**US Army Corps of Engineers**
Hydrologic Engineering Center

# Uses of Simulation in River Basin Planning

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Uses of simulation in planning complex multiple purpose water resources are discussed. The Kanawha River Basin in the eastern U.S. is used to illustrate the application of these uses. Uses of simulation include: annual shortage, shortage index, shortage sequence for water quality; draw-down duration for reservoir recreation; desired and required flow maximum flow and flow-duration for stream recreation and fishery.

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# Uses of Simulation in River Basin Planning

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# USES OF SIMULATION IN RIVER BASIN PLANNING[1]

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## INTRODUCTION

Simulation of water resource systems is a necessary part of the planning process. Its usefulness stems from the need to evaluate system response to changes in design variables. Understanding the complex interrelationships among variables and the consequences of various plans can aid the water resources planner and other resource managers in formulating a comprehensive plan of resource development.

The nature of water resources planning is such that representatives from federal, state, and local agencies as well as private organizations are often involved. Each agency has its own ideas on the best development plan and simulation gives the planning agencies responsible a technique for evaluating alternative plans. Since planning is a process which occurs over perhaps several years, having the capability to simulate the operation of many alternative systems is desirable.

The complexity of most water resource systems, the multiple agency coordination and the ambiguity of objectives or goals makes planning a sequential search for improvement. Seeking the optimum development plan has little meaning unless the optimum can be defined, and usually it cannot. So, the

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immediate objective of the planner is to understand the system under consideration and its design variables and to evaluate the ability of the system to meet established targets. Output from simulation for a complex system is usually voluminous, and the selection, analysis, and presentation of these results in a way which reflects important differences between alternative plans is as important to the planner as the simulation model itself.

It is the purpose of this paper to discuss some of the many uses of simulation in planning complex multiple purpose water resource developments. The Type II Comprehensive Planning Study currently being completed for the Kanawha River Basin in the eastern United States is used to illustrate the application of these uses. Not all of the techniques discussed were used directly in the Kanawha study, but were developed during the course of the study and believed by the writers to have sufficient merit to be included.

## KANAWHA RIVER BASIN

### Description

The Kanawha River Basin is the fourth largest basin tributary to the Ohio River. It drains a total of 12,300 square miles of the southern part of West Virginia, west-central Virginia and northwestern North Carolina (Exhibit 1). The largest basin tributary the New River drains 6,920 square miles of the upper basin flowing 250 miles north to its intersection with the Gauley River at Gauley Bridge. The Kanawha River is formed by the confluence of the New and Gauley Rivers and flows northwesterly 97 miles to join the Ohio River at Point Pleasant, West Virginia.

There are four major reservoirs in the basin at the present time - Claytor Lake and Bluestone Lake on the New River and Summersville Lake and Sutton Lake on tributaries to the Kanawha River. Claytor Dam provides an impoundment for water supply to a hydroelectric plant and Claytor Lake has been developed into a popular state recreation area. The other three reservoirs have flood control storage to protect the highly populated and industrialized area downstream in the vicinity of Charleston and are used for recreational purposes. Total storage capacity in the existing system for flood control (winter) is 1,252,100 acre-feet, and 223,500 acre-feet of storage is reserved for flow regulation.

Basin Development

Future water needs include water quality control (streamflow augmentation), reservoir recreation and fishery, stream recreation and fishery, municipal-industrial water supply, and agricultural water supply. The most serious need is to improve the water quality near Charleston. Poor water quality is caused by the discharge of organic chemical wastes from the large chemical complex in the Kanawha Valley. Dissolved oxygen is severely depressed in this area during the summer and early fall. Both waste treatment and low flow augmentation are necessary to significantly improve the quality of the water. Determination of a development plan to meet the water quality needs as well as other needs in the basin was the major reason for using a simulation model.

## SIMULATION MODEL

Alternative plans were simulated on a monthly-flow basis using a generalized simulation model developed by The Hydrologic Engineering Center, Corps of Engineers. Variations of the model have been used in earlier studies for the Williamette and Susquehanna River basins and for the New England Water Supply Study.

The simulation model is capable of handling reservoirs, power plants, diversions and system control points. While the model is applicable to both flood and conservation operation, its most frequent application is for conservation purposes such as water quality, water supply, recreation and hydropower. Travel time between components of the system, e.g. reservoirs and control points, is instantaneous and no provision is made for channel routings or time translations. The model offers a great amount of flexibility for specifying reservoir operating rules, system configurations and target requirements.

Alternative plans for the Kanawha River Basin varied from 13 to 18 reservoirs with 16 control points. Hydrology for the system was based on 38 years of historical record, 1929-1966. While each system operation was evaluated for a variety of conservation purposes, flood control, and hydropower, only three conservation targets - water quality, reservoir recreation, and stream recreation and fishery - will be discussed here. Strategies for meeting these targets, i.e. which reservoirs would operate to meet specific needs, were specified by the planner. Target requirements for various purposes were specified through coordination with the agency responsible.

## EVALUATION OF WATER QUALITY

There are a number of present and anticipated water quality problem areas in the basin where streamflow augmentation in combination with treatment of municipal and industrial waste will be necessary. The most critical reach is the lower Kanawha River near Charleston, West Virginia. Studies by the Federal Water Quality Administration (FWQA) using a mathematical model characterizing the assimilative capacity of the river, resulted in monthly flow requirements in the lower Kanawha to maintain minimum dissolved oxygen levels of 3.0 mg/l and 4.0 mg/l for the years 1985, 2000, and 2020.

During simulation of system operation, conditions develop where the regulated flow is inadequate to meet the water quality target demands. When this occurs, shortages (target flow-regulated flow) are computed on a monthly basis. Of interest are the magnitude, number and sequence of shortages. Using these three parameters the ability of a particular system to meet water quality needs can be evaluated for different shortage tolerances.

Annual Shortage

Table I shows the partial results from a simulation run at a control point where target flows for water quality were specified. These data are useful where shortage tolerance criteria are expressed in terms of shortage probability. For example, to provide a system with a 10% probability of annual shortage, one annual shortage would be tolerated in a 10 year period. For a period of analysis of 38 years, as in the Kanawha-New study, four annual shortages could be tolerated. Evaluating the shortage tolerance in this manner reflects the number of annual shortages but gives no indication of the magnitude or sequence of shortage.

TABLE I

| YEAR | MONTH | TARGET FLOW C.F.S. | REGULATED FLOW C.F.S. | SHORTAGE C.F.S. |
|---|---|---|---|---|
| 1930 | SEP | 10800 | 7539 | 3261 |
| | OCT | 8820 | 995 | 7825 |
| | NOV | 6720 | 1696 | 5024 |
| | DEC | 4940 | 3226 | 1714 |
| 1955 | DEC | 4940 | 4804 | 136 |
| 1965 | NOV | 6720 | 4212 | 2508 |
| | DEC | 4940 | 2736 | 2204 |

## Shortage Index

A measure of the number and magnitude of annual shortages is provided by a shortage index (1) (2). This index, is defined as the sum of the squares of annual shortage ratios for the analysis period, converted to a 100 year base.

$$\text{Shortage Index} = \frac{100}{N} \sum_{1}^{N} \left( \frac{\text{Annual Shortage}}{\text{Annual Requirement}} \right)^2$$

N = period of analysis in years.

Table II shows a partial summary of shortage indices for several alternative plans operating for water quality target flows in the lower Kanawha River. The lower the index the smaller the number or magnitude of shortages. While Plans 2 and 3 have the same number of annual shortages, hence the same probability of failure according to the number of annual shortage criteria, Plan 3 has a lower shortage index thereby indicating it is more adequately meeting the target requirements. Plans 1 and 4 have very nearly the same index, yet Plan 4 has one more annual shortage. Comparing the relative difference of shortage indices between alternative plans has been found to be especially useful in the early planning stages when the differences are greater.

TABLE II

| PLAN | STORAGE (ac-ft) | SHORTAGE INDEX | NUMBER OF ANNUAL SHORTAGES | NUMBER OF MONTHLY SHORTAGES |
|---|---|---|---|---|
| 1 | 2,489,000 | .103 | 3 | 7 |
| 2 | 2,489,000 | .098 | 2 | 6 |
| 3 | 2,499,000 | .089 | 2 | 5 |
| 4 | 2,410,000 | .106 | 4 | 8 |

Shortage Sequence

While no single index is used to measure the magnitude, number and sequence of flow shortages, this information is available in tabular form from the simulation. At each control point where target demands are specified the shortage is computed for each month and year. Critical shortage points in the system can be identified, additional storage or revised operating rules specified, and the accuracy of target demands investigated to improve the system performance and eliminate critical reaches.

Shortage data provided by the simulation model enables the planner to evaluate the system's effectiveness in meeting system targets such as water quality, whether the shortage tolerance is in terms of probability of annual shortages, a specified shortage index, or some other criteria. Although these shortage parameters were used primarily to evaluate water quality targets, they have application to other needs such as water supply, irrigation, hydropower, stream recreation and fishery, etc.

## EVALUATION OF RESERVOIR RECREATION

Following designation of reservoir sites for recreational purposes it is necessary to evaluate their ability to be used for this purpose during system operation. Two important factors which reflect this ability are the magnitude and frequency of reservoir drawdown. While it is desirable to keep all reservoirs at a constant pool level during the prime summer recreation season, it is not practicable when other purposes such as water quality compete for stored water. Whether specified tolerable limits are exceeded in terms of magnitude and frequency depends upon the purposes for which the reservoir is being operated, refill capability, operating criteria, storage volume and topography. By assigning priorities of operation to competing purposes, drawdown in reservoirs utilized for recreation can be delayed. Also, draw-down duration curves can be constructed to evaluate each reservoir's ability to provide a pool fluctuation within tolerable limits.

### System Priorities

Since streamflow augmentation and reservoir recreation are competing uses during the summer months, it is desirable to minimize the competitive aspects by developing system priorities and operating rules which allow the recreation reservoirs to remain as full as practicable during these months. By dividing each reservoir in the system into storage balancing levels according to purpose and by grouping them according to priority of emptying, those reservoirs to be operated primarily for water quality can be drawn upon first, and those designated for prime recreation last. In this way, the magnitude and frequency of drawdown at recreation sites can be minimized while at the same time meeting other downstream targets. Exhibit 2 illustrates this technique. Reservoirs are grouped according to purpose and desired priority of operation. Within each group each reservoir is divided into storage balancing levels. In this case six levels were used. All reservoirs within a group are drawn upon equally to meet those targets for which they operate. In this example only Group I has flood control storage, level 5 to 6, and this storage is exhausted before drawing upon any conservation storage. The conservation storage of Group I between levels 4 and 5, is released to meet power requirements which in turn contribute to meeting downstream water quality targets. Targets served by Group II are met between levels 3 and 4. When level 3 is reach in Group II, the storage between levels 2 and 3, Group III becomes the primary source of water for downstream requirements. At level 2, Groups III and IV are drawn upon.

This grouping and leveling technique provides considerable flexibility for adjusting the magnitude and frequency of drawdown at individual reservoirs.

Drawdown-Duration Curves

For each reservoir, storage frequency data is output on a monthly basis as shown in Table III. Storage is expressed in percent of total conservation storage available (top of conservation storage minus storage at minimum pool) and the frequency each month is the number of months within the 38-year period of analysis the reservoir is within the range of percentage storage. For example, in August the reservoir was within 99-100% of the conservation storage 22 times during the 38 year analysis period.

TABLE III

Storage Frequency Per 38 Years at Location

| Cons Pool | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 99-100 PCT | 31 | 36 | 38 | 38 | 38 | 38 | 31 | 22 | 13 | 9 | 13 | 24 |
| 95-99 PCT | 1 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 0 | 1 | 0 |
| 90-95 PCT | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 1 | 0 |
| 80-90 PCT | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 5 | 0 | 3 | 1 | 1 |
| 70-80 PCT | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 3 | 2 | 0 | 1 |
| 60-70 PCT | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 4 | 1 | 1 | 1 |
| 40-60 PCT | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 3 | 5 | 3 |
| 20-40 PCT | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 8 | 12 | 7 | 3 |
| 1-20 PCT | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 7 | 7 | 2 |
| 0-1 PCT | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 3 |

Using these data drawdown-duration curves can be constructed for each reservoir. Since the summer months (June, July, August) represent high recreational activity, the number of years are combined for these months and percent of time is computed. Exhibit 3 illustrates small, moderate, and severe drawdown conditions.

The effects of 10, 20, or 30 feet of reservoir drawdown, during prime recreation season, are not the same for each reservoir, hence any reduction in benefits that might occur will vary depending on the reservoir and on the magnitude and frequency of drawdown. The drawdown-duration curves graphically illustrate drawdown and are used in conjunction with benefit criteria to evaluate the reservoir's performance for recreation. Reservoirs being drawn down too frequently or too greatly during the prime recreation season are flagged and changes in priority of emptying or reservoir storage allocations are made to improve performance.

## EVALUATION OF STREAM RECREATION AND FISHERY

River reaches with high recreational and fishery potential are evaluated for effectiveness in meeting these purposes according to the magnitude of flow. Three flow conditions are of particular concern: minimum desired flow, minimum required flow, and maximum flow. One evaluation approach is to specify minimum desired (target flow), minimum required and maximum flows at selected control points in the system. Where the regulated flow is less than the required or desired target, a shortage is computed as previously described. A second approach is to simulate the system operation without targets or constraints for stream recreation and fishery and evaluate the resulting regulated flows.

### Minimum Desired and Required Flow

A minimum desired flow requirement would be the optimum flow condition for selected stream recreation and fishery use objectives. The minimum required flow would be a lower flow which could be tolerated by fish life or stream related recreational uses without significant benefit losses. Optimum and minimum flows for fishery and recreation are not necessarily the same and significant differences are taken into consideration in the evaluation procedure.

During normal operation the reservoirs will operate to meet desired flow targets, but when the reservoirs are drawn down during periods of critical low flow, the minimum required flow becomes the target. For both desired and required flows, shortages are computed. As was the case for water quality, the simulation model provides shortage data in terms of magnitude, number and sequence; and shortage tolerance can be evaluated in terms of probability, shortage index or using the data array showing shortages by month and year.

## Maximum Flow

A maximum flow is the maximum monthly flow which could be tolerated by fishery or stream-related recreation uses. While a maximum flow constraint is not generally required to limit streamflows for recreational requirements during low-flow periods, it does offer a means of controlling flow where conflicts occur between purposes. By specifying a maximum flow at any control point, those reservoirs operating for that control point will only exceed the maximum when the reservoir exceeds top of flood control pool. Generally, during conservation operation the result of limiting flow is to increase the time usable storage is available.

## Flow-Duration Curves

Another important output of a simulation run is the natural and regulated flows for each month and year at each control point. With these data flow-duration curves for any period may be constructed. An example for the three month period June, July, and August is shown in Exhibit 4. For this example, a target flow (minimum desired) of 5000 cfs was specified. Under natural river conditions 5000 cfs is equaled or exceeded only about 20% of the time, whereas under regulated conditions 5000 cfs is equaled or exceeded about 80% of the time.

This increased duration is attributable to upstream storage and can be used as a measure of system effectiveness at this point of need. Using these curves a system's performance can be measured without specifying target flows or using maximum flow. This is important in complex systems where several targets make it difficult to determine which targets are driving the system and which reservoirs are affected.

## BENEFIT EVALUATION

Benefits associated with providing water for purposes such as water quality, reservoir recreation, and stream recreation and fishery are computed as part of detailed economic studies conducted by the federal agencies responsible for each purpose. These benefits, which are often difficult to quantify, reflect the dollar value for meeting various water needs. Even more difficult to measure is the reduction in benefits caused when the needs are only partially met. Because of this difficulty, it is desirable to use all available information about system performance. That is to say, additional information is available from simulation that is not reflected in a monetary benefit value but which is useful in evaluating system performance.

### Benefit Allocation to Reservoirs

The simulation model computes benefits for project purposes using single variable benefit functions. Benefits at downstream control points are allocated to the reservoirs supplying the flow in proportion to the volume supplied. Both allocated and unallocated benefits are output together with gross and potential system benefits. Determining the benefits allocated to each reservoir for each purpose over the period of analysis is useful for evaluating its annual contribution to meeting downstream requirements and comparing various storage allocations, operating rules and system configurations. To illustrate this allocation procedure, a simple two reservoir system with one downstream control point is shown in Exhibit 5.

Assumptions regarding release from storage are:

1) The total annual flow contribution by releases from storage equals 100% at control point 3.

2) Release of storage for the downstream point of need will be considered beneficial only up to the regulated flow condition, and will not be considered when the natural or unregulated flow is equal to or greater than the target flow.

3) A reservoir will be credited only when active or usable storage is withdrawn to satisfy a downstream requirement.

Table IV shows flow data at control point 3 by month for one year of operation. Reservoir release data are tabulated in Table V for the three months during which releases were made. Using these data, the contribution of each reservoir is computed - each reservoir is credited each month with a contribution based on its share of the total augmentation supplied for the point of need during the month. Table VI summarizes the computations for the annual contribution of each reservoir. In this example, 57.7% is contributed by Reservoir 1 and 42.3% by Reservoir 2.

TABLE IV

STREAMFLOW DATA - CONTROL POINT 3

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Target Flow, cfs | 900 | 900 | 900 | 1000 | 1500 | 1700 | 1900 | 2000 | 1800 | 1600 | 1200 | 1000 |
| Natural Flow, cfs | 2000 | 2000 | 2200 | 1800 | 1500 | 1200 | 1000 | 800 | 1900 | 1800 | 1500 | 1800 |
| Regulated Flow, cfs | 2000 | 2000 | 2200 | 1800 | 1500 | 1700 | 1900 | 2000 | 1800 | 1600 | 1500 | 1800 |
| Releases, cfs | 0 | 0 | 0 | 0 | 0 | 500 | 900 | 1200 | 0 | 0 | 0 | 0 |
| Percent Total Release, % | | | | | | 19 | 35 | 46 | | | | |

**TABLE V**

**RESERVOIR DATA***

| | Reservoir 1 | | | Reservoir 2 | | |
|---|---|---|---|---|---|---|
| | Jun | Jul | Aug | Jun | Jul | Aug |
| Outflow, cfs | 350 | 530 | 720 | 240 | 435 | 550 |
| Inflow, cfs | 50 | 30 | 20 | 40 | 35 | 50 |
| Change in Storage, cfs | 300 | 500 | 700 | 200 | 400 | 500 |

* Evaporation assumed zero.

TABLE VI

PERCENT CONTRIBUTION EACH RESERVOIR

| | Monthly % Contribution | | | |
|---|---|---|---|---|
| Reservoir | June | July | August | Annual Total |
| 1 | 11.4%** | 19.5% | 26.8% | 57.7% |
| 2 | 7.6% | 15.5% | 19.2% | 42.3% |
| Total | 19.0% | 35.0% | 46.0% | 100% |

**June % Contribution Reservoir 1 = $\frac{300 \text{ cfs}}{500 \text{ cfs}} \times (19\%) = 11.4\%$

Summing the annual contributions over the analysis period indicates the total percent contribution of each reservoir toward meeting a particular flow requirement. In this example, only flow values were used. When using simulation, a benefit function based on dollar value or on percent total benefit can be input. The resulting output is the total average annual allocated benefits at each reservoir for each purpose. Using these data, percent contributions may be calculated.

The important point is that, by computing each reservoir's contribution to meeting system targets, useful information is provided to compare the relative performance of the reservoirs and to identify those where improvements need to be made.

Reservoir Recreation Benefits

As discussed earlier, magnitude and frequency of drawdown are important factors in evaluating a reservoir's effectiveness for providing recreation and may be represented by duration curves constructed from simulation results. Another use of these data is to apply benefits functions to drawdown conditions - either in terms of magnitude or frequency. To illustrate this, consider the drawdown-benefit curve in Exhibit 6. Such a curve could be developed by considering decreased reservoir surface area resulting from drawdown, and of the effect of recreational facility development on contiguous lands.

Exhibit 7 depicts a typical distribution of monthly recreation benefits (in percent) occurring during the year. From the curve, 65% of the annual benefits occur during June, July, and August, the prime recreation season; combining the two curves, monthly benefits-drawdown functions can be constructed (Exhibit 8). This function can be input to the simulation model for computing average annual benefits (percent realized) occurring over the period of analysis.

The complement of this would be the percent benefits lost because of reservoir drawdown.

## CONCLUSION

Simulation of reservoir system operation for the Kanawha River Basin has been found to be a very versatile and powerful tool during the planning process. Simulation data can be used in many different ways to help the planner understand the performance of alternative plans in meeting basin water needs. A few of these uses have been described in some detail in this paper. There are, of course, other uses of these and other data.

When planning complex water resource systems many questions are asked by many persons representing a diversity of interest. Rarely has the plan progressed to the point where all design variables are specified and all necessary data is available. Using simulation, the planner has an effective learning tool. A tool which answers many question, and asks many new ones, but when used properly helps to achieve the ultimate objective - a comprehensive development plan.

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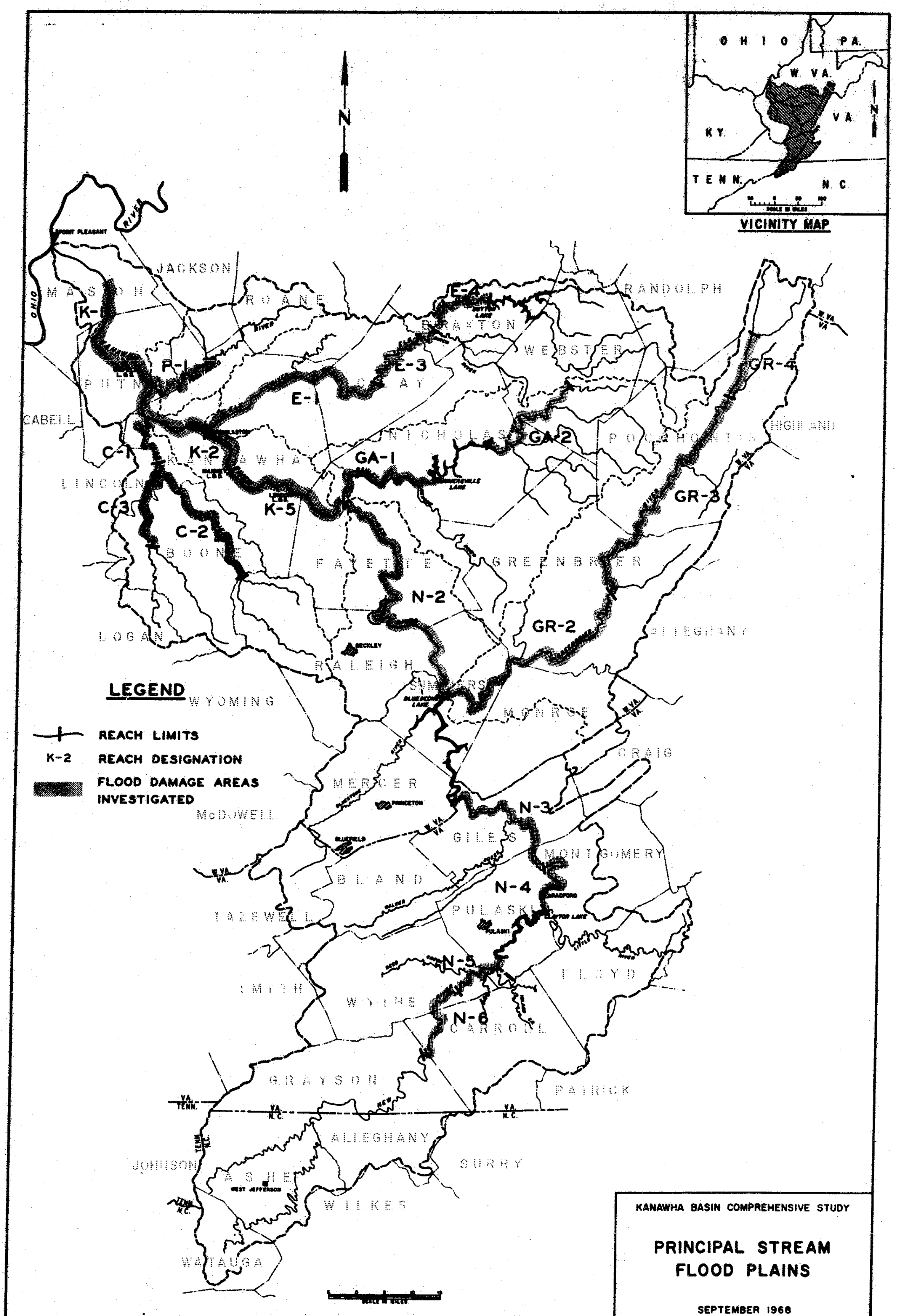
2. Close, Edward R., et al, 'Objective Determination of Safety Factor in Reservoir Design', Journal of Hydraulics Division, ASCE, Vol. 96, No. HY 5. May 1970, pp 1167-1177.

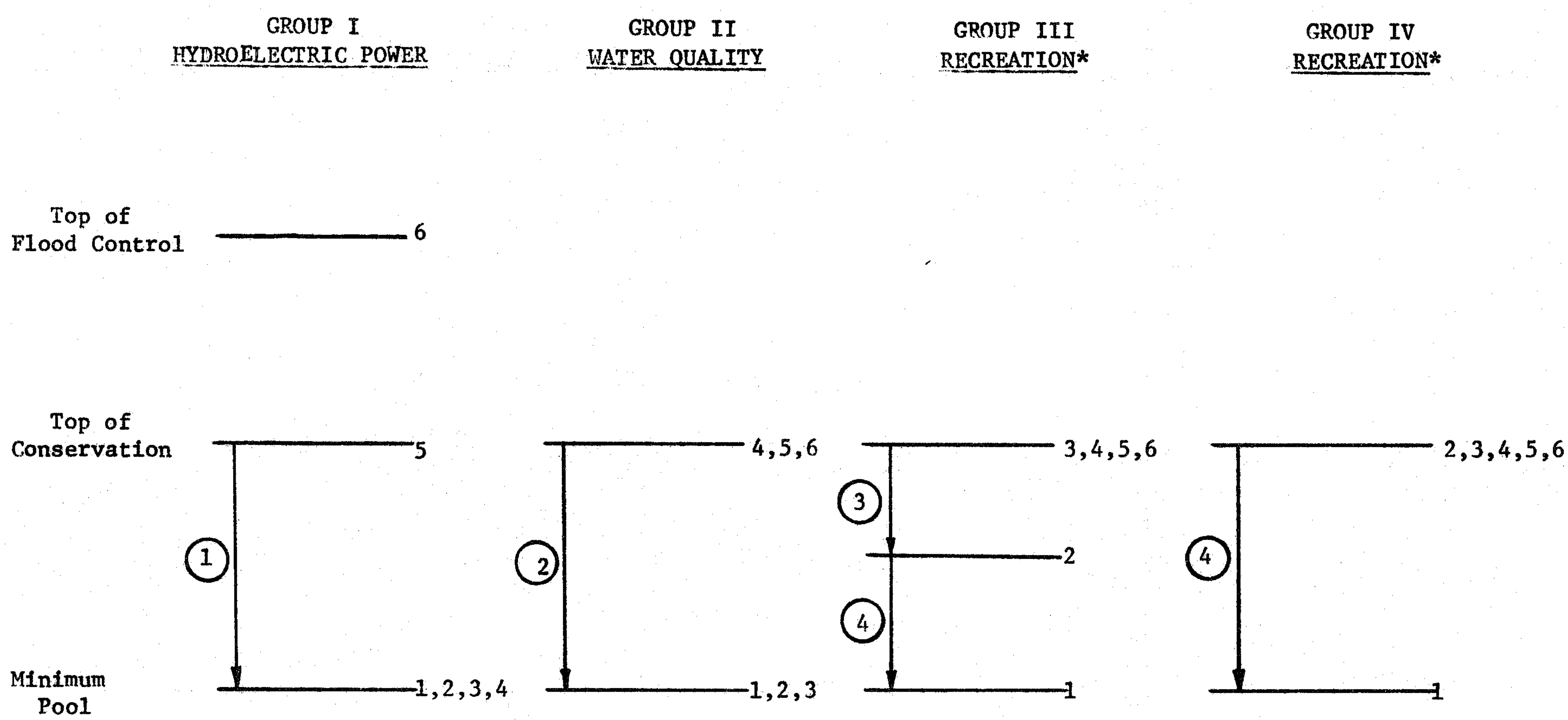



KANAWHA BASIN COMPREHENSIVE STUDY

PRINCIPAL STREAM FLOOD PLAINS

SEPTEMBER 1968

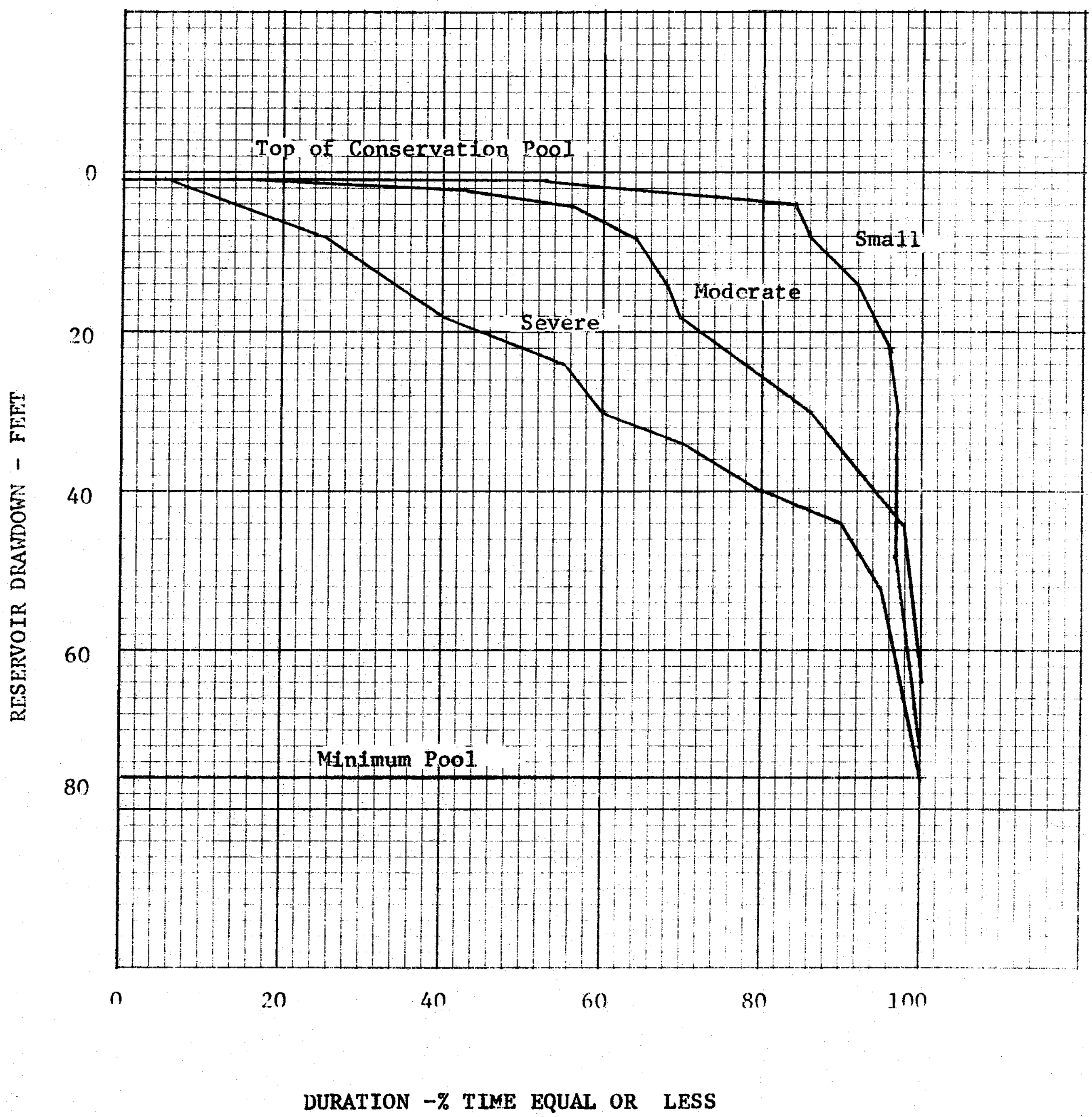
EXHIBIT NO. I




RESERVOIR SYSTEM
PRIORITY OF OPERATION

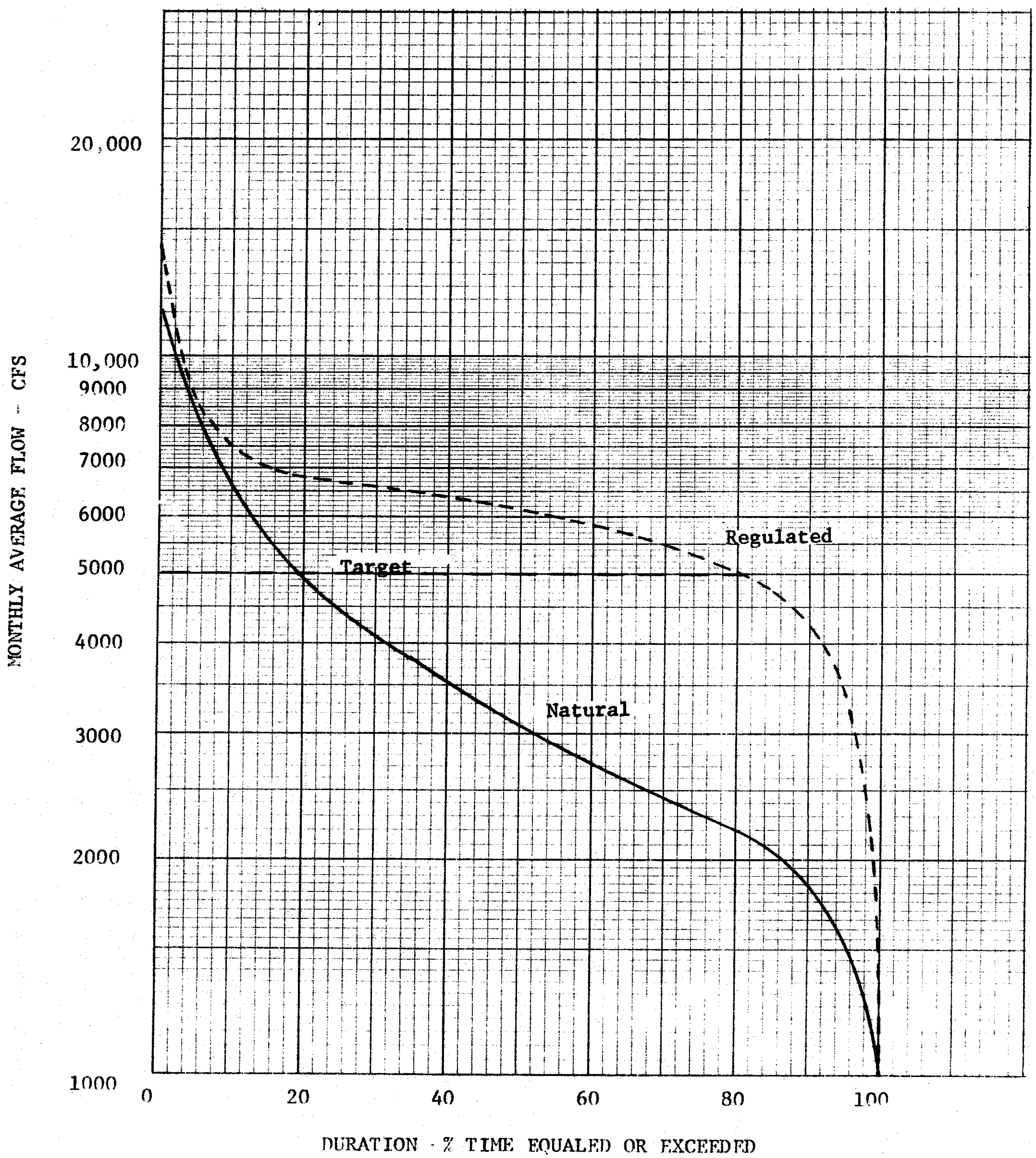
*Major project purpose

EXHIBIT 2



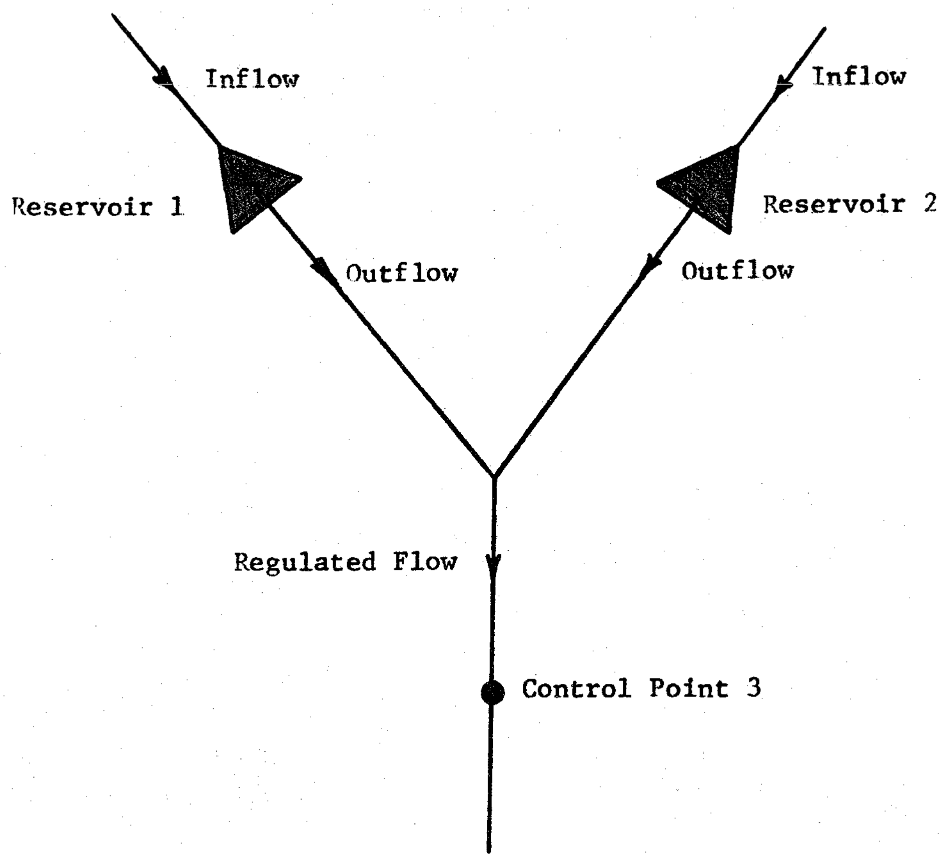

RESERVOIR DRAWDOWN-DURATION CURVES

EXHIBIT 3




FLOW DURATION CURVE
Period: June, July, August

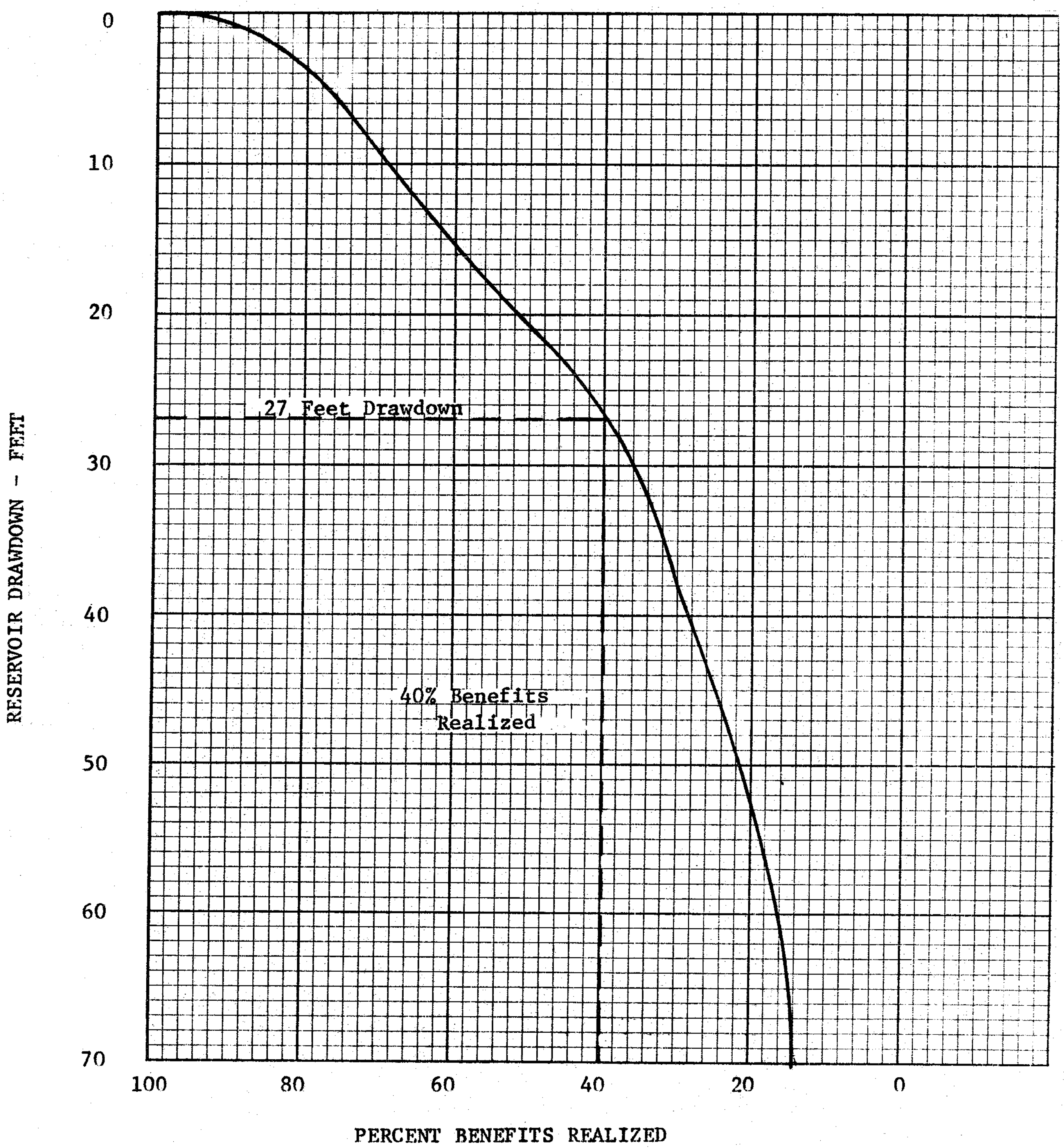
EXHIBIT 4




BENEFIT ALLOCATION

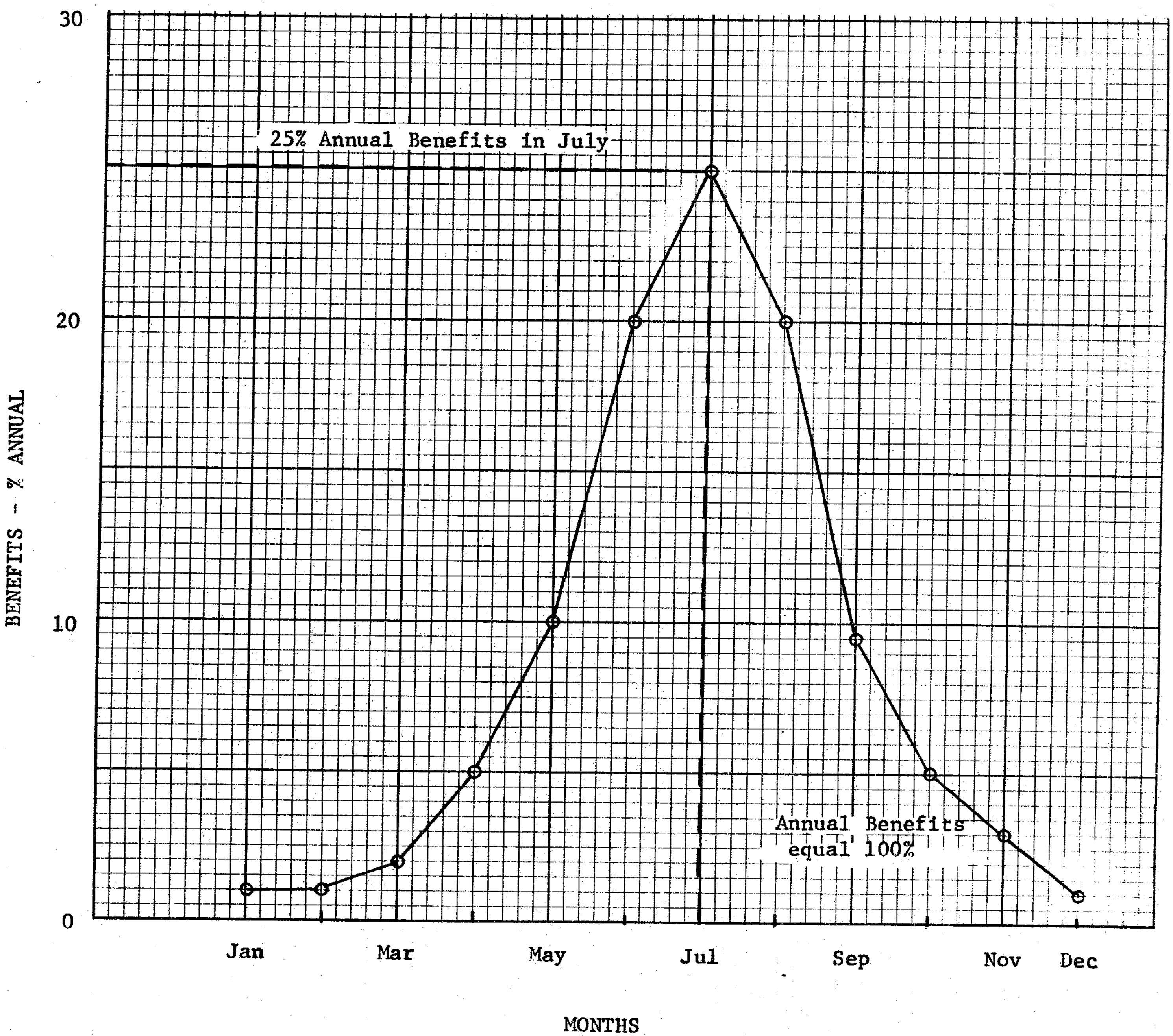
TWO RESERVOIR SYSTEM

EXHIBIT 5



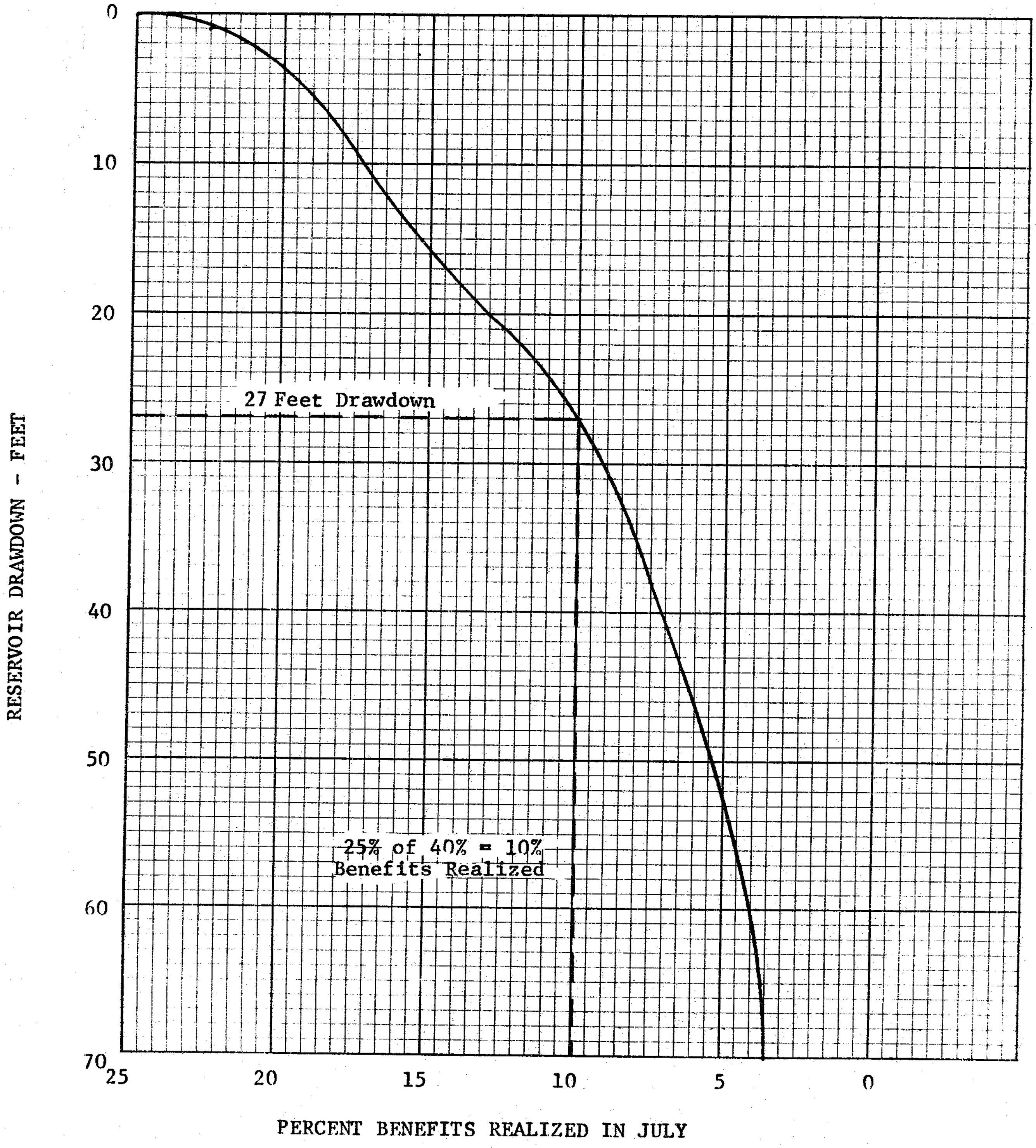

DRAWDOWN - RECREATION BENEFIT CURVE

EXHIBIT 6




MONTHLY DISTRIBUTION OF
RECREATION BENEFITS

EXHIBIT 7




DRAWDOWN - RECREATION BENEFIT
CURVE FOR JULY

EXHIBIT 8

# Technical Paper Series

TP-1 Use of Interrelated Records to Simulate Streamflow
TP-2 Optimization Techniques for Hydrologic Engineering
TP-3 Methods of Determination of Safe Yield and Compensation Water from Storage Reservoirs
TP-4 Functional Evaluation of a Water Resources System
TP-5 Streamflow Synthesis for Ungaged Rivers
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