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

# Hydroelectric Power Analysis in Reservoir Systems

**August 1970**



TP-24

# REPORT DOCUMENTATION PAGE

*Form Approved OMB No. 0704-0188*



| 1. REPORT DATE *(DD-MM-YYYY)* | 2. REPORT TYPE | 3. DATES COVERED *(From - To)* |
|---|---|---|
| August 1970 | Technical Paper | |

**4. TITLE AND SUBTITLE**
Hydroelectric Power Analysis in Reservoir Systems

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Augustine J. Fredrich

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5F. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center (HEC)
609 Second Street
Davis, CA 95616-4687

**8. PERFORMING ORGANIZATION REPORT NUMBER**
TP-24

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

**10. SPONSOR/ MONITOR'S ACRONYM(S)**

**11. SPONSOR/ MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION / AVAILABILITY STATEMENT**
Approved for public release; distribution is unlimited.

**13. SUPPLEMENTARY NOTES**
Presented at the ASCE Hydraulics Division Specialty Conference, Minneapolis, Minnesota.

**14. ABSTRACT**
In recent years there has been an increasing need for analytical techniques for use in studies related to the planning, design, and operation of water resource multi-purpose systems. The inclusion of hydropower as a project purpose introduces special problems because of the non-linear relationship between water and power production and because of the marked disparity between project purposes.

A generalized digital simulation model (HEC-2) is proposed to be used in attempting to study water resource problems of this type. This model permits evaluation of reservoirs, power plant diversions and control points in any configuration desired. Although the model is designed for use in analysis of conservation purposes, some consideration is given to flood control constraints. Use of the model on the Arkansas-White-Red River System is presented and discussed by the author.

**15. SUBJECT TERMS**
reservoir systems simulation, multi-purpose operation, sequential routing, power systems, computer applications

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | |
| U | U | U | UU | 22 | 19b. TELEPHONE NUMBER |

**Standard Form 298** (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

# Hydroelectric Power Analysis in Reservoir Systems

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US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

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# HYDROELECTRIC POWER ANALYSIS IN RESERVOIR SYSTEMS[1]

By

Augustine J. Fredrich, M. ASCE[2]

## INTRODUCTION

Although the pace of development of conventional hydroelectric facilities in multiple-purpose projects has diminished somewhat in recent years, the operational requirements for existing systems and the requirements of comprehensive basin planning in basins where there are existing power facilities have caused a continuing need for analysis of hydropower potential and capability in reservoir systems. But the emphasis on multiple-purpose water resources development and use and the increasing awareness of water problems on the part of large segments of society have limited the usefulness of single-purpose operation and single-purpose analysis. Consequently, in recent years there has been a growing need for analytical techniques for use in comprehensive studies related to the planning, design, and operation of water resource systems. The inclusion of hydroelectric power as one of the purposes in a system creates special problems because of the nonlinear relationship between water and power production and because of the frequency with which there is a marked disparity between the projects comprising a hydroelectric system and the projects comprising the hydraulic system in the same region.

Although mathematical methods such as linear and dynamic programming have been reported to be of significant value for use in some planning studies and are believed to be of value in some types of operation studies, it is doubtful that

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(1) Presented at the ASCE Hydraulics Division Specialty Conference, Minneapolis, Minnesota, August 1970.

(2) Chief, Research Branch, The Hydrologic Engineering Center, 609 Second Street, Davis, California 95616.

any of these mathematical methods could form the core of an analysis of an existing system or of a proposed system where there are existing components. Because of the complex interactions among the various purposes and because of the numerous physical, legal, social, and institutional constraints inherent in most systems, it has been found that digital simulation is one of the most effective techniques for studying and evaluating system performance.

## THE SIMULATION MODEL

A generalized digital simulation model for use in studying water resource systems has been developed by The Hydrologic Engineering Center and is in use in several Corps of Engineers offices. This generalized model permits evaluation of as many as 50 reservoirs, power plants, diversions and control points in any configuration. Any number of purposes can be studied in a sequential routing study with routing intervals as short as a week. Although the model was designed for use in analysis of conservation purposes in situations where the time variation of flow within the routing interval is unimportant, some consideration is given to flood control constraints. Multiple hydraulic systems can be accommodated in a single run as can multiple power systems. Also, the power systems are not required to coincide with any of the hydraulic systems.

By developing a system model through specification of reservoir and power plant characteristics, system configuration, and physical and hydrologic constraints, the system response under a variety of historical or synthetic conditions can readily be analyzed. For example, by supplying historical hydrologic data and alternative operating plans the response of the system to the various plans of operation could be determined. The response could be measured in terms of power production, reservoir storage fluctuation, water supplied for navigation, or any other parameter chosen by the user. Similarly, with fixed operating criteria a user could supply several critical hydrologic data sequences to test the versatility of the operating criteria and the degree to which they provide adequate operation under critical conditions not experienced in the historical record. Other problems which usually require changes in operating rules and which could be readily studied with this model include: changes in physical conditions in the system such as changes in channel capacity or power transmission lines, addition of new components to the system, addition of new purposes, changes in criteria or priority of existing purposes, and alteration of legal or institutional requirements.

A relatively unique feature of the generalized model is that it is constructed in a way which permits the user to specify the relative response of each component in the system to a system demand which can physically be supplied by one or more components in the system. This allows the user to specify any type of "balance" that he wishes to see maintained in the system and to evaluate the effects of alternative operation objectives. Target storage levels for each reservoir are used to create the balance or imbalance desired by the user. There can be as many as eight of these levels for each reservoir in the system and the levels can be different for each routing interval if desired. Although monthly routing intervals are frequently used, the interval may be of any length, and it is not necessary for each interval to be of the same length. By using different target storage levels for each interval the seasonally varying rule curves which have been used for reservoir operation quite frequently in the past can be specified.

The general method of analysis used in the model is to consider each reservoir project in downstream order. At each reservoir the at-site demands are met, and the capability of the project to supply water for system demands is determined by an index which is based on water stored in the reservoir and on the physical and hydrologic constraints applicable to that project. After all projects have been studied in this manner the sums of the at-site productions are obtained for the various water and power systems and these are compared with the system requirements. If the sums of the at-site productions exceed all of the pertinent requirements for the various systems the operation for that period is satisfactory and complete. If any system requirement exceeds the sum of the at-site productions for any water or power system, the amount of deficit is computed, the projects that are capable of supplying water or power to reduce the deficit are identified, and an allocation of the deficit is made among these projects. These allocated quantities are, in effect, added to the at-site demands to create new demands, and the entire evaluation begins again for the period. This process is continued until all system demands are satisfied or until there is no water available to supply the demands.

Initially it was decided that the computations for power and water demand should not be separate. The effect of this decision was to apply hydroelectric power constraints at the same time that other physical and hydrologic constraints were applied to estimate capability for meeting system demands. This proved to be infeasible because of the effect of estimating average head, the effect of tandem power projects, and the effects of multiple ownership projects on a single stream. The problem was resolved by providing separate computation sequences for calculating power potential for each power system in addition to the computation sequence of calculating water availability.

## PROBLEMS IN IMPLEMENTATION OF THE MODEL

One problem encountered in using the model is the lack of information on maximum and minimum limitations for usable power generation. For example, it is known that usually some minimum generation is required to maintain streamflow below a project, and furthermore the minimum can usually be related to the load requirements for the power system, but definitive information on minimum generation is not readily available. Likewise, there is a maximum amount of energy generation that is usable on a given load without special arrangements--particularly if a project is operated for peaking purposes. And, again, information as to the nature of this limitation has not been found to be easily obtainable.

In addition to the foregoing problem, a major factor which has impeded the application of this model has been an inability to quantify operational objectives for existing systems. Quite frequently the approach has been to obtain from the operating entity as much information as possible, simulate the operation for a recent historical period using that information, compare the results with the actual operation, question the operating entity about discrepancies, revise the operational criteria and resimulate the operation. The process must be repeated until a reasonable simulation is obtained. This is, however, a valuable part of the overall study because it forces the engineer to identify and quantify operation objectives. In cases where the current operating plan has evolved from piecemeal revisions of old policies this is a very valuable exercise.

Another major problem associated with simulation studies of reservoir systems is the tremendous volume of output generated in the study. With this model one can easily produce in a week or two far more output than can be intelligently analyzed by many people in a year or so. The roots of the problem and the key to its solution are in the presimulation planning. Carelessly thought-out, limited-objective studies with poorly documented criteria almost always result in studies of only limited utility. These studies frequently are not worth documenting and consequently a valuable link in a chain of studies can be lost--making it impossible to trace the logic of the sequence of studies after some time has passed. In early stages of a simulation study the proper answer to any question always seems to be "perform another simulation". However, as the unanalyzed or partially analyzed studies pile up, it becomes evident that this is not only not the proper answer--it is a very poor answer. There is no substitute for a well-planned, properly executed, carefully documented simulation study. Resisting the temptation to perform analyses as rapidly as possible leads to the discovery that a little planning for a single simulation analysis can answer many questions and save immeasurable time and manpower. Also, a little forethought in identifying output parameters of value or of interest is well worthwhile. It is much easier and much less costly to have the computer calculate and print out parameters of interest than to have to develop them from the output by hand.

## ARKANSAS-WHITE-RED RIVERS SYSTEM STUDY

One of the major studies on which the previously described model has been used is a study of system conservation operation in the Arkansas-White-Red River basins. In this study 23 existing or authorized reservoir projects located in three hydraulically independent but electrically interconnected river basins are being studied. The locations of the projects are shown in figure 1. The projects serve several different purposes: flood control, hydroelectric power, water supply, navigation, fish and wildlife, water quality, and recreation. Not all purposes are served by each project, but almost all of the projects serve at least two purposes.

Although the three basins are electrically interconnected so that system power demands could theoretically be met by any one of the 19 power projects in the three basins, there are legal and institutional constraints which create special marketing problems which in turn create special analysis problems. There are no physical facilities for diversion of water among basins so all demands for water for any purpose must be met by projects within the basin where the demand occurs. Again, legal and institutional constraints limit the services which can be provided from some of the reservoirs so that it is not always possible for all projects which have the physical capability to supply water for a given demand to do so.

The reservoir projects range in size from 4,350,000 acre-feet of usable multiple-purpose storage to 19,000 acre-feet of power pondage. The total installed capacity of the hydroelectric projects is almost 2 million kilowatts. The projects are owned by the Federal Government (20 projects), state governmental agencies (2 projects) and a privately owned utility (1 project). The power projects are interconnected and their outputs marketed in a way which, for purposes of the study, creates three power subsystems which must be analyzed separately. As shown on figure 2, the Bull Shoals and Table Rock projects are interconnected and their output is marketed to an area which has a seasonally varying demand with a substantial peak demand during the winter. The non-Federal projects (Ozark Beach, Markham Ferry and Pensacola) are operated by their owners, and their output is not marketed by the Federal marketing agency. Consequently, they form a system with water outputs that contribute to the Federal power supply. The remaining 14 projects are interconnected and they comprise a third system. The output from these projects is marketed in an area with a seasonally varying demand with a substantial peak demand in the summer. Furthermore, a portion of the output of the Denison project is marketed to utilities in Texas which are not connected to the utilities in the major marketing area. Therefore, this output must be deducted from the total power output of Denison before calculating Denison's contribution to the main system.

The bulk of the power demand in the market area is met by thermal generation, and the hydroelectric generation is usually primarily to meet peaking demands. More than 400,000 kilowatts of the 1,112,000 kilowatts of installed capacity in the large Federal system is located at navigation lock and dam projects. The storage at these projects is only adequate to sustain peaking generation for daily or, at most, weekly cycles. Since the storage volume upstream of these essentially "run-of-river" projects is not large with respect to the water required to provide energy to support this installed capacity, and since there are no physical facilities for diversion of water from the large storage projects in the White and Red River basins, the power generation allocations among the basins must be carefully planned to fully utilize the available streamflow and meet the system power demands. The development of operation criteria to accomplish this allocation effectively is a major part of the problem of operating the hydroelectric system.

In arranging to market the hydroelectric power it is necessary to provide for the capability to purchase thermal energy to support the hydroelectric capacity during periods of deficient streamflow. Since the thermal purchases represent a cost which must be deducted from the revenues obtained from the sale of the hydroelectric energy, it is not sufficient to simply maximize the hydroelectric energy production. Instead, the hydroelectric generation must be integrated with the thermal purchases in a way which minimizes the thermal purchases without endangering the capability of the hydroelectric plants.

The operation of the system is studied by simulating its performance through 45 years of historical hydrologic data. The range of hydrologic events during this period is believed to be such that it includes representative critical conditions for evaluating alternative operating plans and gives a reasonable approximation of the long-term average output of the system. The volume of output data resulting from a single simulation study of this system is so large that major efforts have been made to produce graphical and tabular summaries to minimize the amount of data which must be reviewed upon completion of a simulation analysis.

Operation guides of the type shown in figure 3 are currently being considered for development and implementation. Guides of this type, based on performance of the system during the historical hydrologic record would be very valuable in determining the timing and quantities of thermal purchases. System energy in storage, the parameter used on plate 3 to indicate the state of the system in making the decision to purchase energy, is believed to be a better indicator than, say, water in storage in the system. However, it is anticipated that problems may arise with respect to this parameter because of the run-of-river plants on the Arkansas River being unable to avail themselves of the benefits of storage on the White and Red rivers. It is anticipated that future studies may require modification of this parameter to reflect the consequences of the inequitable storage distributions. The application of weighting factors to the computed energy in storage in each basin before developing a system composite value for energy in storage would be one way of modifying the parameter.

Further plans for the model include provisions for more flexible output arrangements including better graphical and tabular summaries of study results. Also, it would be desirable for the model to have the capability for at least limited self-optimization. However, the feasibility of providing this capability is dependent on progress in quantifying the objectives of operation and on obtaining consistent and comparable measures of value for all project purposes.

## SUMMARY

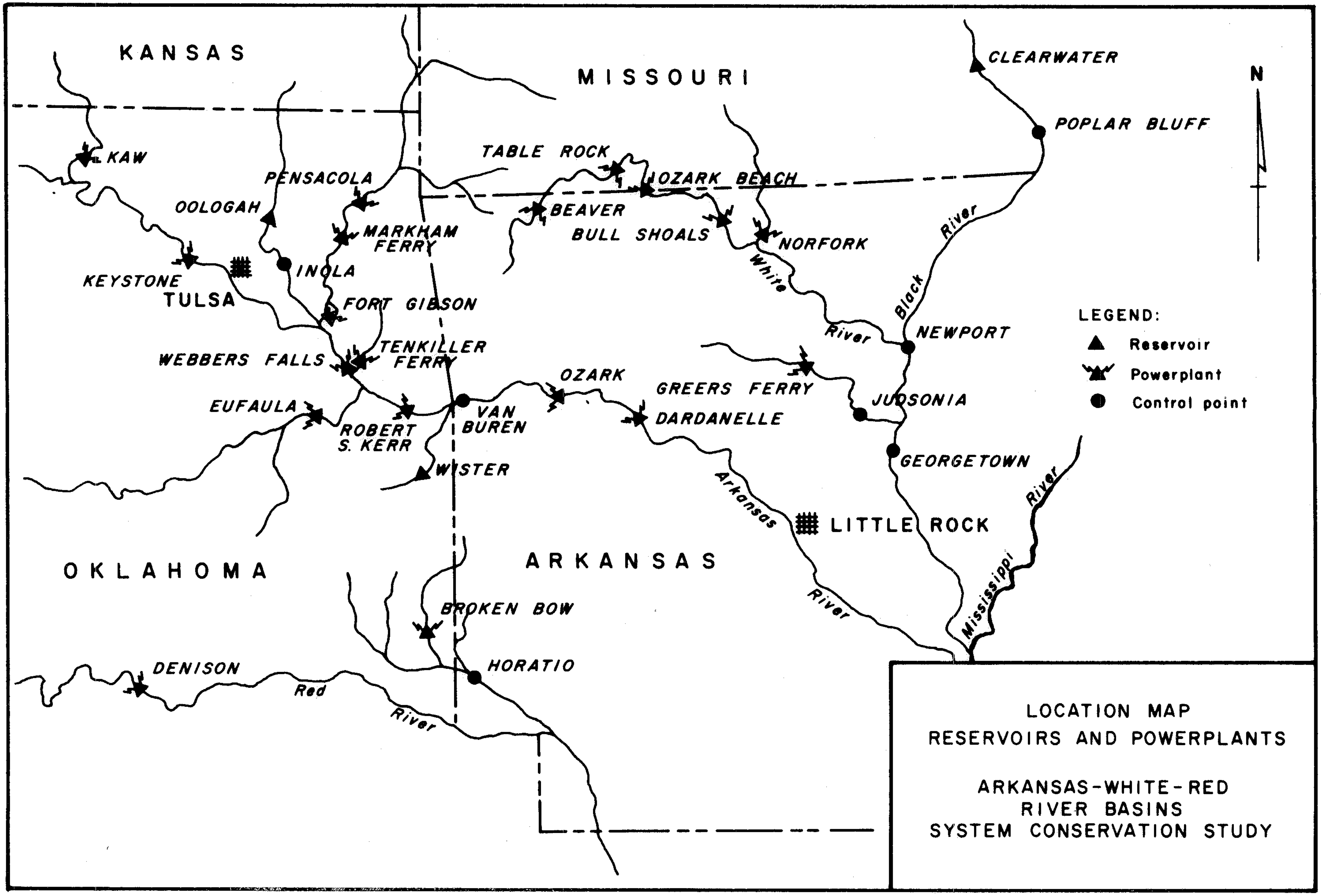
The need for comprehensive studies of multiple purpose operation in large water resources systems is increasing at a rapid pace because of the increasing interest in all facets of resources use and management. At the present time mathematical analysis do not appear to be amenable to these comprehensive studies because of the difficulties involved in complete representation of all pertinent factors that influence the operation of large systems. The use of digital simulation in the study of large, complex systems indicates that a relatively complete analysis and evaluation of multiple purpose operation can be achieved. In particular, the results obtained in the study of the Arkansas-White-Red Rivers system indicate that the primary constraints on further analyses are in the area of defining and quantifying operation objectives. Also, the present studies indicate the necessity for developing consistent measures of utility or worth for all water uses so that operation conflicts can be properly resolved.

The digital simulation model described herein can be employed effectively in studies that require comprehensive analyses of hydroelectric power and other purposes in large systems. However, the need for better information concerning many operation constraints is apparent. Also, the necessity for developing better procedures to document the assumptions and criteria for simulation studies and the need for better methods of reviewing and analyzing the study results are evident.

ACKNOWLEDGEMENTS

The digital simulation model described herein was developed by Mr. Leo R. Beard, Director of The Hydrologic Engineering Center. Mr. David C. Lewis of the HEC staff, Messrs. Pat Davis and Bill Swanson of the Southwestern Division office of the Corps of Engineers, and Messrs. Gerald E. Thomas and Jim Dalton of the Little Rock District office of the Corps have all participated actively in the Arkansas-White-Red Rivers system study described herein.

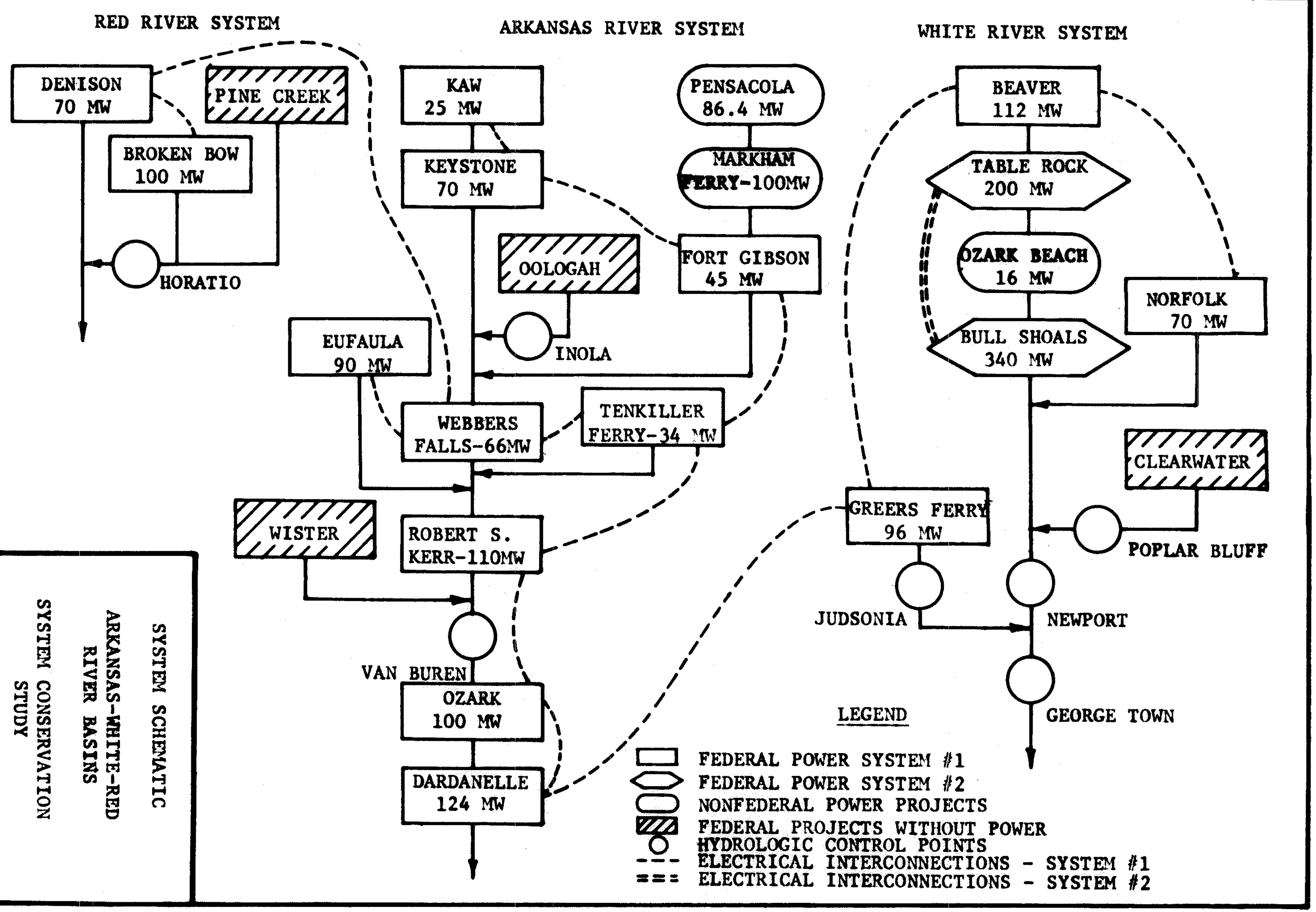
The views expressed herein are those of the author and do not necessarily reflect the policies of the Corps of Engineers.




LOCATION MAP
RESERVOIRS AND POWERPLANTS

ARKANSAS-WHITE-RED
RIVER BASINS
SYSTEM CONSERVATION STUDY

PLATE I




SYSTEM SCHEMATIC

ARKANSAS-WHITE-RED RIVER BASINS

SYSTEM CONSERVATION STUDY

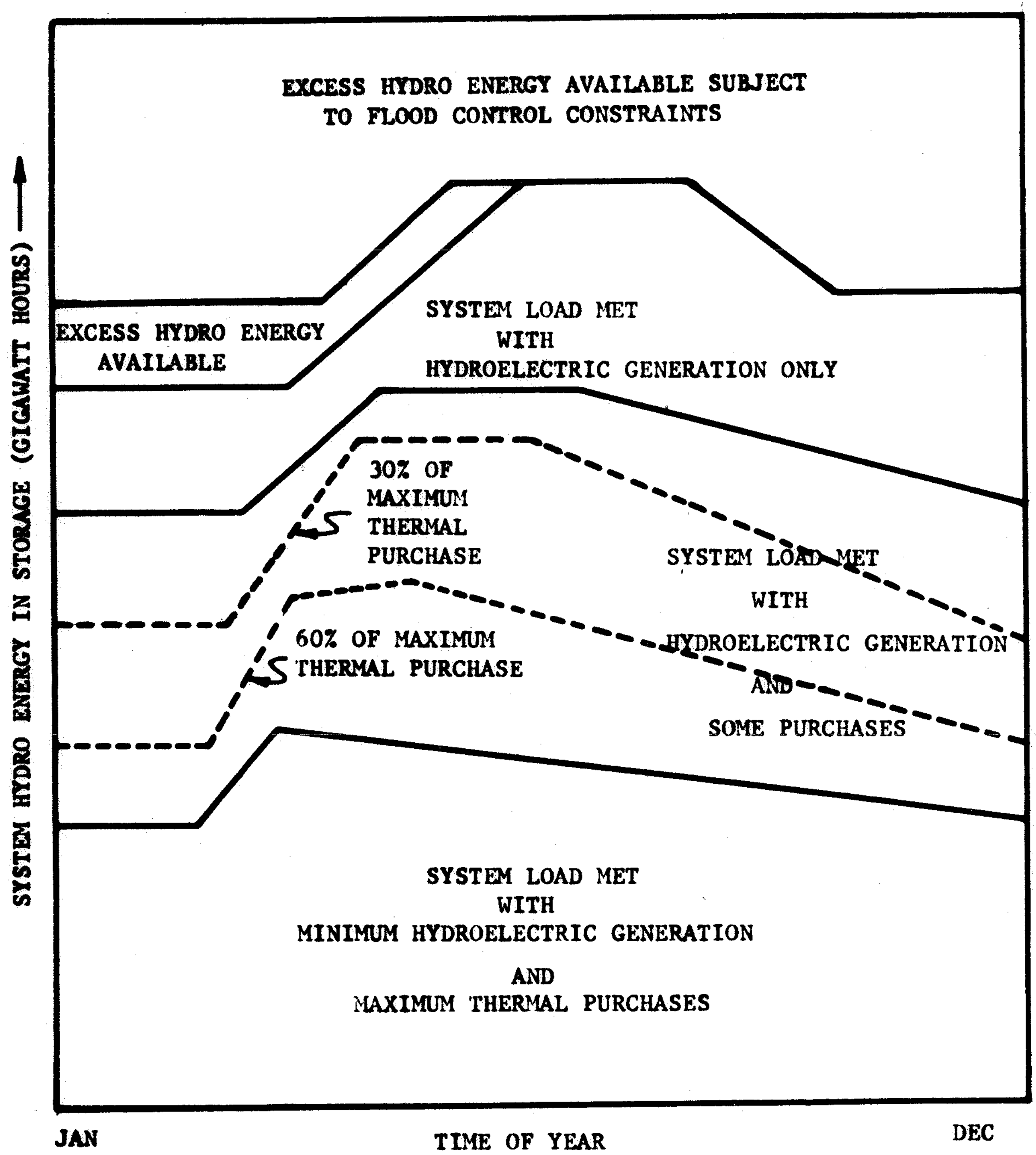



ILLUSTRATION OF SYSTEM OPERATING CURVES

ARKANSAS-WHITE-RED RIVER BASINS

SYSTEM CONSERVATION STUDY

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