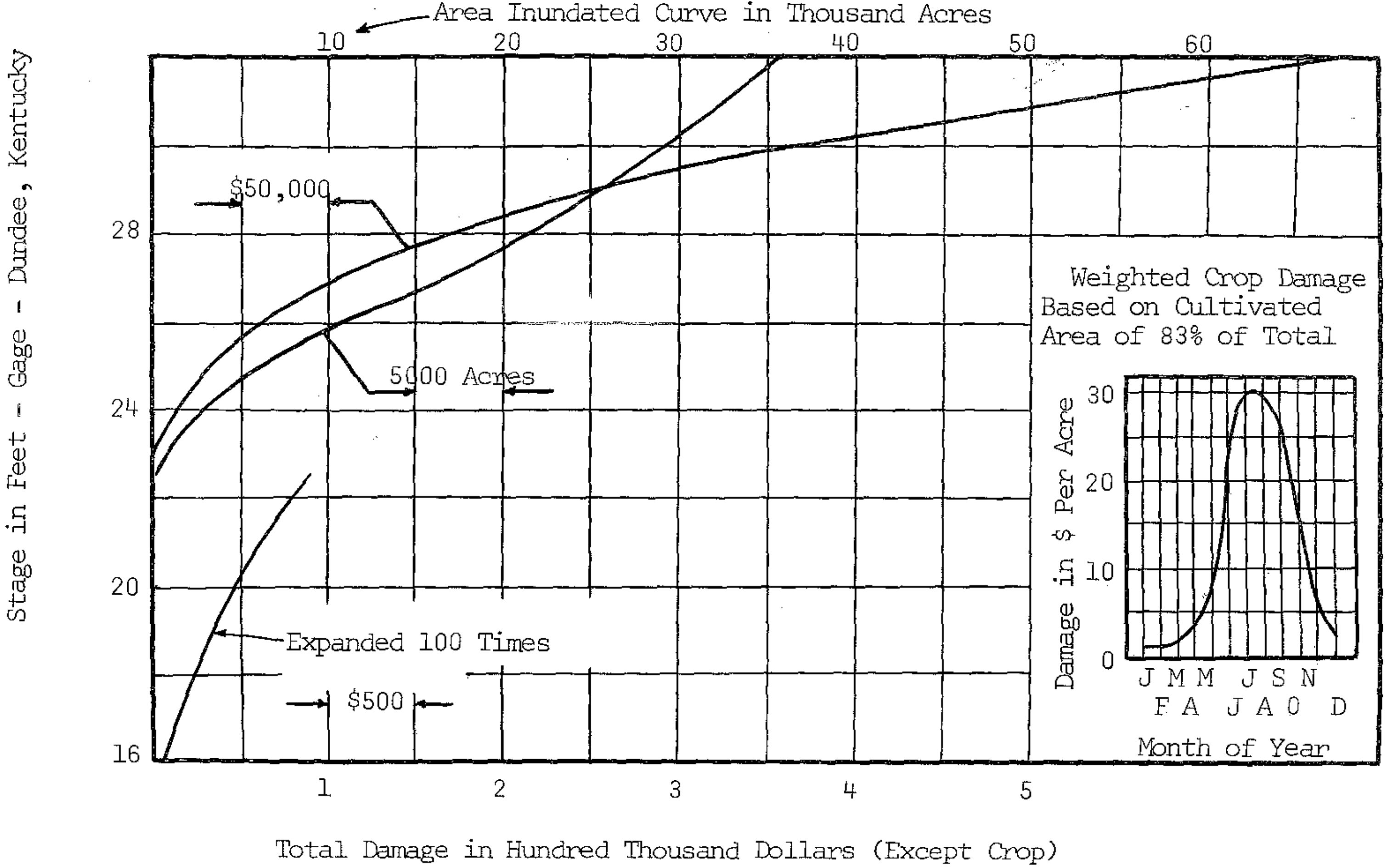


Figure 12. Stage-Discharge Relationship at Dundee, Kentucky

Figure 13. Stage-Damage Relationship for Reach Six Based on Stages at Dundee*



*Source: Data and format supplied by the Corps of Engineers.

for the six reaches. Thus, the first benefit on Table 11, $881500, is the sum of six numbers, one for each reach, and represents the expected benefits if the 200-year storm for January occurs with an available storage in the reservoir of 231500 acre feet. If the available storage in the reservoir is reduced to 185000 acre feet, the expected benefits will decrease to $856000. Table 11 is a summary of how the benefits will vary with changing available storages and magnitude of storms. A table similar to Table 11 was obtained for each month of the year.

If, for each month and for each available storage, the five values of benefits (one row in Table 11, for example) were plotted versus the frequency of occurrence, the area under the resulting curve would equal the average annual benefits expected in that month if the reservoir were held at that storage. Figure 14 is the benefit-frequency graph for January with an available storage equal to the volume of the 200-year flood or 231500 acre feet and the area under this curve,

TABLE 11

JANUARY EXPECTED BENEFITS IN DOLLARS
FROM ROUGH RIVER RESERVOIR FOR SELECTED STORMS

Available Storage	Storm Return Period, Years				
	200	100	25	6.7	2.33
231500	881500	867500	495500	329500	57400
185000	856000	862000	495000	329500	57400
138700	736600	746000	457500	329500	57400
92600	609500	659400	423500	329500	57400
46300	500500	544500	257000	316300	57400
0	470500	384200	210000	277700	34000

$120000, is the average annual benefit to be expected in January if that available storage is maintained. There were six of these curves, one for each available storage, for each month.

The figures on Table 11 reveal that for several storage values there is an increase in benefits in going to the second largest storm. This trend also occurred in other months and may be explained by looking at Table 10 and Figure 12. In Table 10, column 1, a change in streamflow of 16468 cfs changed the stage by 1.5 feet while in column 2 a change in flow of only 14599 cfs changed the stage by 1.9 feet. Thus in going to higher streamflows in Figure 12, the curve flattens and a fixed increase in streamflow produces a smaller increase in stage. If the stage-damage curve is also sufficiently flat in the same region, the increase in damage will also be smaller.

The family of six curves each like Figure 14 were drawn for each month of the year, and Table 12 summarizes the resulting benefits if the reservoir had the available storage specified on Table 9 before each storm. The curves in Figure 15 show benefits decline as the

TABLE 12

EXPECTED ANNUAL FLOOD BENEFITS BY MONTH BASED ON THE AVAILABLE STORAGE VALUES OF TABLE 9

January	$120000	July	$12500
February	$156250	August	$10000
March	$145000	September	$42500
April	$137500	October	$ 200
May	$110000	November	$45000
June	$ 47500	December	$95000

available storage is reduced and are plotted from points calculated in the same manner used for Table 12 but with smaller amounts of storage available for flood control. October is not shown because of the very small expected benefit.

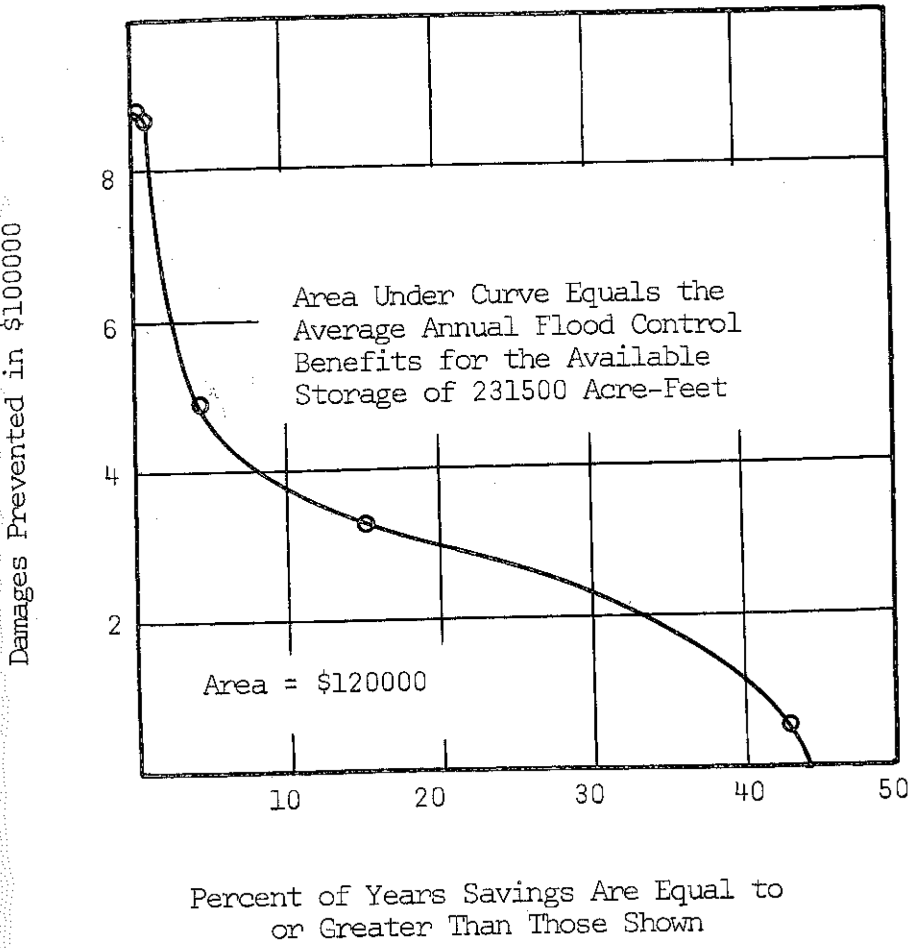


Figure 14. Flood Control Benefit-Frequency Curve for January for 231500 Acre-Feet of Available Storage

ANALYSIS OF THE DERIVED CURVES

The expected flood benefits as shown on Table 12 are, as one would expect, largest in late winter and early spring when the flood danger is most severe. Crop damage is larger in the summer but comprises a relatively small fraction of the damage total. The September value is unusually large because of the one historical flood near Dundee that was so extreme.

The curves in Figure 15 show the reduction in the fraction of benefits still achieved if the available flood storage is reduced to be smallest in winter. In other words, if the flood storage available is less than that required to achieve maximum benefits, the relative, as well as the absolute benefit reduction is greatest in winter. The concentration of their benefits in opposite seasons means little conflict for storage space between recreation and flood control and a greater potential for conflict between water supply and flood control.

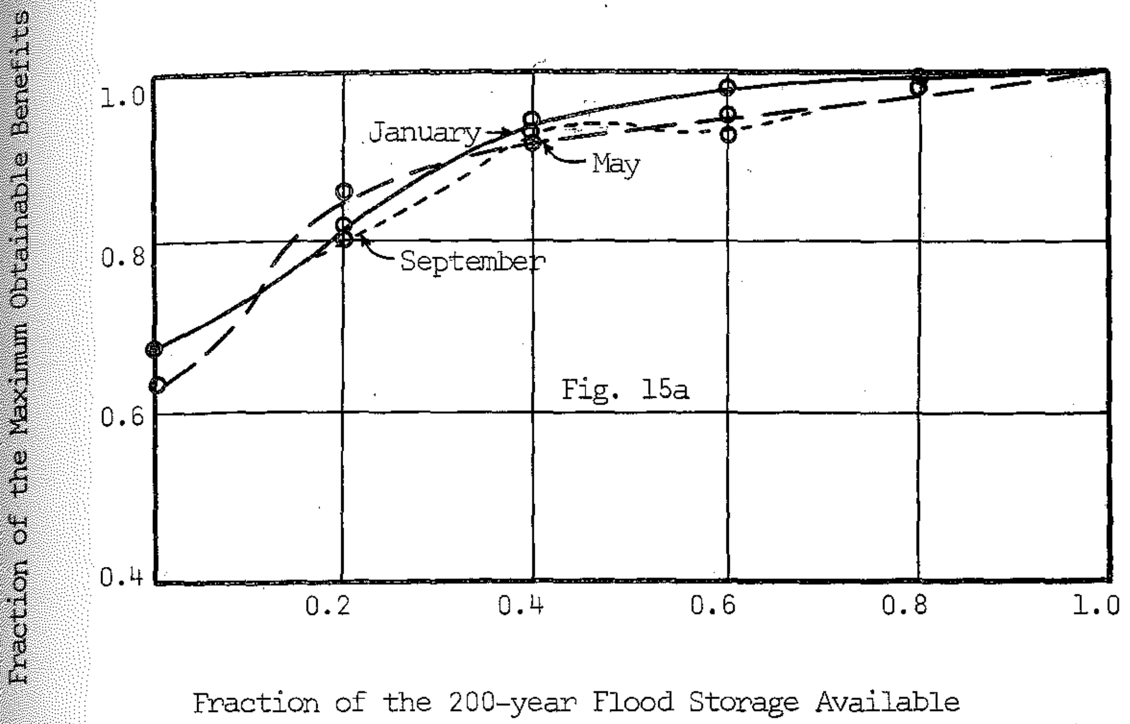


Fig. 15a

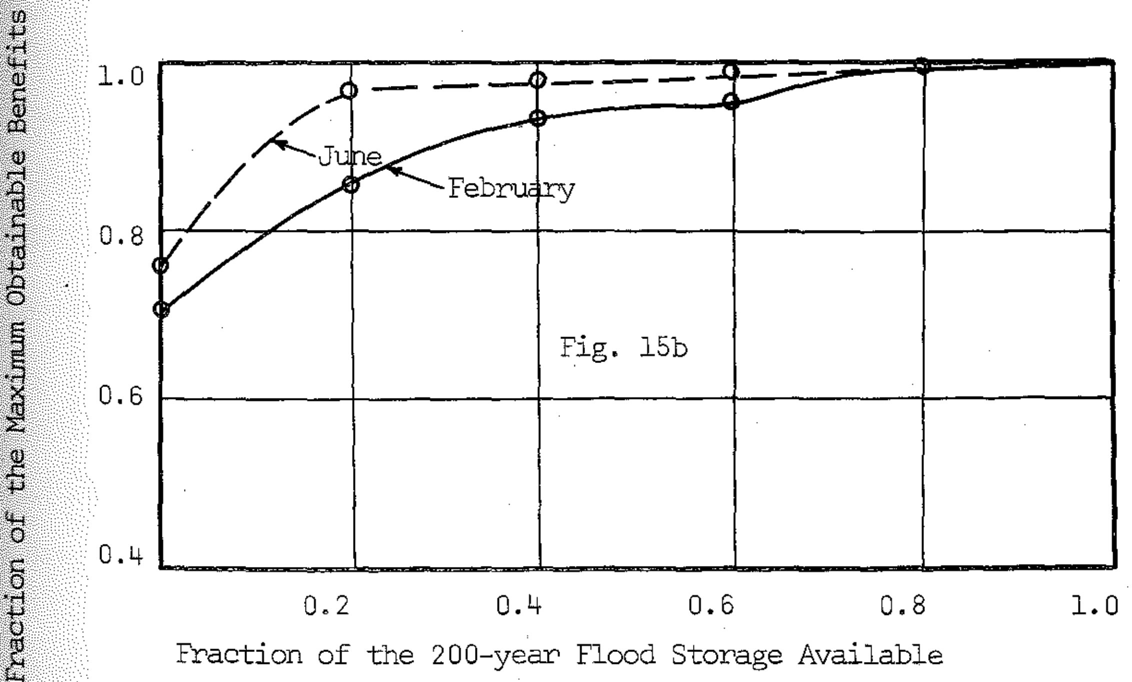


Fig. 15b

Figure 15. Variation of Flood Control Benefits with Maximum Allowable Drawdown

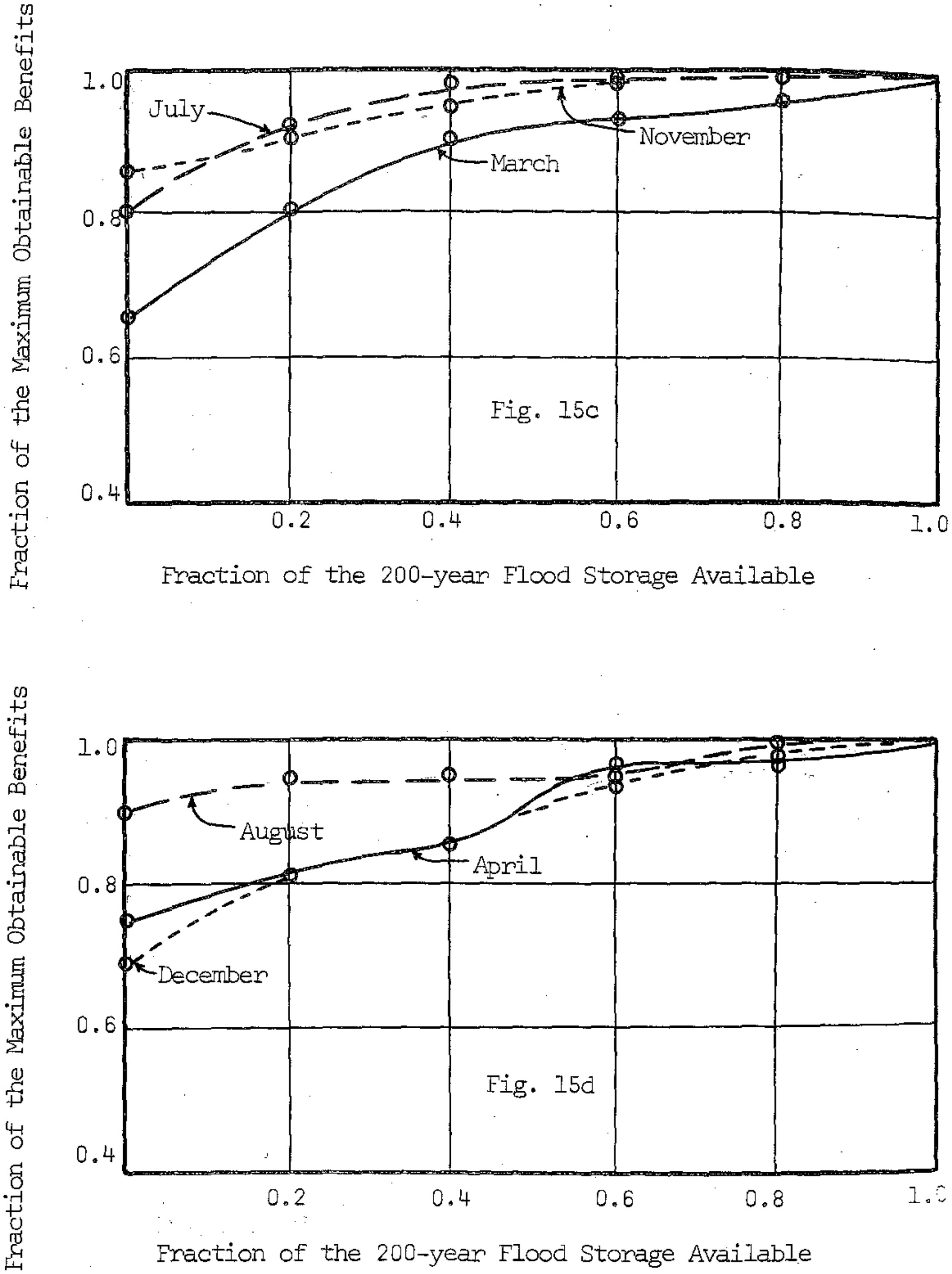


Figure 15.--Continued

Chapter V

RECREATION

INTRODUCTION

Reservoirs provide a body of water which has a natural attraction to visitors and, when developed for recreation, a combination of shoreline facilities wherein outdoor recreation activities can be enjoyed. Some activities (fishing, swimming, boating, and water skiing) cannot be enjoyed without the water. Other activities (sightseeing, picnicking, and camping) could be enjoyed without the water, but the water increases the attraction by adding to the amenities of the site and by making it possible for picnickers and campers to also enjoy the water-based activities. In either case, it would be logical to expect the number of visitors (and hence the recreation benefits) to increase with the size of the body of water. More water provides more space to fish, swim, boat, or water ski as well as a greater scenic attraction for the other activities.

The problem at hand is to determine how the recreation visitation will vary with the size of the body of water as determined by the policy of reservoir operation. The approach used to solve this problem is described on the following pages.

VISITATION BY RECREATION ACTIVITY

The major activities provided at Rough River Reservoir are picnicking, sightseeing, camping, water skiing, boating, fishing, and swimming. Some visitors may participate in only one of these activities during their entire visit while others may participate in several. The kinds and number of activities engaged in depends on individual preference and the time of year.

Because the effect of the amount of water stored in the reservoir on participation in a given activity depends on the activity water requirements, the activities were grouped as follows:

1. Camping, sightseeing, and picnicking as not involving direct use of the water;
2. Fishing and swimming as taking place along the available shoreline;
3. Boating and skiing as taking place over most of the water surface area.

Corps of Engineers visitation records (14) for Rough River Reservoir for June, 1963, through June, 1966, were evaluated to determine the fraction of the total visitors participating in the activities of each group and the fraction of the total activity-days associated with each group found on Table 13.

A visitor-day is one day of recreational experience at the site by one person. An activity-day is one day in which one individual engages in one activity. This does not mean the whole day must be spent in the one activity, but only a significant part of the day. Table 14 shows the month-by-month ratios of visitor-days to activity-days calculated for Rough River Reservoir from Corps of Engineers data (14).

TABLE 13

DISTRIBUTION OF VISITATION AMONG ACTIVITIES AT ROUGH RIVER RESERVOIR

		Type I	Type II	Type III
		Sightsee Picnic Camp	Fish Swim	Boat Ski
Jan.	Participating Fraction	0.48	0.32	0.30
	Activity-day Fraction	0.44	0.29	0.27
Feb.	Participating Fraction	0.46	0.37	0.28
	Activity-day Fraction	0.41	0.34	0.25
Mar.	Participating Fraction	0.65	0.38	0.24
	Activity-day Fraction	0.51	0.30	0.19
Apr.	Participating Fraction	0.77	0.41	0.21
	Activity-day Fraction	0.55	0.29	0.15
May	Participating Fraction	1.00	0.71	0.54
	Activity-day Fraction	0.45	0.31	0.24
Jun.	Participating Fraction	0.98	0.88	0.57
	Activity-day Fraction	0.40	0.36	0.23
Jul.	Participating Fraction	0.97	0.81	0.54
	Activity-day Fraction	0.42	0.35	0.23
Aug.	Participating Fraction	0.98	0.83	0.54
	Activity-day Fraction	0.42	0.36	0.22
Sep.	Participating Fraction	0.87	0.47	0.28
	Activity-day Fraction	0.54	0.29	0.17
Oct.	Participating Fraction	0.87	0.32	0.13
	Activity-day Fraction	0.65	0.24	0.10
Nov.	Participating Fraction	0.61	0.34	0.14
	Activity-day Fraction	0.56	0.32	0.13
Dec.	Participating Fraction	0.59	0.34	0.11
	Activity-day Fraction	0.57	0.32	0.10

Summer visitors are seen to engage in more activities in a day at the reservoir than do winter visitors.

DEGREE OF CROWDING

One would expect the reduction in recreation visitation caused by having less water in the lake to be a function of how crowded the recreational space is. The more crowded the lake, the greater the number of visitors which can be expected to either go to another lake or seek another type of recreation. However, a given lake will be crowded some times and almost unused other times. The greater the amount of time the lake is crowded, the more decreasing storage would be expected to reduce visitation. The variation of use with time was analyzed by studying the distribution of use by month of the year, day of the week, and hour of the day. The monthly and weekly data were calculated from Corps of Engineers visitation counts, and the daily figures were calculated from counts made for the purpose of this study during holidays and Sundays in the summer of 1967. Table 15 shows these visitation trends at Rough River Reservoir.

TABLE 14

RATIOS OF VISITOR-DAYS TO ACTIVITY-DAYS
AT ROUGH RIVER RESERVOIR

Jan.	0.906	Jul.	0.428
Feb.	0.890	Aug.	0.430
Mar.	0.785	Sep.	0.617
Apr.	0.715	Oct.	0.757
May	0.442	Nov.	0.920
Jun.	0.413	Dec.	0.965

The data on Table 15 can be used to estimate the distribution of the degree of crowding of recreation facilities over the course of the year. The goal is to estimate the duration of specific degrees of crowding as a first step in relating lake size to visitation. The approach is to estimate visitation hour by hour through the year and arrange the hours in order according to the number of visitors present.

A computer program was written to compute the expected number of visitors hour-by-hour through the year as a fraction of the number of visitors during the peak visitation hour of the year using the monthly, weekly, and daily visitation data. For example, to find the expected visitation in the third highest hour on a Tuesday in March, multiply the March fraction of the peak month visitation (0.130) by the Tuesday fraction of the peak day visitation (0.131) by the third highest fraction of the daily visitation (0.898) to get 0.0153. This is the fraction of the peak hour visitation of the year estimated to occur that hour. Extra visitors were assumed for holidays by regardless of the day of the week on which the holiday fell using the same visitation as the previous Sunday.

The 8760 expected hourly visitation were used to compute the percentage of annual visitation which could still be accommodated if the maximum amounts of visitors which could be simultaneously accommodated were restricted by various degrees of crowding. This was done by analyzing the 8760 hourly visitation estimates to determine the fraction of the total annual visitation associated with visitors causing crowding

TABLE 15

TIME DISTRIBUTION OF RECREATIONAL USE AT ROUGH RIVER RESERVOIR

MONTHLY VISITATION:[1]

	Fraction of Peak Month	Fraction of Annual Visitation		Fraction of Peak Month	Fraction of Annual Visitation
Jan.	0.101	0.021	Jul.	1.000	0.207
Feb.	0.130	0.027	Aug.	0.937	0.194
Mar.	0.130	0.027	Sep.	0.449	0.088
Apr.	0.357	0.074	Oct.	0.275	0.057
May	0.652	0.135	Nov.	0.082	0.017
Jun.	0.686	0.142	Dec.	0.053	0.011

WEEKLY VISITATION:[1]

	Fraction of Peak Day	Fraction of Weekly Visitation
Sunday	1.000	0.495
Monday	0.131	0.065
Tuesday	0.131	0.065
Wednesday	0.133	0.066
Thursday	0.156	0.077
Friday	0.166	0.082
Saturday	0.301	0.149

DAILY VISITATION:[2]

Fraction of Peak Hour (From peak to lowest hour)

1.000	0.946	0.898	0.809	0.698	0.600	0.497	0.419
0.330	0.221	0.221	0.221	0.221	0.221	0.221	0.221
0.221	0.221	0.221	0.221	0.221	0.221	0.221	0.221[3]

Peak hour fraction of total daily visitation: 0.270

---

[1] Source: Calculated from data furnished by U. S. Army Corps of Engineers, Ohio River Division.

[2] Source: Field data collected for this study.

[3] Assumes the net number of visitors who arrive or leave between 6 P.M. and 8 A.M. is not appreciable.

to pass specified levels. For example, it was found that approximately 46 percent of the potential annual visitation would have to be turned away were the visitation rate limited to 0.1 of the peak potential hourly visitation which would occur were there no crowding restriction. If the peak hourly visitation were potentially 5000 visitors, 46 percent of the yearly total visitors would still visit if the actual peak were limited to 500 persons. The concept is illustrated graphically by Figure 16. The fraction of the total people who wish to visit the site who cannot be accommodated as a function of the ratio of reservoir visitation capacity to peak potential hourly visitation is then developed from this concept and plotted on Figure 17.

The operation of Rough River Reservoir could limit peak hourly visitation by drawing the water level down until the recreational area becomes so crowded that people who otherwise would have visited the lake do not. The reservoir capacity would in fact be set by crowding rather than decree as may have been implied above.

If the size of the reservoir pool were reduced, it would become more crowded if the number of visitors remained the same. If it became intolerably crowded, fewer people would desire to go there. Assuming that crowding sets an upper limit on visitors who will simultaneously visit the reservoir but does not affect visitation when the number of people wishing to visit is less than the visitation capacity permits use of Figure 16 for estimating how many visitors will no longer visit the site. The curve (Figure 17) actually used was calculated on a monthly basis and represents the average of the twelve monthly curves.

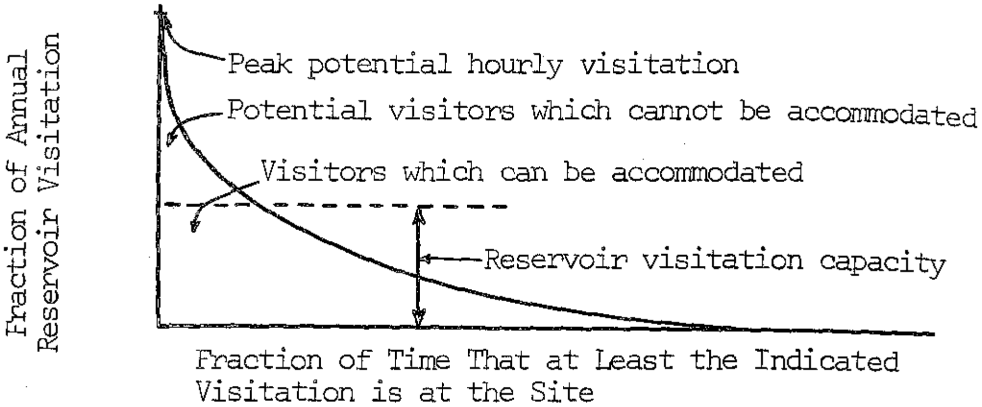


Figure 16. Time Distribution of Reservoir Utilization

RESERVOIR CAPACITY

In order to determine the variation of reservoir visitation capacity with storage changes, certain assumptions were necessary. Highway designers do not provide a capacity equal to the peak hourly traffic count in the year (7, p. 188). It can be shown by economic analysis that it is wasteful to provide facilities that will comfortably move the heaviest flow of traffic when for the greatest part of the year a much smaller facility will suffice. Thus, they have found it successful to design for the 30th heaviest hour of the year. The 29 heavier hours will cause some congestion but the savings in building costs by building for smaller capacity far outweigh the inconvenience of a few persons a few hours of the year.

Using the same logic, a reservoir should not be built to accommodate the maximum number of persons who might ever want to go there simultaneously. Because the true capacity of Rough River Reservoir for recreation was not known, it was assumed that the

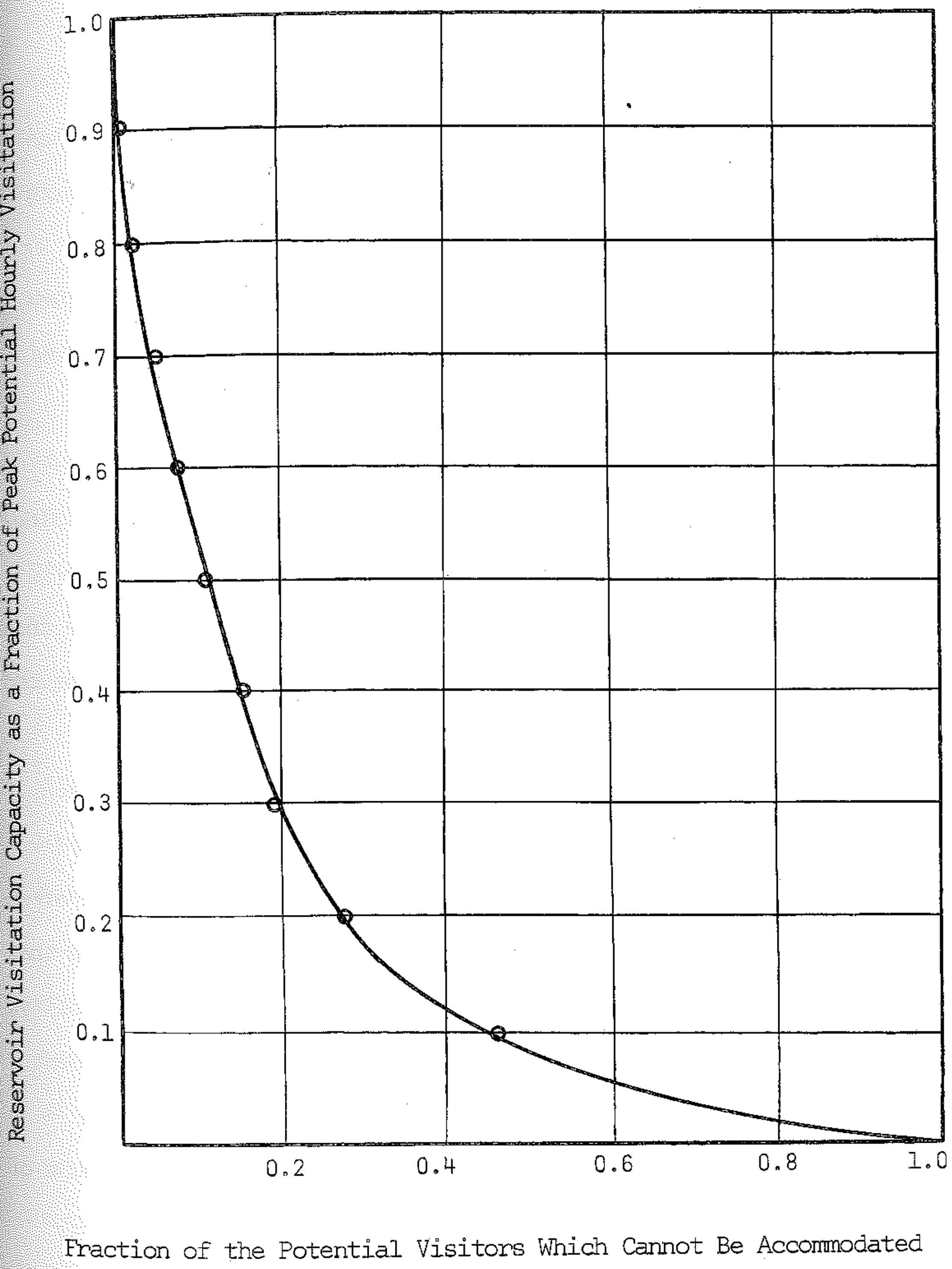


Figure 17. Relationship Between Reservoir Recreation Capacity and the Fraction of the Potential Visitors Which Cannot be Accommodated

reservoir was overcrowded on the peak day of record and that the true comfortable capacity would be something less than this. The computer program used to derive Figure 17 also listed the hourly visitation potential in order of magnitude. Of the 8760 hourly values given, the 15th highest was 0.907 and this 15th hour visitation was used as the comfortable capacity of the reservoir. The 30th highest hour was not used because the relatively large capacity provided by the Rough River facilities would become crowded less often than would those many other places.

The peak daily visitation recorded at Rough River through December, 1965, was 20700 visitors on a day in July, 1965 (16). Using a peak hourly fraction of the daily total of 0.27 (Table 15), the peak hour becomes 5600. The 15th highest hourly visitation would then theoretically be 5600 multiplied by 0.907 and 5080 and will be assumed to be the comfortable capacity for the reservoir.

From Table 13, it can be seen that in July 97 percent of the visitors camp, picnic, and sightsee (activity type I), 81 percent of the visitors fish and swim (activity type II), and 54 percent of the visitors boat and water ski (activity type III). By assuming that the same percentages would apply to determining the activity capacity, the capacity to provide for activities of type I would be 97 percent of 5080 (4925). The same reasoning would apply to the two other activity types to make the capacity for activity type II 81 percent of 5080 (4110) and for activity type III 54 percent of 5080 (2740).

Because the level of the reservoir is a major factor contributing to capacity, it was necessary to determine the level on the 15th highest hour, which was also assumed to occur in July, 1965. Although a goal of the present operating procedure is to maintain a seasonal pool of 120010 acre-feet during the summer months for recreation, it was estimated from the data on Table 2 that the pool level on the peak day was 97780 acre-feet. This pool of 97780 acre-feet represents a water level at an elevation of 490 feet above mean sea level, a surface area of 4550 acres, and a shoreline of 200 miles.

Assumptions were also made as to the variation of visitation capacity by activity type with the volume of water stored in the reservoir. For activity type I, no water is actually needed; but many people prefer to visit a park with a body of water rather than one without because they planned other activities requiring water or because of the scenic attraction.

No data were available to estimate the importance of scenic attraction, but the number engaging in activity type I who also engaged in one or both of the other two activity types could be determined. Of approximately 4500 visitors interviewed by the Corps of Engineers at Dewey Reservoir near Prestonsburg, Kentucky, in June, 1965, 57 percent indicated they planned water-related activities (12). This figure was assumed to be suitable for Rough River also. Since, from Table 13, 98 percent of the June visitors engage in activity type I, 0.57(98) or 56 percent of the visitors engaging in activity type I will also require water. Thus, the capacity of the reservoir for those engaging in activities of type I desiring water would be 56 percent of 4925, the total capacity for the activity type, or 2760.

For those who participate in activity type I and are attracted by the water, it would seem that the number of visitors would increase with the length of the reservoir shoreline. A reservoir such as Rough River with its numerous coves and branches would have greater capacity for picnicking or camping near the water than would a perfectly round pool. The capacity for activities of type II, fishing and swimming, would also most likely be related to the available shoreline because they too are concentrated around the periphery. The capacity for activities of type III, skiing and boating, would more likely vary with the total reservoir surface area because they may occur over most of the surface. Figure 18 shows the variation of shoreline miles at Rough River Reservoir as a function of reservoir storage as derived from a topographic map.

ANNUAL VISITATION EXPECTED

Since empoundment began in October, 1959, visitation has increased year by year at Rough River. The annual attendance shown on Table 16 is indicative of the growth of interest and popularity of the park. This growth of annual visitation makes it reasonable to expect that future visitation may reach twice the present value. Thus, annual visitation of 0.8 (the approximate average annual value over the last two years), 1.0, 1.2, 1.4, and 1.6 million visitors were used in order to analyze the effects increased visitation would have on the optimum operating policy.

TABLE 16

ROUGH RIVER RESERVOIR ANNUAL ATTENDANCE*

Year	Attendance	Year	Attendance
1960	31700	1964	695300
1961	84200	1965	777500
1962	265000	1966	824200
1963	554318		

*Source (16)

REDUCTION IN BENEFITS DUE TO CROWDEDNESS

Table 17 shows the procedure for month by month analysis of recreation visitation as a function of water stored in the reservoir during that month. Only those months are shown in which the highest level of potential visitation considered required a significant amount of water.

Given the visitation per month, the potential peak hour visitation expected during the month would equal (monthly visitation) x (peak day fraction of the week) x (number of months in a week) x (peak hour fraction of the day) or (monthly visitation x (0.495) x (12/52) x (0.27) or monthly visitation x (0.0307). Thus 0.0307 is the fraction of the potential monthly visitation expected in the peak hour of the month for any month of the year. The value as derived is a potential value which would apply were crowding never a factor.

The balance of the computational process is best explained by

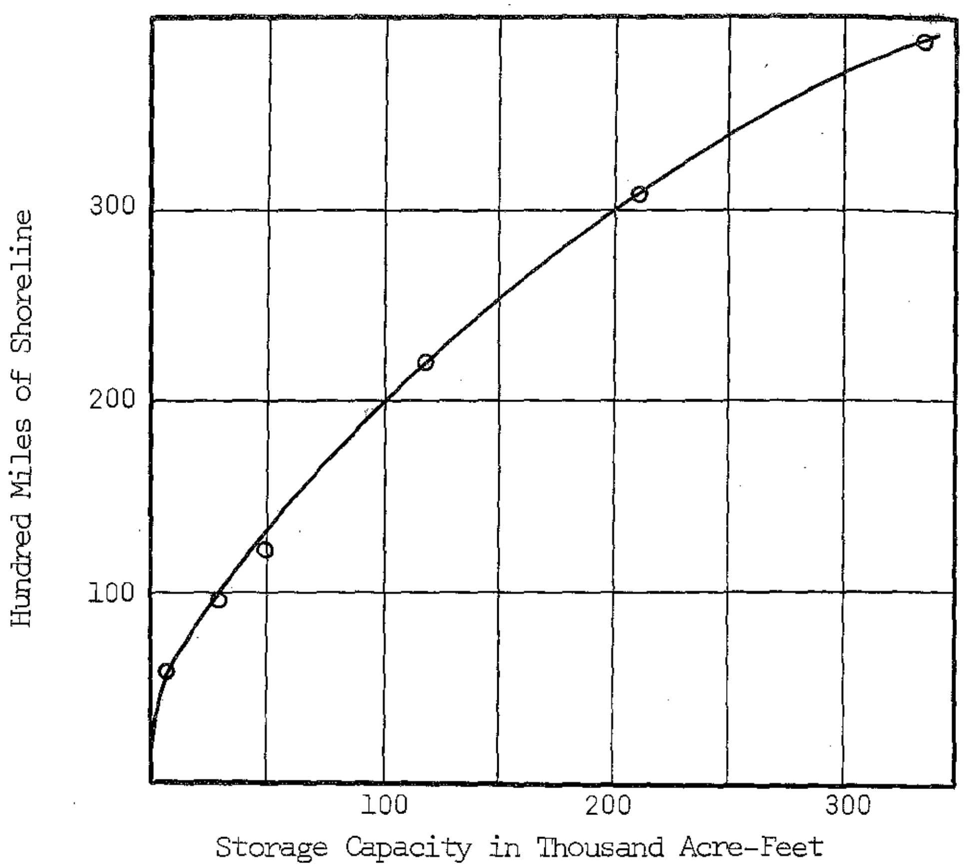


Figure 18. Variation of Miles of Shoreline with Storage Within Rough River Reservoir

proceeding through Table 17, row by row:

1. The potential monthly visitation is found by multiplying the monthly fraction of annual visitation (Table 15) by the annual visitation (800000).
2. The potential peak hour visitation during the month is found by multiplying the monthly visitation by the peak hour fraction (0.0307).
3. The shoreline miles required by those interested in activities of type I is found by:

$$M_I = \frac{(V)(A_I)(W)(M)}{C_I}, \qquad (2)$$

TABLE 17

CALCULATION OF RECREATION BENEFITS

Row		Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.
1	Potential Visitation	59200	108000	113600	165600	155200	70400	45600
2	Potential Peak Hour	1820	3310	3490	5080	4775	2160	1400
	Activity Requirement:							
3	I Shoreline Miles	57	134*	138	200	187	77*	49
4	II Shoreline Miles	36	114	149*	200*	193*	50	22
5	III Surface Area (Acres)	635*	2960	3300	4560	4200	1000	302*
6	Required Storage (Ac-Ft)	5550	57000	68700	105200	100560	14000	2640
7	0.8 of Required Storage	4430	45600	55000	84200	80440	11200	2110
8	New Capacity	1460	2970	3110	4370	4320	2010	1235
9	New Capacity ÷ Peak Hour	.800	.900	.890	.860	.910	.930	.803
10	Fraction Not Accommodated	.025	.010	.013	.017	.010	.008	.025
11	Fraction Accommodated	.975	.990	.987	.983	.990	.992	.975

*Activity requirement implying the most storage where M_I = the shoreline miles required,

V = potential hourly visitation engaged in all activities which can be accommodated and equals the value in Row 2 when the storage is large enough for there to be no capacity restriction,

A_I = fraction of visitors participating in activity type I for the month (Table 13),

W = fraction of visitors wishing to engage in activities of type I that need water (0.56),

M = number of shoreline miles available during the peak day (200),

C_I = capacity of the reservoir when M shoreline miles are available for those wishing to engage in activity type I and needing water (2760).

Substituting the above values gives:

$$M_I = 0.0406(V)(A_I), \tag{3}$$

where values of V and A_I for the appropriate months should be used in specific calculations.

4. The shoreline miles required by those interested in activities of type II is found by:

$$M_{II} = \frac{(V)(A_{II})(M)}{C_{II}}, \tag{4}$$

where A_{II} = fraction of visitors participating in activity type II for the month (Table 13),

C_{II} = capacity of the reservoir when M shoreline miles are available for those wishing to engage in activities of type II(4110).

Substituting the appropriate values gives:

$$M_{II} = 0.0487(V)(A_{II}) \tag{5}$$

5. The surface area required by those interested in activities of type III (S_{III}) is found by:

$$S_{III} = \frac{(V)(A_{III})(S)}{C_{III}}, \tag{6}$$

where S = number of surface-area acres available during the peak day (4550),

A_{III} = fraction of visitors participating in activity type III for the month (Table 13),

C_{III} = capacity of the reservoir when S acres of surface area are available for those wishing to engage in activities of type III (2740).

Substituting the appropriate values gives:

$$S_{III} = 1.66\ (V)(A_{III}) \tag{7}$$

6. The storage required to accommodate the total peak hour visitation is taken as the maximum of the three storage values required to provide the shoreline or surface area of the three activity types as calculated in

the previous three rows. Table 17 shows how fishing and swimming tend to be the relatively most crowded activities in mid-summer while boating is the controlling factor on the fringes of the recreation season. Type II activities controlled in between.

The minimum amount of storage theoretically required to accommodate the expected visitors by month has now been found. If, for any given month, the storage dropped below the values found, the recreation capacity would decrease so as to restrict visitation. The second portion of Table 17 shows how benefits decrease as the storage decreases.

7. A fraction of the needed storage was taken.
8. The recreation capacity provided by the storage of Row 7 was calculated for each of the activity types by using the appropriate capacity equation (3, 5, or 7) to calculate values of V and the smallest of the three values was taken (in most design procedures it is usual to use the worst possible condition, which in this case would be the greatest of the three demands for recreation water).
9. The fraction, visitors which can now be accommodated (Row 8) divided by the potential peak hour visitation (Row 2) was calculated to be used in Figure 17.
10. The fraction of potential visitors not accommodated was found by entering Figure 17 with the fraction in Row 10.
11. The fraction of visitors accommodated is the difference between the value in Row 11 and 1.0.

The calculations of Rows 7 through 12 were repeated three more times by reducing the fraction of the needed storage each time by an increment of 0.2. The whole series of calculations was then repeated by increasing the visitation from 0.8 million to 1.6 million in increments of 0.2 million. Although separate calculations were made for each of the five levels of visitation, the fraction of the visitors accommodated as a function of the fraction of the total needed storage available was very similar for all five levels. Figure 19 shows the curves for April through October. Each curve is a monthly average of the five separate analyses.

DISCUSSION OF RESULTS

Table 18 (values from Row 6 on Table 17) indicates the storage required by calendar month to accommodate the indicated visitation. Figure 19 shows the fraction of the potential recreation visitors which can still be accommodated were the available storage to drop below the level of Table 18. Table 19 applies the monthly visitation fractions of Table 18 to the indicated annual visitation.

Recreation increases by month beginning in April and reaches a peak in July and August. Because visitation becomes more water oriented in the warm summer months, a reduction in the available storage is relatively most effective in reducing visitation during these months. Figure 19 shows the greatest sensitivity of visitation to storage in June, July, and August.

TABLE 18

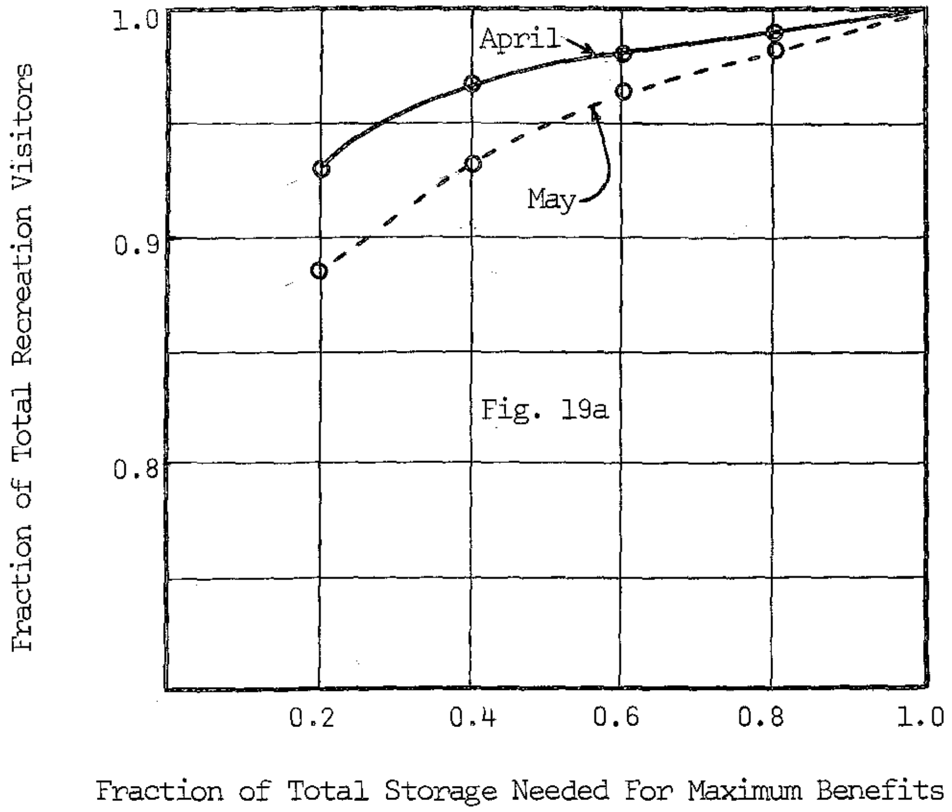
REQUIRED STORAGE IN ACRE-FEET BY MONTH TO ACCOMMODATE THE SPECIFIED ANNUAL VISITATION

	Annual Visitation (Million Visitors)				
	1.6	1.4	1.2	1.0	0.8
Jan.	4530	4000	3430	2930	2270
Feb.	5450	4800	3675	3420	2740
Mar.	4660	4100	3160	2930	2350
Apr.	41100	30000	20000	10400	5500
May	165000	130500	105200	79000	57000
Jun.	198000	156000	122500	93600	68700
Jul.	334000	272500	200250	148000	105200
Aug.	329000	251000	184000	136000	100500
Sep.	70000	54000	45000	27700	14000
Oct.	28500	20000	13000	6000	2640
Nov.	1700	1480	1280	1075	860
Dec.	850	770	650	540	436

TABLE 19

POTENTIAL RECREATION VISITATION BY MONTH FOR THE SPECIFIED ANNUAL VISITATION

	Annual Visitation (Million Visitors)				
	1.6	1.4	1.2	1.0	0.8
Jan.	33600	29400	25200	21000	16800
Feb.	43200	37800	32400	27000	21600
Mar.	43200	37800	32400	27000	21600
Apr.	118300	103500	88800	74000	59200
May	216000	189000	162000	135000	108000
Jun.	227000	198500	170000	142000	113600
Jul.	331000	290000	248500	207000	165600
Aug.	310000	271000	233000	194000	155200
Sep.	140500	123000	105500	88000	70400
Oct.	91200	79800	68400	57000	45600
Nov.	27200	23800	20400	17000	13600
Dec.	17600	15400	13200	11000	8800



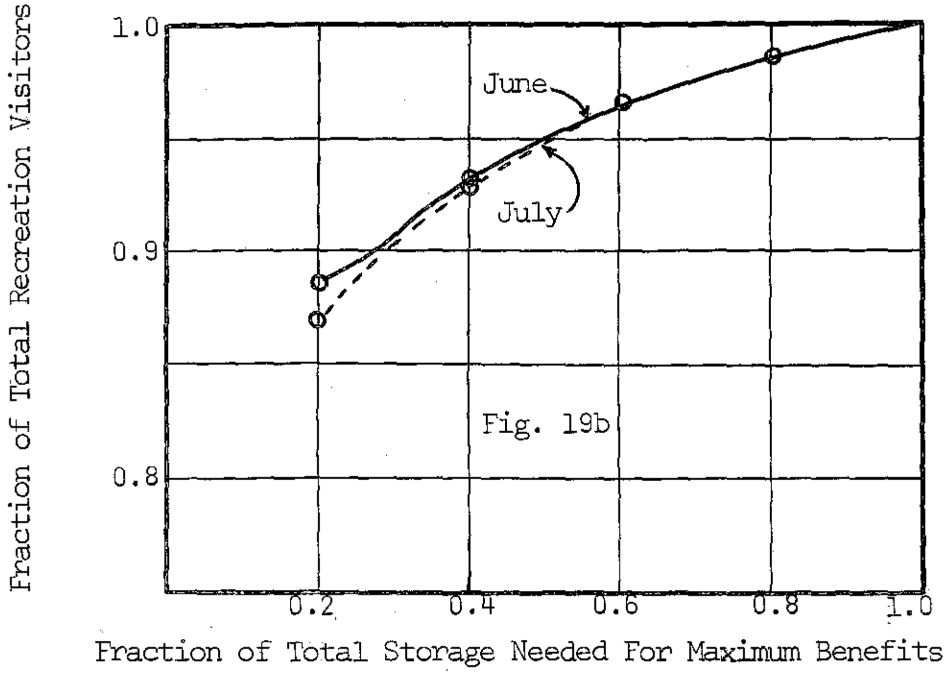
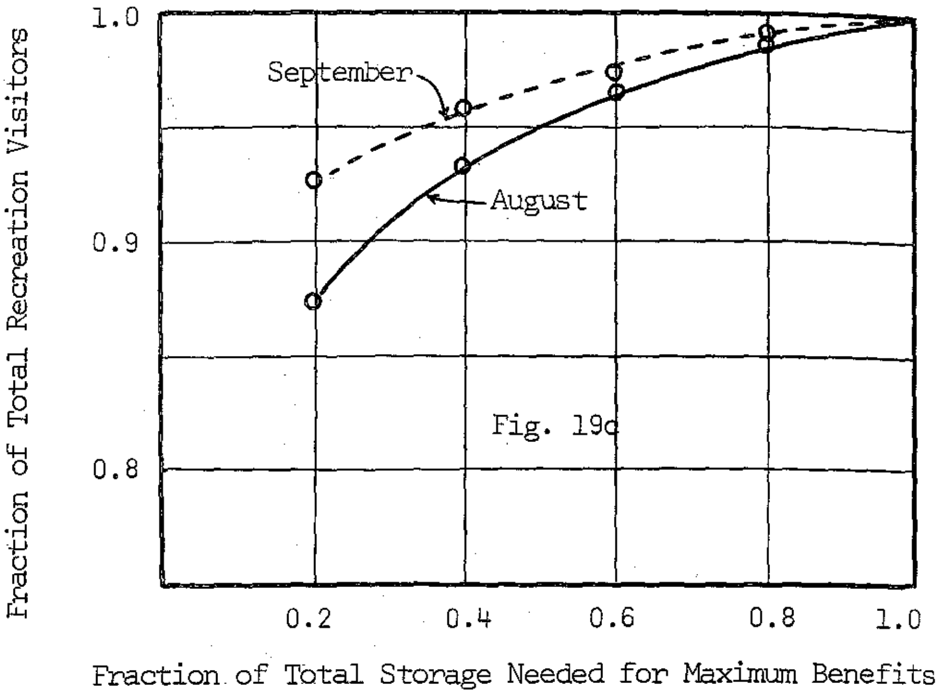


Figure 19. Variation of Recreation Visitors with Maximum Allowable Storage



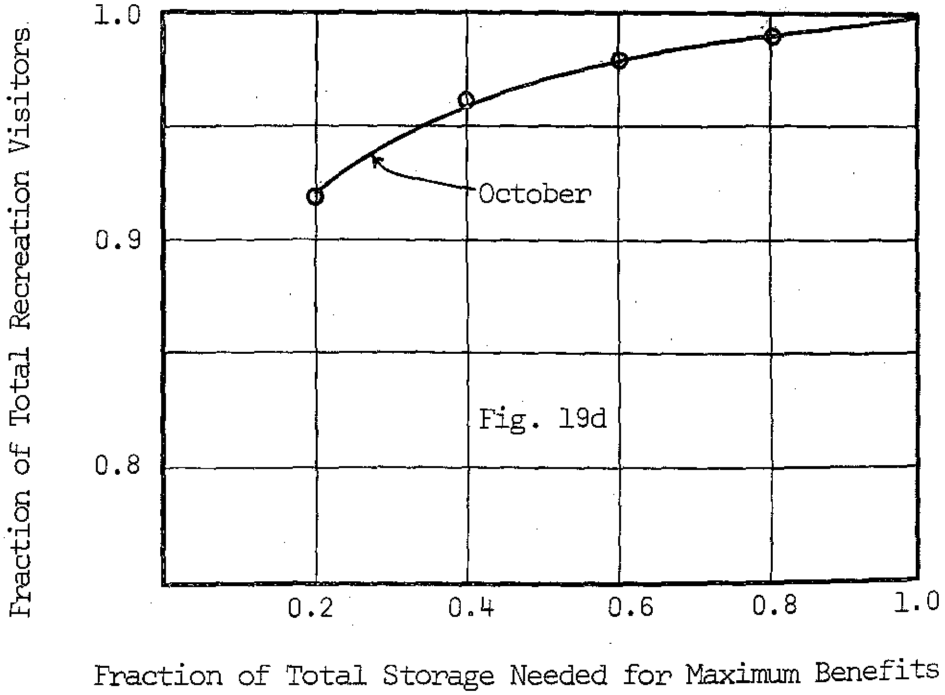


Figure 19.--Continued

Chapter VI

DERIVATION OF OPERATING RULES

INTRODUCTION

Once the operating procedures had been individually derived which for each purpose would maximize the resulting benefit and the loss in benefit which would result were there an infringement on the required operation had been determined, the next step was to derive the operating procedure maximizing the total combined benefit from all three purposes. The first step was to determine the zone of conflict between purpose requirements. Within this zone, marginal benefits for alternative purposes were compared to select the optimum policy. A separate policy was selected for each month. Alternate values of water for water supply and alternate levels of recreation visitation were analyzed to determine resultant effects on the optimum operating policy.

DEFINING THE ZONE OF CONFLICT

Figures 20, 21, and 22 indicate the operating requirements to maximize the benefits by project purpose. Figure 20 is plotted from Table 6 to show the zone of allowable fluctuation so water can be stored during periods of high flow and so drawdown can be continued during extended droughts to obtain maximum water supply yield. Figure 21 is plotted from Table 9 to show the amount of empty storage

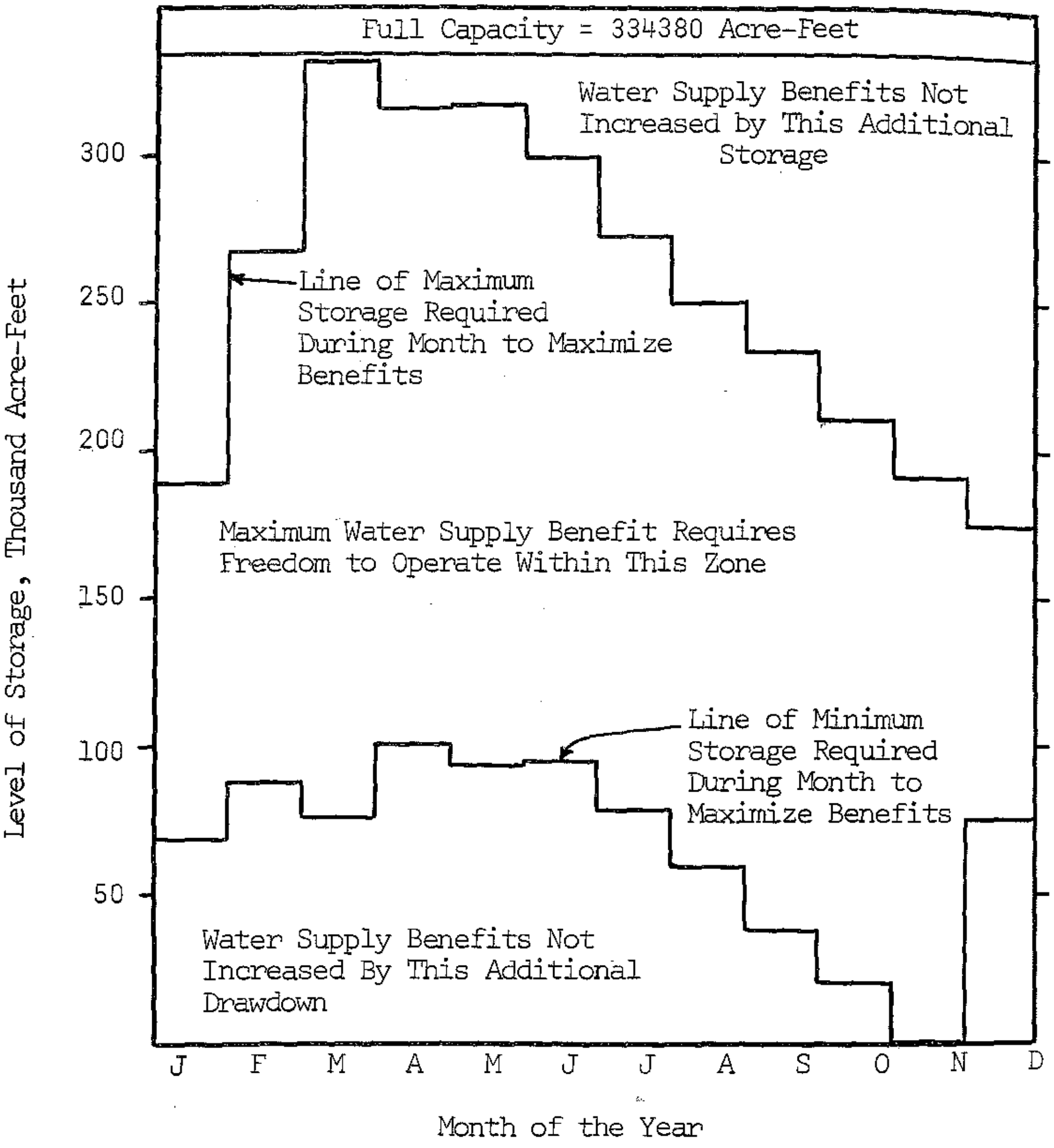


Figure 20. Water Supply Operating Policy For Maximum Benefits

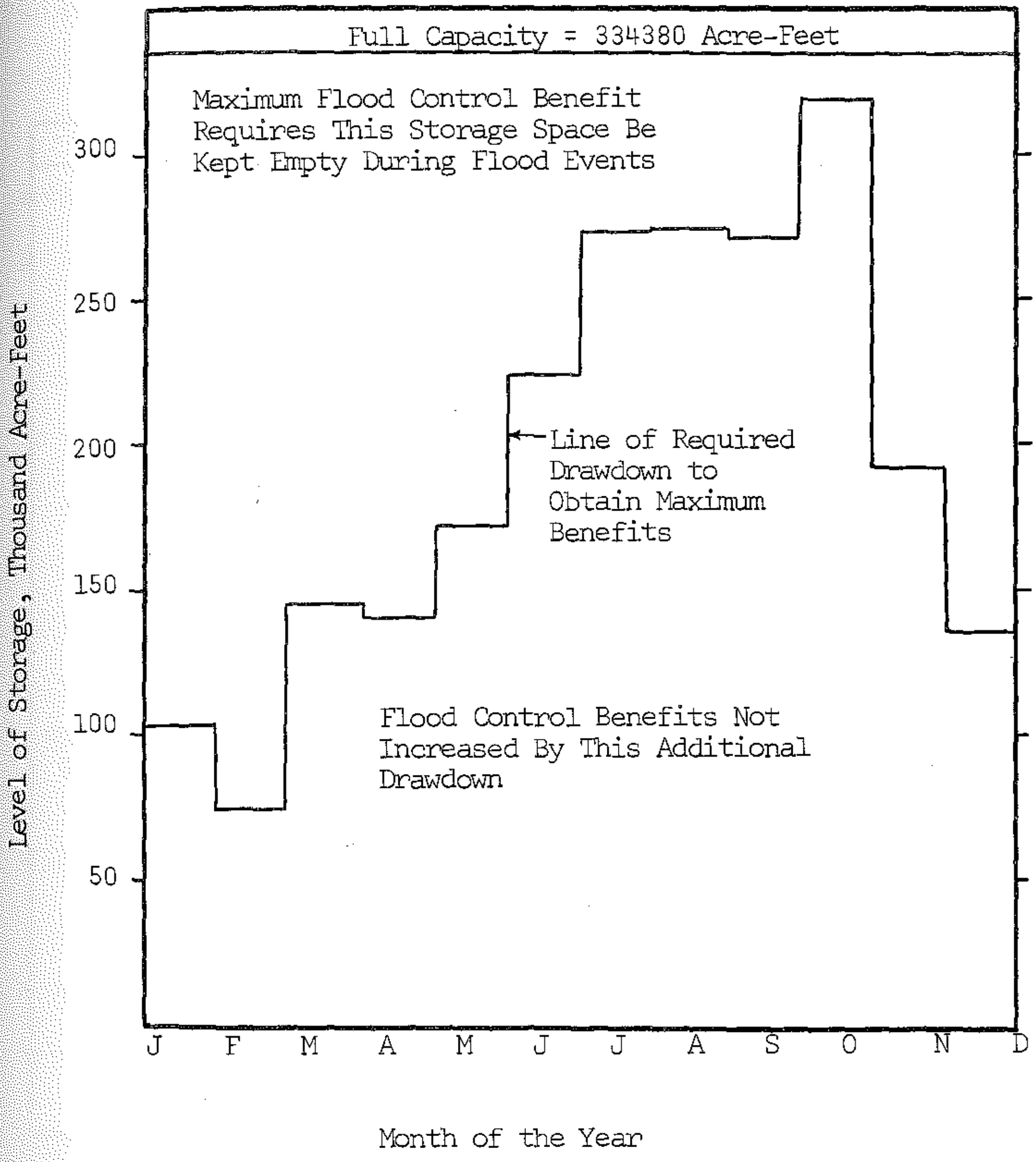


Figure 21. Flood Control Operating Policy for Maximum Benefits

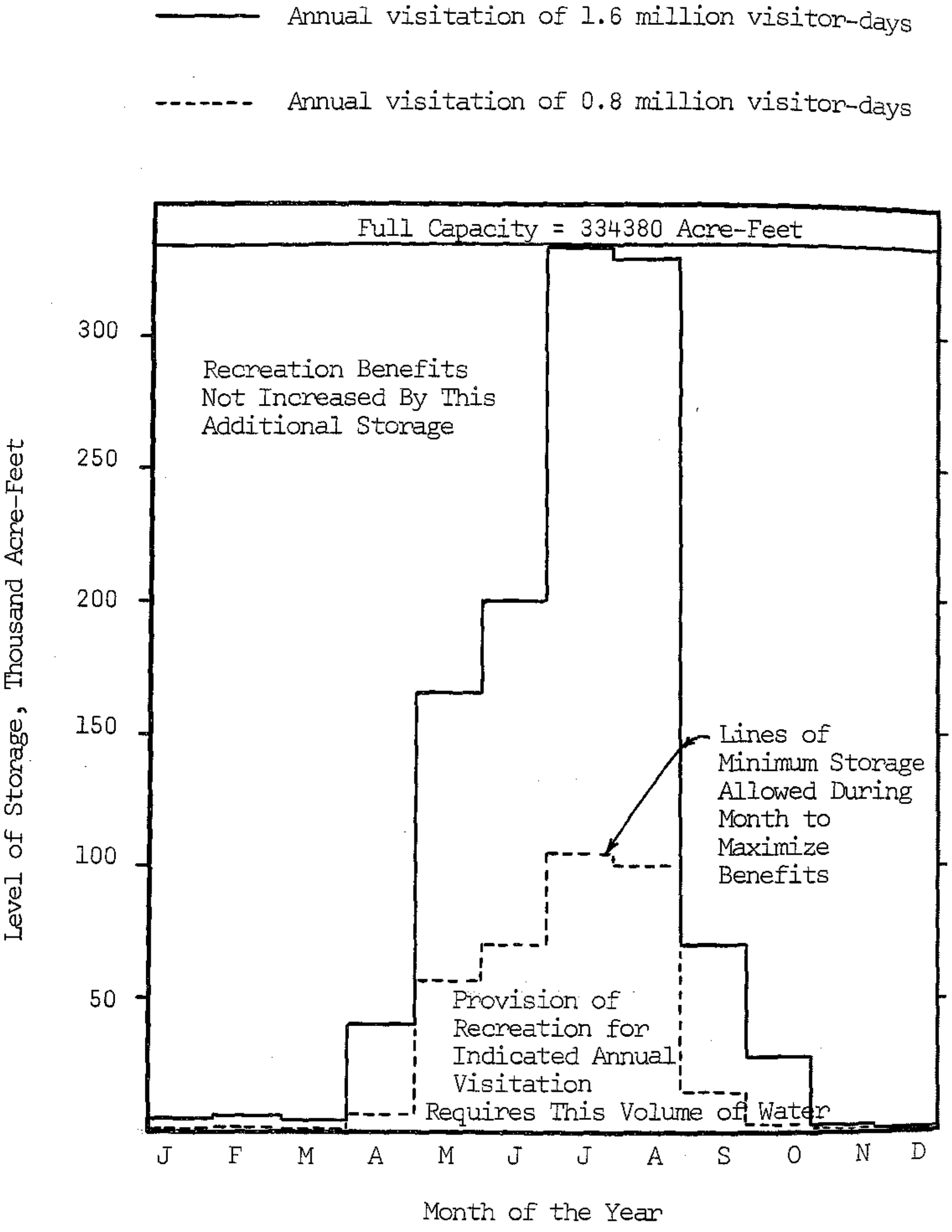


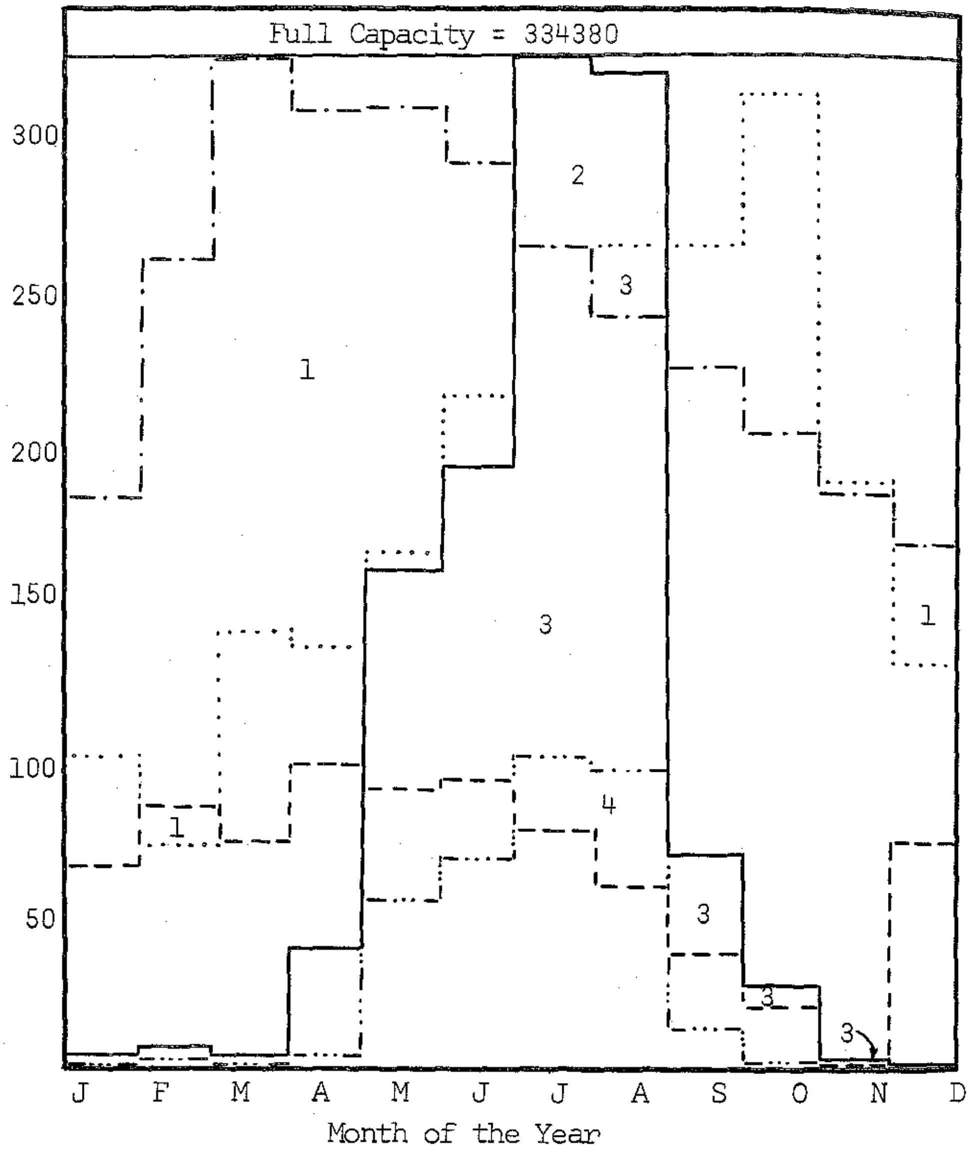
Figure 22. Recreation Storage Requirements for Maximum Benefits

space required in the reservoir to maximize flood control benefits as based on the 200-year flood. Figure 22 is plotted from Table 18 to show the minimum amount of water required in the reservoir to accommodate the maximum and minimum annual rates of recreational visitation considered.

Inspection of Figures 20, 21, and 22 in combination reveals the areas of conflict between the storage requirements for the various purposes shown in Figure 23. In the months from December through June, the drawdown required to preserve storage for flood control conflicts with the amount of water which must be accumulated in the reservoir to maximize yield. In the months from May through November, the amount of water which would be required to provide sufficient recreation space for 1.6 million visitors annually conflicts with the drawdown required during low flow periods to maximize yield. During July and August current recreation water requirements conflict with water supply and the larger visitation would come in conflict with flood control. The annual recreation visitation at which the storage space requirements for recreation will first come in conflict with those for flood control is slightly more than 1.4 million. Within each zone of conflict, marginal benefit analysis is required to determine the operating level which will maximize total benefit.

UNIT VALUES USED

In order to combine the marginal curves, each has to be expressed in dollar units. For recreation, the value of a visitor-day



1--Areas of conflict between water supply and flood control

2--Areas of conflict between water supply, recreation, and flood control

3--Areas of conflict between recreation and water supply

4--Areas of conflict between current recreation and water supply

- - -Minimum storage requirements for full water supply yield

—·—Maximum storage requirements for full water supply yield

······Minimum drawdown level for full flood control benefits

——Minimum storage required for 1.6 million visitor-days

—···—Minimum storage required for current visitation

Figure 23. Zones of Conflict Among Competing Purposes

spent at Rough River Reservoir had previously been determined by Tussey to be $1.27 (19, p. 148); and this value was multiplied by each visitation figure to estimate benefits. For flood control, a curve of dollars damage per foot of stage was supplied by the Corps of Engineers. The analysis in Chapter IV related acre-feet of storage to change in stage downstream, so a curve of dollars per acre-foot of storage was made available for flood control.

Although curves of yield versus allowable drawdown and yield versus conservation storage were derived, it was thought to be unwise to try to pinpoint the value of an acre-foot of yield. Because of the wide variation of value depending on quantities available, other sources, and changes in need, it seemed more realistic to determine how the economic operating procedure would vary with the value of an acre-foot of yield.

EXAMPLE CALCULATIONS

As an example of selecting the operating procedure for benefit maximization, the month of December was chosen for illustrative purposes. Figure 23 shows the zone of conflict in December between flood control and water supply. Table 20 lists calculations as they were made and shows the variation of the optimum operating level with the unit value of yield. Obtaining maximum benefits from flood control for the month requires a drawdown to 135500 acre-feet but water supply requires an allowable conservation storage up to 174100. Obviously both requirements cannot be met so the analysis is used for the range of conflict, or between 135500 and 174100 acre-feet.

TABLE 20

SAMPLE OPTIMUM STORAGE CALCULATIONS

Part A: Water Supply Yield and Flood Control Benefits Versus Storage

Level of Storage Considered (Acre-Feet)	Water Supply Yield Realized (Acre-feet/year)	Flood Control Benefits (Dollars)
174100	269100	94000
170000	268180	94120
165000	267380	94250
160000	265820	94375
155000	264590	94500
150000	263500	94620
145000	262000	94750
140000	260000	94875
135500	258000	95000

Part B: Net Benefits From Both Uses If Value of Water Supply Is As Shown

Storage	Cents Per Acre-Foot					
	6	8	10	12	14	15
174100	110146	115528	120910	126292	131674	134365
170000	110212	115576	120938	126302	131665	134348
165000	110294	115642	120990	126336	131683	314360
160000	110323	115639	120956	126272	131590	134246
155000	110400	115700	121000	126300	131543	134250
150000	110430	115695	120965	126235	131510	134140
145000	110470	115710	120950	126190	131430	134050
140000	110475	115675	120875	126075	131275	133875
135500	110480	115640	120800	125960	131120	133700

Table 20 can best be explained by considering each column.

1. The range of levels of storages considered covered the range of conflict between uses.
2. The water supply yield was restricted by the maximum

allowable conservation storage and the amount of restriction was determined from Figure 4. As the allowable conservation storage is reduced, the possible firm yield is reduced. It should be emphasized that the curves used are the yield versus conservation storage allowed. The curves of yield versus drawdown allowed would not be needed for this month because no conflict exists to restrict drawdown.

3. The flood control benefits for each level of storage considered can be found by multiplying factors read from Figure 14 by the potential benefits from Table 12. The expected flood control benefits would of course increase as greater drawdown is allowed.
4. The figures in the columns in Part B are calculated by adding the product of the selected unit value of water and the yield to the flood control benefit for each indicated storage. The greatest net benefit indicates the level of storage which should be maintained.

The underlined benefits on Table 20 are the maximum obtainable net benefits with a unit value of water supply equal to that listed at the top of the column. Thus, if the present marginal value of water for water supply is $0.08 the maximum net benefit from water supply and flood control in December would be realized if the maximum allowable storage level for the reservoir were 145000 acre-feet. If the marginal value of water were to decrease to $0.06, the optimum level would drop to 135500 acre-feet. Because there is no conflict among purposes outside the range from 135500 to 174100 acre-feet, a marginal unit value of water over \$0.15 would indicate a level of 174100 acre-feet while a value under \$0.06 would indicate 135500 acre-feet.

Analagous computations were made for each of the twelve months and the results are presented as curves in Figure 24. A month-by-month discussion should clarify the results.

MARGINAL VALUE OF WATER

Because the curves in Figure 24 express the optimum operating policy as a function of the marginal value of water, the marginal value concept needs to be defined before the curves can be properly interpreted. The marginal value is the value the last acre-foot of water is worth after all the preceding yield has been put to beneficial use. In the case of Rough River Reservoir, 269100 acre-feet annually of firm yield can be produced. Since this value is so large compared with current demand, it abundantly satisfies all ordinary water requirements long before the available yield is exhausted; and the marginal value is reduced to zero. In the case where operation restrictions reduce the yield below 269100 acre-feet, the marginal value for the last acre-foot of remaining yield should be used. However, the reductions found were not for Rough River Reservoir large enough to raise the marginal value above zero. As a result, water supply is not a factor in current reservoir operation.

The function of the curves on Figure 24 is primarily to promote better understanding of the factors determining optimum operating policy and to provide an idea as to the form of the governing functional relations. When viewed in this light, the results are of much more general significance than when applied to Rough River Reservoir alone.

MONTH-BY-MONTH RESULTS

January: In January recreation demands are not great enough to conflict with drawdown for water supply. However, flood control for this month requires drawdown to 103000 acre-feet while water supply requires conservation storage up to 188000 acre-feet. Using the type of analysis shown on Table 20 on the range of conflict between 103000 and 188000 acre-feet produced the results shown on Figure 24a to define the maximum level of water for water supply which should be allowed as a function of marginal value. A marginal value of water any greater than $0.50 would cause the benefits of water supply to overcome the benefits of flood control in the range of conflict so that the reservoir should be operated solely for water supply. A value of $0.04 or less would make flood control dominant. Although January is a wet month with large expected floods, a conservation storage of 188000 acre-feet will still leave considerable room for flood storage. For this reason, a small value for water supply is enough to overcome the small marginal flood benefit in the conflict range.

February: The conditions in February are very similar to those in January except that there is a wider range of conflict between required flood control drawdown and the required allowable conservation storage for water supply. The maximum storage required by water supply is greater and would leave only 66000 acre-feet for flood control storage if water supply is utilized fully. At $0.05 per acre-foot all room should be allotted to flood control but as the value increases to $0.35 flood control benefits are overshadowed for the conflict range (Figure 24b).

March: In March flood threat has lessened somewhat, but the reservoir must be allowed to be completely filled to produce maximum water supply yield because of the chance later inflows may not be large enough to fill the reservoir. Although Rough River Reservoir reduces the flood threat downstream just by surcharge storage over its large surface area, some controlled storage is necessary. Because the zone of conflict extends to the top of the controlled storage, the value of water required to reach the upper end of the zone is quite high. The analysis shows that water supply must be worth at least $10 an acre-foot to allow the level to remain at 290000 acre-feet or above (Figure 24c). Although not shown in the March curve, even a value of water of $20 per acre-foot would not pay for allowing the reservoir to completely fill with conservation storage.

April: Flood control and water supply still conflict in April, but flood threat has lessened, which reduces the amount of required drawdown which in turn reduces the size of the range of conflict. The April curve (Figure 24d) shows that the optimum storage remains close to 225000 acre-feet from a value of $0.25 to $0.80 per acre-foot. The flat part of the curve was caused in part by the sharp break in the flood control benefit curve (Figure 15d). Recreation still does not conflict with needed water supply drawdown in this month.

May: Figure 23 shows May to be the first month of the year with conflicts with respect to both maximum and minimum water supply storage to be allowed. In the range from 172000 to 317000 acre-feet, maximum storage conflicts with flood control while in the range from 91000 to 165000 acre-feet minimum storage conflicts with recreation. For storages between 57000 and 91000 acre-feet the minimum level depends entirely on visitation. Figure 24e shows the economic maximum level as a function of the marginal value of water for water supply in the same format used for the preceding four months. Figure 24f shows the economic minimum level as a function of both the marginal value of water and the annual rate of recreation visitation. As the three curves show, the range of conflict and the value of water yield required to justify a specified level of drawdown within that range both increase as the recreation visitation increases.

June: June also has conflicts at the upper (Figure 24g) and lower (Figure 24h) levels of operation, but the flood threat is so small as to make any value of water supply over \$0.11 dominate the range. A recreation visitation of at least 1.2 million brings about enough benefits to require a water supply value of \$0.52 in order to allow drawdown into the conflict range. The June curve shows that if recreation visitation increases to 1.6 million annually water supply yield must increase to \$1.48 to use the entire conflict range for yield.

July: As shown in Figure 23, July is the first month in which the conflicts with respect to maximum and minimum water supply storage overlap. For storages over 274800 acre-feet and a visitation over

1.4 million, recreation is in conflict with flood control. The maximum storage requirement for water supply is not in conflict because it is more than satisfied by 274800 acre-feet. The optimum operating rule for maximum storage is to not exceed 273000 acre-feet (the maximum water supply requirement) unless visitation exceeds 1.4 million annually. For greater visitations the maximum level is a function of visitation with the optimum storage for 1.6 million visitors being 322000 acre-feet. The curves indicating the minimum level (Figure 24i) are influenced by flood control as well as water supply drawdown and recreation requirements. This is the reason why the minimum level curves do not reach the top of the zone of conflict even for a zero marginal value of water. Recreation use peaks in July, but a marginal value of $3.41 for water will force storage for this use from the zone of conflict. July is also the first month to have a conflict between the minimum water supply storage to be allowed and the storage requirements of current recreation use.

<u>August</u>: The format of the optimum policy is the same for August as for July. For storages over 274300 acre-feet and a visitation over 1.4 million, recreation conflicts with flood control. The economic operating rule for maximum storage is not to exceed 249700 acre-feet unless visitation exceeds 1.4 million annually. If the visitation rate reaches 1.6 million, the optimum level is 329000 acre-feet. The minimum level of storage curves are similar to those for July and are provided in Figure 24j. A slightly smaller recreation demand reduces its conflict with flood control, but a greater drawdown

requirement for water supply increases the recreation-water supply conflict.

September: In September, the only remaining conflict is between water supply and recreation over the minimum water supply storage to be allowed (Figure 24k). The conflict begins with an annual visitation of 1.2 million over a range of 7000 acre-feet. The critical values of water supply for this month range between $0.24 and $0.44.

October: The only conflict in October is also between water supply and recreation over the minimum allowable storage. The range of conflict, however, only extends over 10000 acre-feet and only exists at all for the annual visitation rate of 1.6 million. Figure 24l shows a value of water over $1.15 would favor drawdown to the bottom of the range as needed for water supply while a value under $0.50 would favor maintenance of the recreation pool at the top of the range.

November: The flood threat nearly increases enough in November to come in conflict with water supply storage requirements but not quite. However, because the end of the critical drawdown period comes in November, a conflict is created between achieving full drawdown for water supply and the small remaining recreation demand. Actually, the controlling factor would be the maintenance of a minimum pool to preserve the fish population as this would most certainly require a larger pool than the 1700 acre-foot size base on November visitation. Because of this intangible factor and the small range of conflict, a set of operating curves was not drawn.

December: A low recreation visitation and a less severe water supply drawdown requirement erases the conflict for minimum allowable storage in December. However, the much larger flood threat creates a conflict between maximum conservation storage requirements and flood control storage needs. The resulting curve (Figure 24m) follows the same basic pattern found from January through April.

OPERATING POLICY FOR ROUGH RIVER RESERVOIR

While the results of Figure 24 portray the type of analysis which can be used to ascertain the optimum operating policy in a wide range of conditions, this study should not conclude without considering how the current operating policy followed by the Corps of Engineers compares with the derived optimum policy. Under current conditions of zero marginal value of water for water supply and annual recreation visitation of 0.8 million, all zones of conflict (Figure 23) are erased. Any operating policy is optimum as long as it does not violate the flood storage requirements of Figure 21 or the recreation pool requirements of Figure 22. The current operating policy as presented in Chapter II does neither.

Nevertheless, the curves contain two important implications for future reservoir operation. First, as annual recreation visitation increases past 1.0 million, the benefits achieved by the reservoir would be increased by further enlarging the seasonal pool during July and August and initiating the spring rise in March instead of April. The midsummer pool, however, should not be enlarged so much as to cause problems by inundation of existing shoreline recreation facilities. Second, if a water supply is needed locally in future

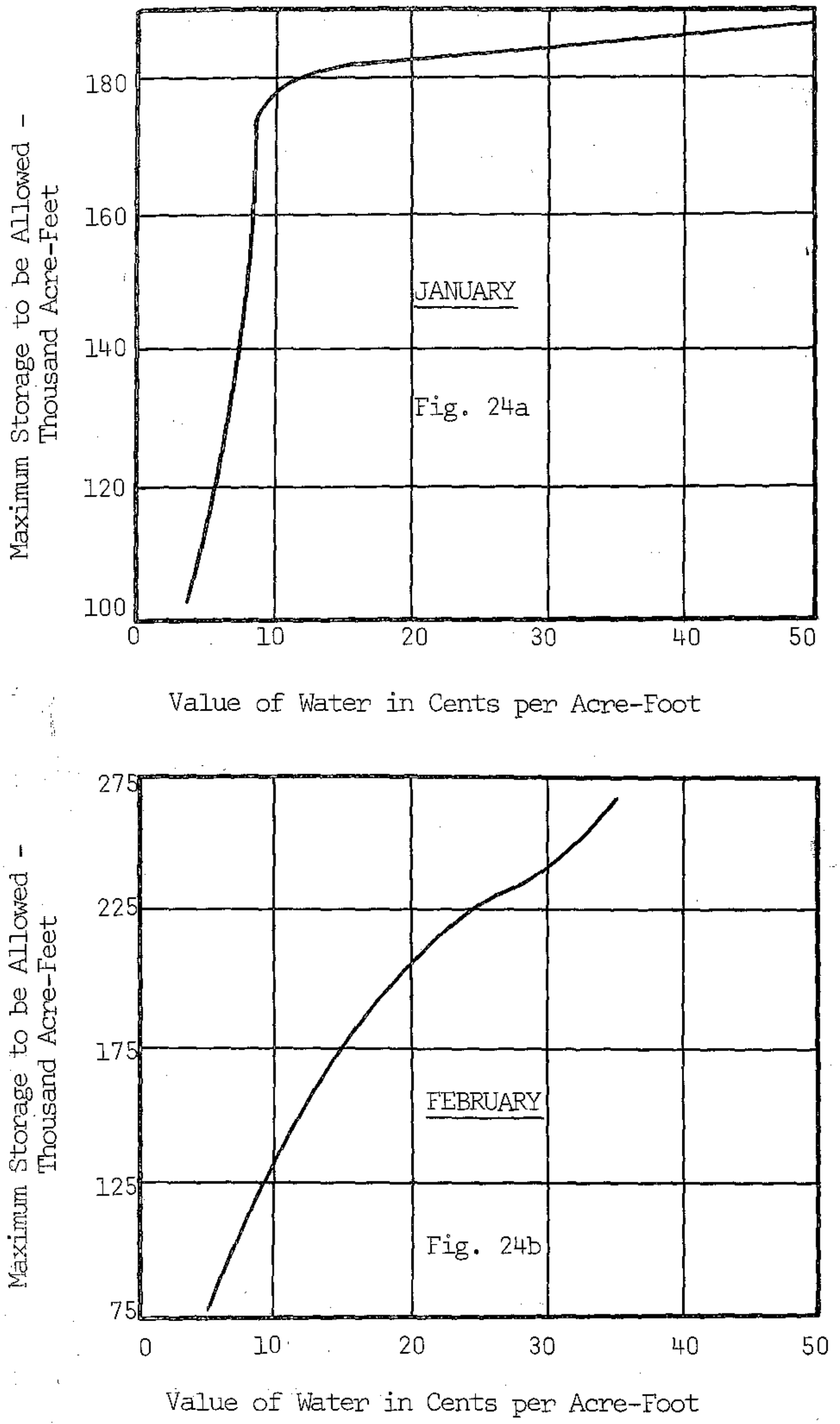
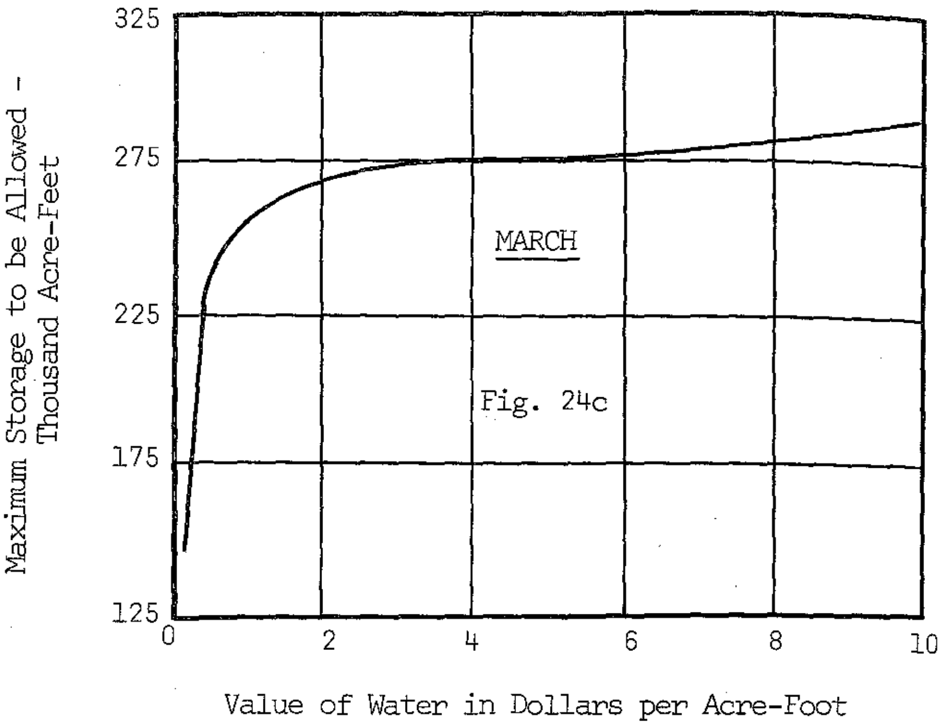


Figure 24. Month-by-Month Operating Curves as Related to the Marginal Value of Water



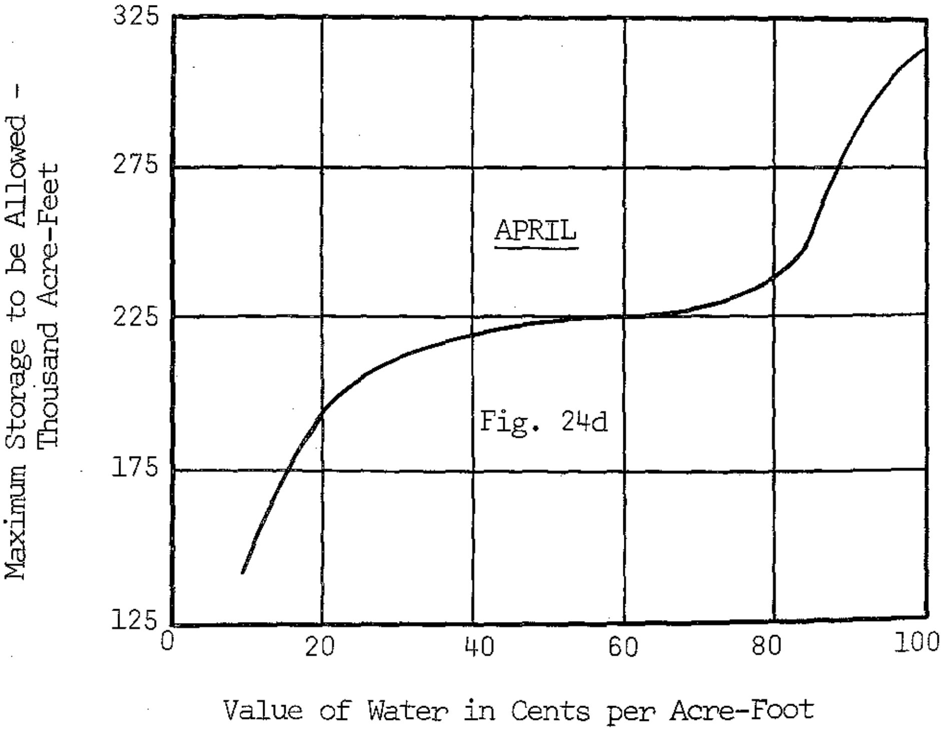


Figure 24.-- Continued

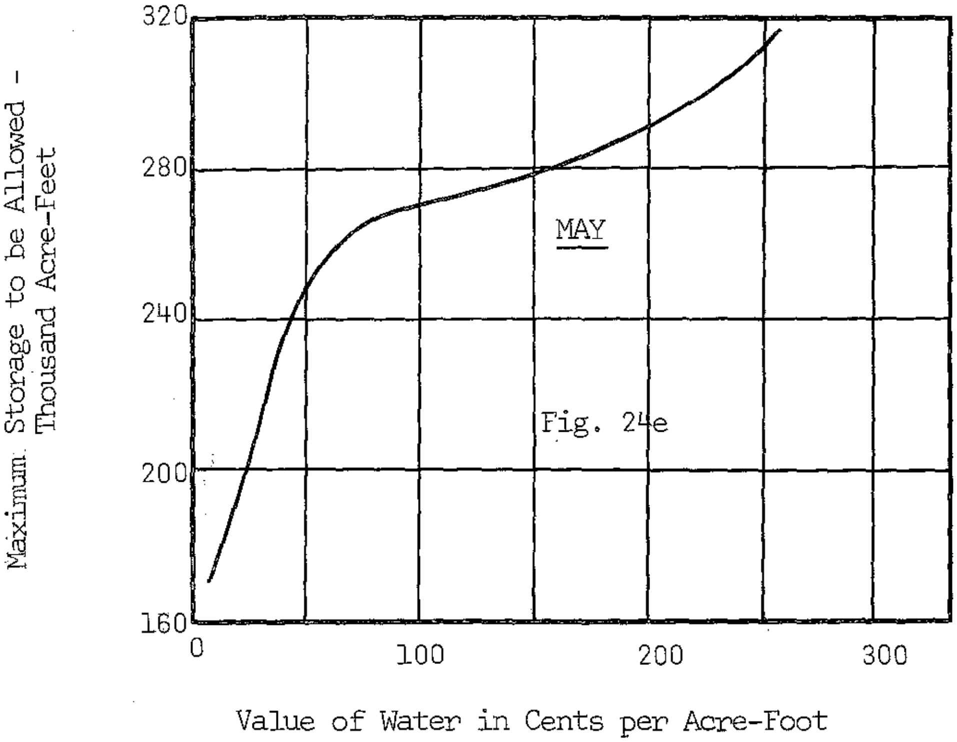


Fig. 24e

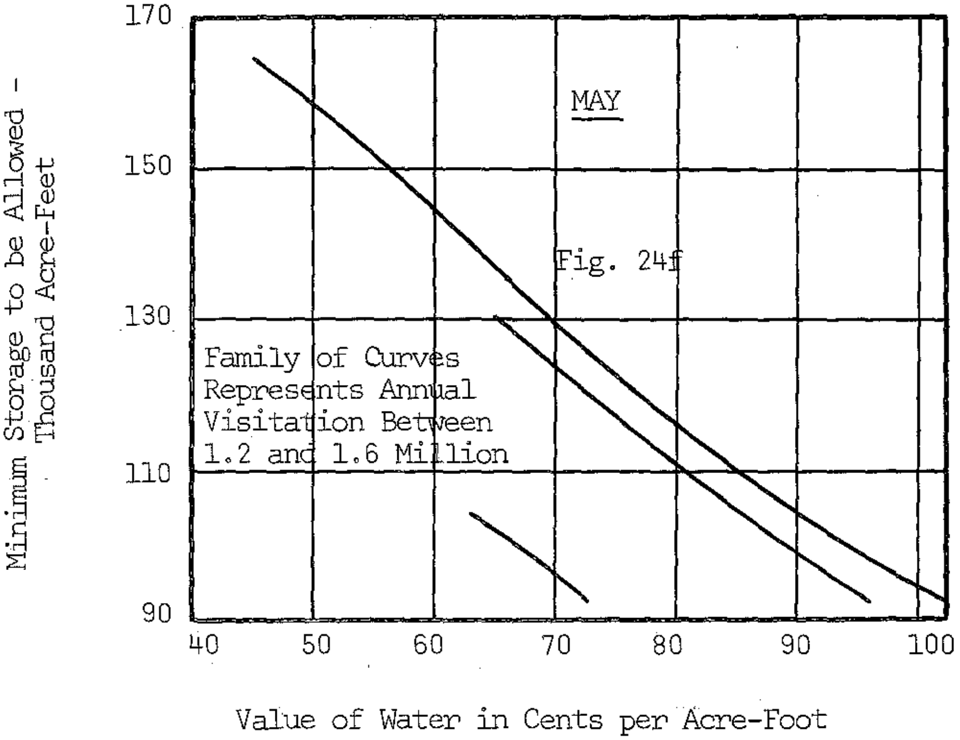
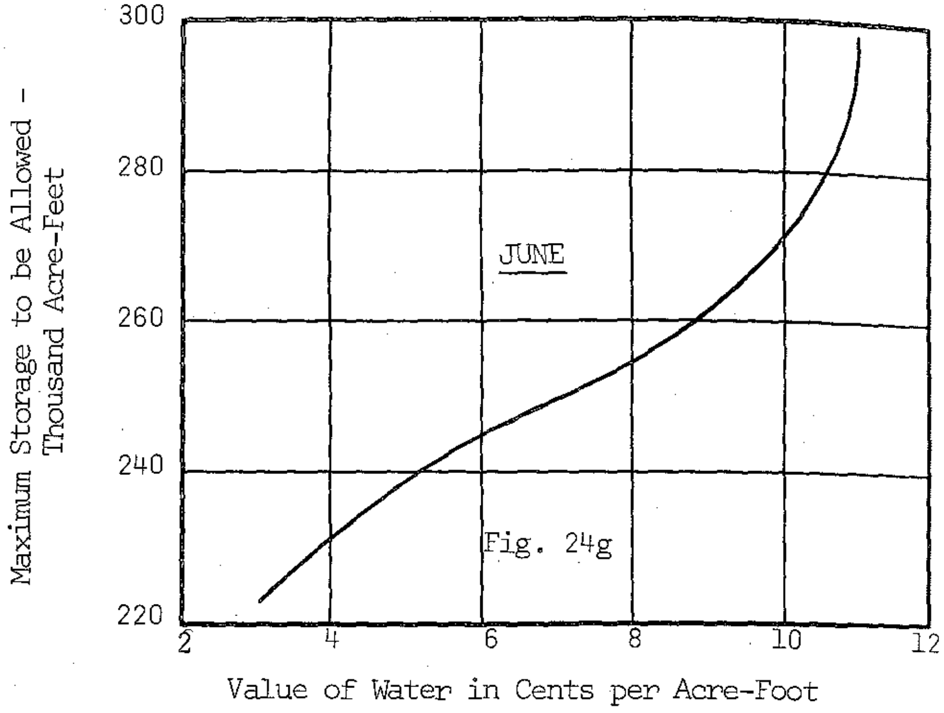


Fig. 24f

Figure 24.--Continued



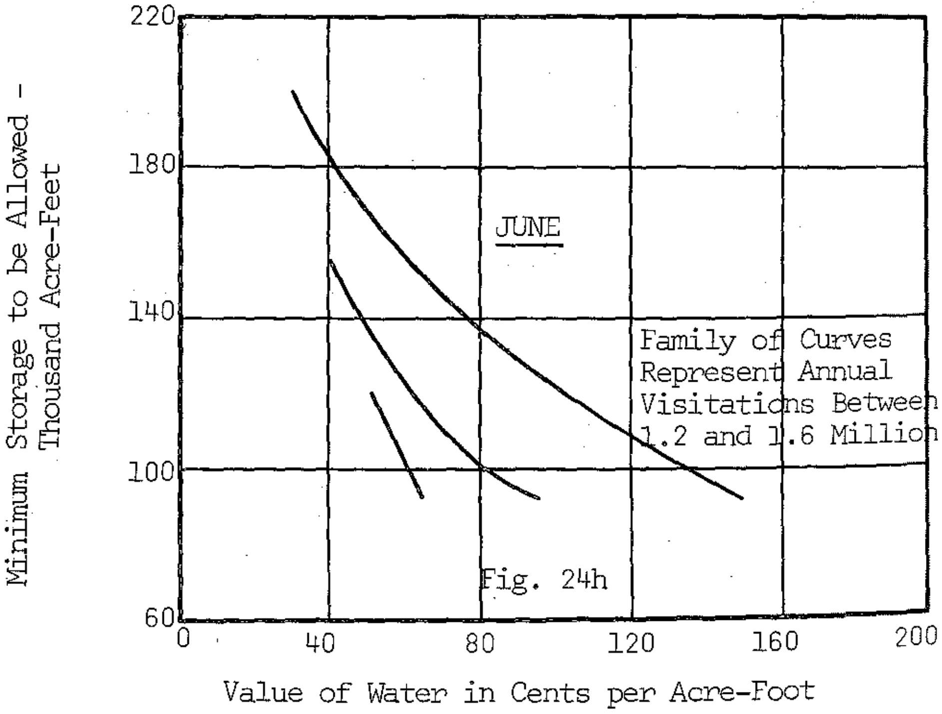
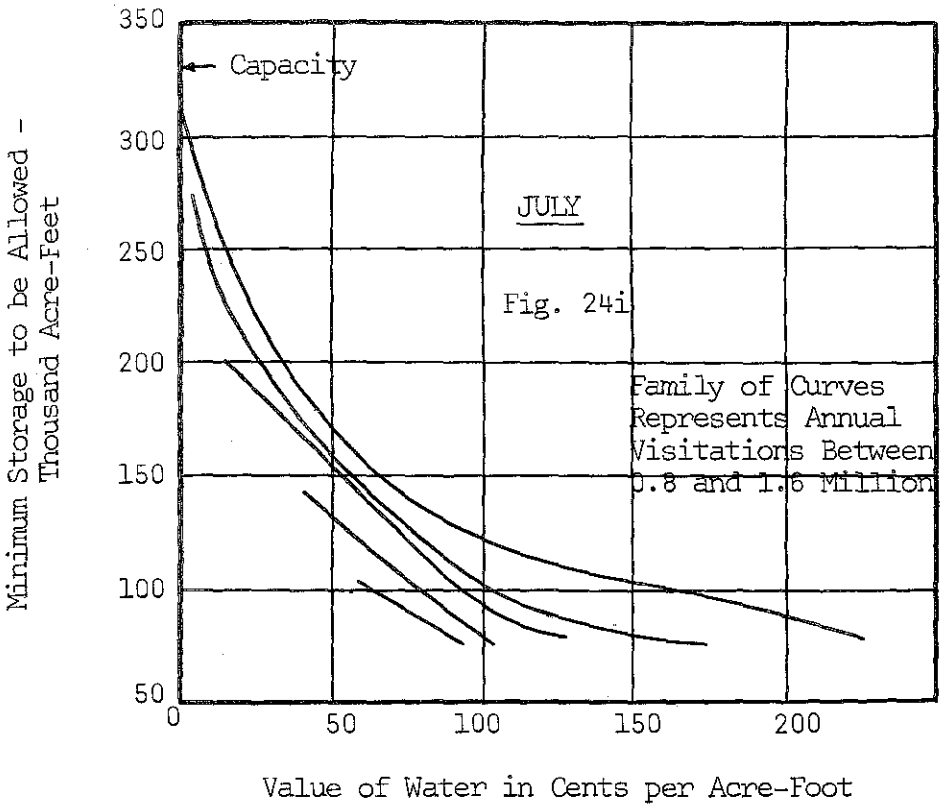


Figure 24.--Continued



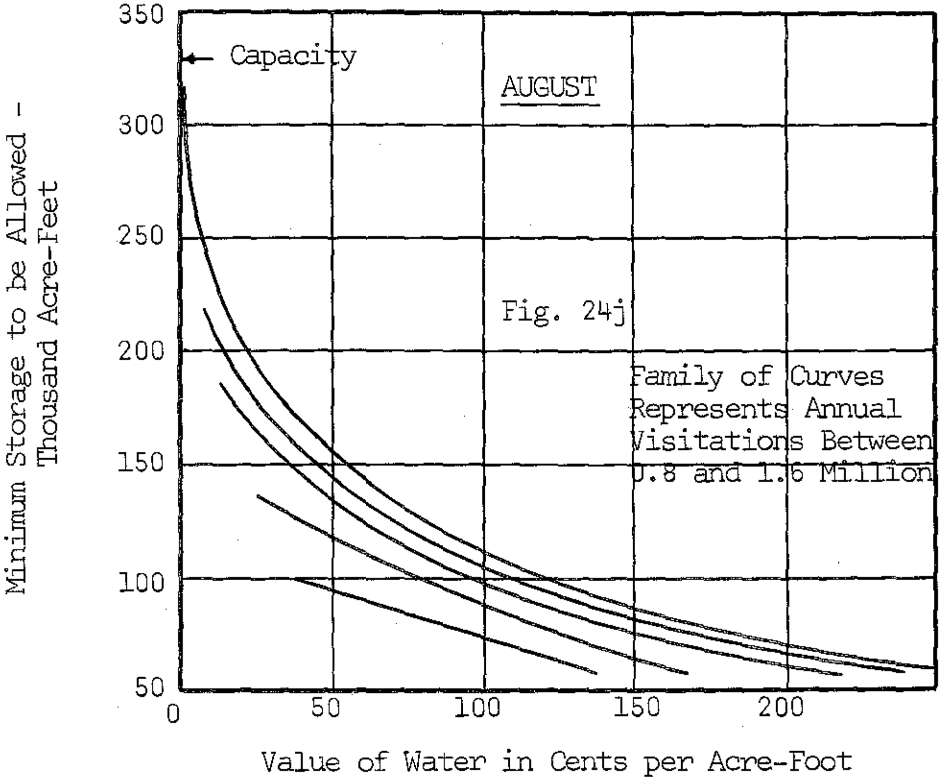
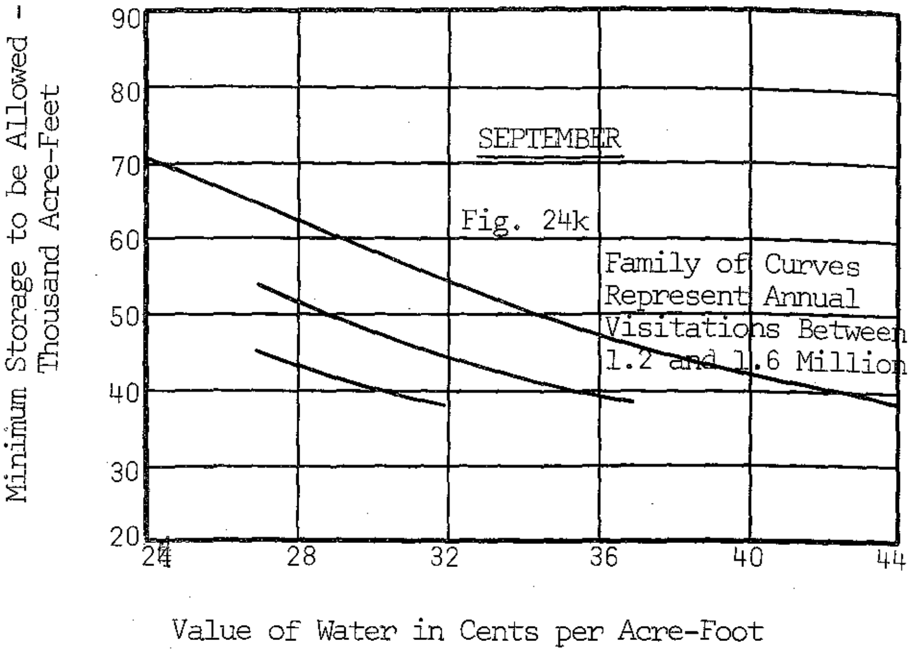


Figure 24.--Continued



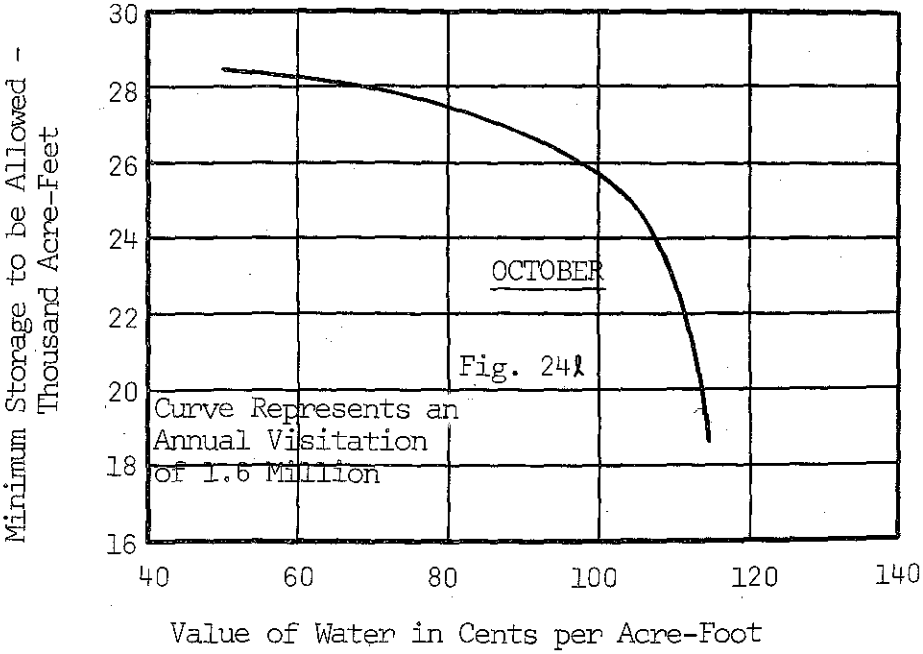
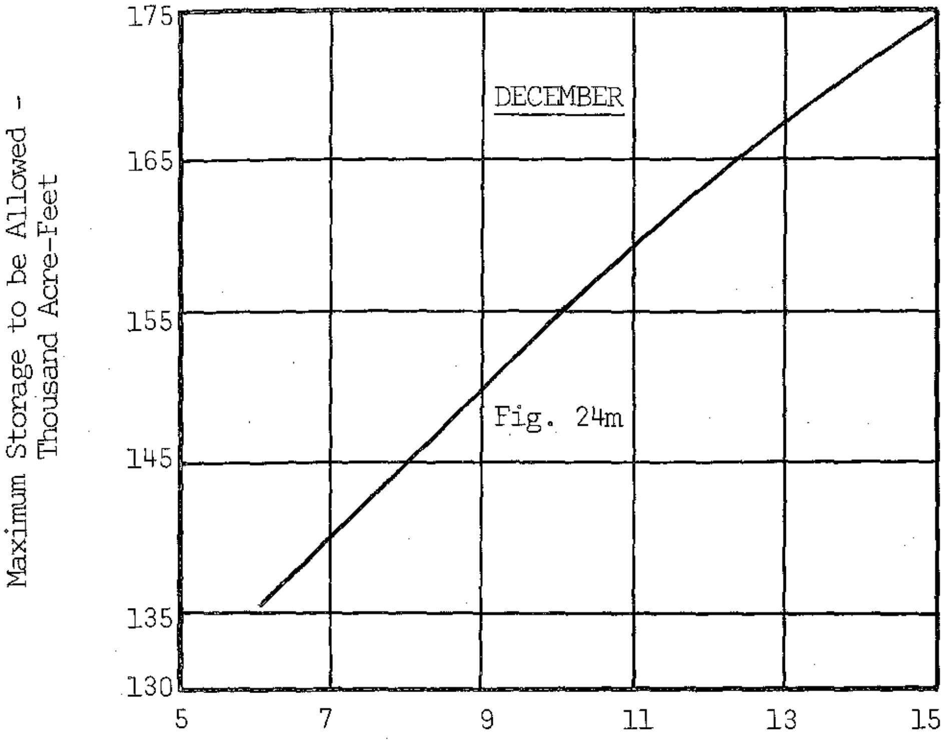


Figure 24.--Continued



Value of Water in Cents per Acre-Foot

Figure 24.--Continued

years, large quantities of water could be developed from Rough River Reservoir without substantially reducing the benefits from the other purposes. In fact, many communities requiring water supply should consider the economics of obtaining it from existing rather than building new reservoirs.

Chapter VII

SUMMARY AND CONCLUSIONS

SUMMARY OF METHODS

The purpose of this study was to develop a methodology for determining an optimum set of reservoir operating rules based on the example of Rough River Reservoir and assuming this multipurpose reservoir had as its uses flood control, water supply, and recreation. The operating rules were to be derived by the method of marginal analysis which uses as its criteria achievement of maximum net benefits from the available storage capacity. To derive the optimum operating rules, individual marginal benefit curves were needed for each use; and Chapters III, IV, and V dealt with the derivation of these benefit curves.

The variation of potential yield for water supply with conservation storage was calculated using historical streamflow data to synthesize a 500-year record for use in the yield studies. After the firm yield for the present reservoir was found assuming operation was in no way restricted by requirements for other purposes, certain restrictions were placed on the amount of allowable fluctuation of the water level to determine how the firm yield would be reduced. The results of this part of the analysis was shown in two sets of curves. One set shows the yield would vary as restrictions were placed on the maximum allowable conservation storage for each month of the year (Figure 4). The other set shows the variation of yield as the minimum allowable water level was changed (Figure 5).

Benefits from flood control were derived by using Corps of Engineers data from stage-damage curves for the reaches downstream and by using historical data and statistical analysis to estimate the expected streamflow magnitude for several different storm frequencies. The storage space available at the beginning of each storm was varied to determine the variation of streamflow peak downstream, and thus, the change in the peak stage and resulting damages. By studying a range of initial storages, curves were derived showing the average annual benefits expected as the available storage in the reservoir was varied (Figure 15).

Expected recreation benefits were found by applying historical visitation data and the unit value of a visitor-day derived by Tussey (10, p. 148) and assuming use would vary with the reservoir surface area or the shoreline length according to the activity type. As the water level drops, fewer people wish to visit the park, so that benefits are reduced. The analysis covered annual visitation of up to double the present annual visitation of approximately 0.8 million visitors.

The combination of benefit curves to obtain optimum operation rules consisted of a marginal benefit analysis that considered the use of increments of reservoir space and determined the way to use this space which would produce the maximum net benefit. The entire analysis was based on the probability of the occurrence of natural events based upon historical data.

THE DERIVED OPERATING RULES

The following monthly operating rules were derived by the methods described in Chapter VI using results from the three previous chapters.

1. January--Keep at least 2270 to 4530 acre-feet of water in the reservoir to accommodate an annual visitation of 0.8 to 1.6 million persons, allow a maximum conservation storage level at or below a value between 103000 and 188600 acre-feet depending on the current value of an acre-foot of water for water supply (see Figure 24a), and fluctuate between these two levels as needed for water supply yield.

2. February--Keep at least 2740 to 5450 acre-feet of water in the reservoir to accommodate an annual visitation of 0.8 to 1.6 million persons, allow a maximum conservation storage level at or below a value between 77000 and 267000 acre-feet depending on the current value of an acre-foot of water for water supply (see Figure 24b), and fluctuate between these two levels as needed for water supply yield.

3. March--Keep at least 2350 to 4660 acre-feet of water in the reservoir to accommodate an annual visitation of 0.8 to 1.6 million persons, allow a maximum conservation storage level at or below a value between 145000 and

334380 acre-feet depending on the current value of an acre-foot of water for water supply (see Figure 24c), and fluctuate between these two levels as needed for water supply yield.

4. April--Keep at least 5600 to 41100 acre-feet of water in the reservoir to accommodate an annual visitation of 0.8 to 1.6 million persons, allow a maximum conservation storage level at or below a value between 141000 and 316000 acre-feet depending on the current value of an acre-foot of water for water supply (see Figure 24d), and fluctuate between these two levels as needed for water supply yield.

5. May--Keep at least an amount between 57000 and 165000 acre-feet of water in the reservoir depending on the current value of an acre-foot of water for water supply and the current annual visitation (see Figure 24f), allow a maximum conservation storage level at or below a value between 172000 and 317000 acre-feet depending on the current value of an acre-foot of water for water supply (see Figure 24e), and fluctuate between these two levels as needed for water supply yield.

6. June--Keep at least an amount between 68700 and 198000 acre-feet of water in the reservoir depending on the current value of an acre-foot of water for water supply

and the current annual visitation (see Figure 24h), allow a maximum conservation storage level at or below a value between 223000 and 299000 acre-feet depending on the current value of an acre-foot of water for water supply (see Figure 24g), and fluctuate between these two levels as needed for water supply yield.

7. July--Keep at least an amount between 77700 and 322000 acre-feet of water in the reservoir depending on the current value of an acre-foot of water for water supply and the current annual visitation (see Figure 24i), do not let the level get higher than 322000 acre-feet to allow room for flood storage, and fluctuate between these two levels as needed for water supply yield.

8. August--Keep at least an amount between 59300 and 329000 acre-feet of water in the reservoir depending on the current value of an acre-foot of water for water supply and the current annual visitation (see Figure 24j), do not let the level get higher than 329000 acre-feet to allow room for flood storage, and fluctuate between these two levels as needed for water supply yield.

9. September--Keep at least an amount between 14000 and 70000 acre-feet of water in the reservoir depending on the current value of an acre-foot of water for water supply and the current annual visitation (see Figure 24k),

do not let the level get higher than 271000 acre-feet to allow room for flood storage, and fluctuate between these two levels as needed for water supply yield.

10. October--Keep at least an amount between 2680 and 28500 acre-feet of water in the reservoir depending on the current value of an acre-foot of water for water supply and the current annual visitation (see Figure 24l), do not let the level get higher than 320800 acre-feet to allow room for flood storage, and fluctuate between these two levels as needed for water supply yield.

11. November--Keep at least 860 to 1700 acre-feet of water in the reservoir to accommodate an annual visitation of 0.8 to 1.6 million persons, do not let the level get higher than 191000 acre-feet to allow room for flood storage, and fluctuate between these two levels as needed for water supply yield.

12. December--Keep at least 440 to 850 acre-feet of water in the reservoir to accommodate an annual visitation of 0.8 to 1.6 million persons, allow a maximum conservation storage level at or below a value between 135500 and 174100 acre-feet depending on the current value of an acre-foot of water for water supply (see Figure 24m), and fluctuate between these two levels as needed for water supply yield.

APPLICATION OF RESULTS

The rules outlined above differ from the present operating rules for Rough River Reservoir for two major reasons. First, they were derived and presented on a monthly basis, and second, water supply has been used as an integral part of the plan for the reservoir.

The major problem in following the derived rules would be changing the storage levels as required from one month to the other. In some cases, the rules might vary radically from one month to the other because the months were treated as separate units independent of the past or next month. The principal difficulty would be in raising the storage as prescribed for recreation if periods of high runoff do not occur at the required time. As historical streamflow records show, the fall would be the easier part of the year to keep on schedule because drawdown can always be accomplished.

It should be once again emphasized that these rules were derived using historical records and statistical analysis. The rules were designed to give maximum net benefits over a long period of time; and barring radical changes in local climatic conditions, the rules should accomplish this goal. If an extremely rare flood or a large flood out of season were to occur, considerable damage is sure to result downstream, but this cannot economically be prevented. Nevertheless, an experienced operator presented with a good set of operating rules can do much toward obtaining the maximum benefits from any reservoir.

LIST OF REFERENCES

1. Eckstein, Otto. Water Resources Development - The Economics of Project Evaluation. Cambridge, Massachusetts: Harvard University Press, 1961.

2. Krutilla, John V. and Eckstein, Otto. Multiple Purpose River Development. Baltimore, Maryland: John Hopkins Press, 1961.

3. Linsley, R. K., Kohler, M. A., and Paulhus, J. L. H. Hydrology for Engineers. New York: McGraw Hill Book Co., Inc., 1958.

4. Maass, Arthur, et. al. Design of Water Resource Systems. Cambridge: Harvard University Press, 1962.

5. McCabe, John A. Floods in Kentucky-Magnitude and Frequency. Lexington, Kentucky: University of Kentucky, Kentucky Geological Survey, 1962.

6. McKean, Roland N. Efficiency in Government Through Systems Analysis. New York: John Wiley and Sons, Inc., 1963.

7. Oglesby, Clarkson H. and Hewes, Laurence I. Highway Engineering. New York: John Wiley and Sons, Inc., 1964.

8. Rosenbaum, David H. Review of the Economic Benefits and Costs Resulting from Dewey Reservoir. Lexington, Kentucky: University of Kentucky, Water Resources Institute, Research Report No. 5, 1967.

9. Thomas, H. A. and Fiering, M. B. "Mathematical Synthesis of Streamflow Sequences for the Analysis of River Basins by Simulation," Maass, et. al., Design of Water Resources Systems. Cambridge: Harvard University Press, 1962.

10. Tussey, Robert C., Jr. Analysis of Reservoir Recreation Benefits. Lexington, Kentucky: University of Kentucky, Water Resources Institute, Research Report No. 2, 1967.

11. U. S. Army Corps of Engineers. Design Memorandum No. 8B, Master Plan Rough River Reservoir. Louisville, Kentucky: Louisville District, U. S. Army Corps of Engineers, 1961.

12. U. S. Army Corps of Engineers. Dewey Dam Recreation Use Survey, Unpublished. Huntington, West Virginia: Huntington District, U. S. Army Corps of Engineers, June, 1964.

LIST OF REFERENCES
(Continued)

13. U. S. Army Corps of Engineers, Mississippi River Commission. Mississippi River Reservoir Benefit Study. Vicksburg, Mississippi: Vicksburg District, U. S. Army Corps of Engineers, 1961.

14. U. S. Army Corps of Engineers. "Reservoir Project Monthly Visitation Data, Rough River Reservoir," OVL Form 448. Louisville, Kentucky: Louisville District, U. S. Army Corps of Engineers, 1963-1966.

15. U. S. Army Corps of Engineers. Report of the Chief of Engineers. Washington, D. C.: U. S. Army Corps of Engineers, 1959-1966.

16. U. S. Army Corps of Engineers. Recreation Facilities and Related Data, Civil Works Projects, Annual Reports, Rough River Reservoir, Engineering Form 2527. Louisville, Kentucky: Louisville District, U. S. Army Corps of Engineers, 1959-1965.

17. U. S. Army Corps of Engineers. Rough River Reservoir, F/C 118-6. Louisville, Kentucky: Louisville District, U. S. Corps of Engineers, June 30, 1965.

18. U. S. Army Corps of Engineers. Water Resources Development by the U. S. Army Corps of Engineers in Kentucky. Cincinnati, Ohio: Ohio River Division, U. S. Army Corps of Engineers, January, 1967.

19. U. S. Department of Commerce, Weather Bureau. Kentucky Climatalogical Data, Annual Summary, 1940-1960.

20. U. S. Department of the Interior, Geological Survey. Surface Water Records of Kentucky. Louisville, Kentucky, 1939-1965.

21. U. S. Weather Bureau Agricultural Service Office, Unpublished Evaporation Data, Lexington, Kentucky, 1959-1964.