US Army Corps
of Engineers

The National Study of Water Management During Drought

A PRELIMINARY ASSESSMENT OF CORPS OF ENGINEERS' RESERVOIRS, THEIR PURPOSES AND SUSCEPTIBILITY TO DROUGHT

September 1991

IWR Report 91-NDS-2

National Study of Water Management During Drought Reports

This report is part of a series of reports which will be published during the study.

Report on the First Year of Study (IWR Report 91-NDS-1) was published in May 1991. The Corps of Engineers began the study after the severe droughts of 1988. The primary objective of the study is to find strategies to improve water management during droughts in the United States. The report explains how and why water is managed the way it is now, lists the impacts of drought, the problems in the current water management system, and the roadblocks to change for the better. It presents three recommendations which will be pursued in the remainder of the study.

An Research Assessment (IWR Report 91-NDS-3) was published in August 1991. Planning Management Consultants, Ltd. critically reviews reported impacts of past U.S. drought, the factors that affect vulnerability, and the current state of preparedness throughout the U.S. The report also highlights some innovative approaches to drought preparedness throughout the U.S. that are now being used in parts responding to drought. Finally, the report suggests the areas where further research would be most productive.

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A PRELIMINARY ASSESSMENT OF CORPS OF ENGINEERS' RESERVOIRS, THEIR PURPOSES AND SUSCEPTIBILITY TO DROUGHT

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Contents

FOREWORD

Recent droughts in the United States have caused water management agencies to examine the operation of their facilities to develop ways to improve their capability for providing water during times of short supply. During fiscal year 1990 the Corps of Engineers received initial funding from Congress to examine their facilities to develop a consensus on water resource priorities for management during drought, provide a base of information for such management, and to formulate and evaluate alternatives to improve their current systems. The Institute for Water Resources, Corps of Engineers was given the responsibility for what has become known as the National Study of Water Management During Drought. As one part of this study, the Hydrologic Engineering Center was asked to conduct a preliminary assessment of the susceptibility of Corps of Engineers' reservoirs to drought. This document is the product of that effort.

Analyses presented in this report use data from computer databases developed or obtained by the Hydrologic Engineering Center as part of its Reservoir Database Network. With the network, data describing Corps of Engineers' reservoirs and their purposes are linked to databases on drought, precipitation, temperature, evaporation, streamflow, recreation and population which are maintained by other agencies. The Corps of Engineers' reservoirs used in this study are listed by division office in Appendix 2. Database analyses were made using R:Base for DOS by Microrim Inc. Geographic data for the United States and sub-regions were analyzed and displayed using a Geographic Information System (GIS), PC ARC/INFO by Environmental Systems Research Institute, Inc.

While databases played an important and necessary part in this study and made both national and regional assessments possible, the reservoir data for the analyses and much helpful information were provided by personnel from water control and planning in the Corps of Engineers' field offices. Their assistance is greatly appreciated.

Roger Kohne made excellent contributions throughout the study and is responsible for the technical work with the databases and the analyses with climate divisions, precipitation and runoff. Rochelle Huff contributed significantly through the application of her exceptional computer skills to GIS. Marcus Linden prepared the sections on congressional authorizations and growth of water use in the United States. Jeanne Takeuchi assisted with the research on historical droughts. The report was typed, and the graphs and tables creatively finalized, by Chris Brunner. Bill Johnson served as project engineer for the study. Mike Burnham, Chief, Planning Division and Darryl Davis, Director, Hydrologic Engineering Center supervised the project.

INTRODUCTION

Purpose and Scope

This report examines 516 Corps of Engineers' reservoirs, including locks and dams, in the continental United States and describes the purposes they serve and the type and volume of their storage capacity. It also discusses drought: its occurrence, duration, frequency, severity, and relationship to Corps' reservoirs. The report is a preliminary look at these subjects. It is intended to inform the reader about Corps of Engineers' reservoirs, their purposes, and to assist in their effective planning and management for drought.

The word "reservoir" as used throughout this report includes 144 locks and dams. While a lock and dam is usually distinguished from a reservoir by its capacity to pass waterway traffic and its small storage volume, it may, however, serve purposes other than navigation. Some Corps' locks and dams serve one or several additional conservation purposes: recreation, hydroelectric power, irrigation, low-flow augmentation, municipal and industrial water supply, and fish and wildlife. In this way locks and dams are similar to reservoirs. Because the emphasis here is on project purposes and their susceptibility to drought, it is felt appropriate to discuss the two facilities under one category, reservoir. The difference, however, is recognized and is documented in Appendix 2 where all projects included in this study are listed.

The purposes described in this study are the day to day operating purposes served by a reservoir. They include the original authorizing purposes, but are not limited to them. Since an objective of the study is to discuss the affects of drought on all uses made of water stored in Corps' reservoirs, it is important to include all purposes even though some came through later general Congressional authorizations.

There are three principal sections to this report. The first examines reservoirs, purposes and drought for the nation. It provides a national assessment. Each region, however, is unique in the types and characteristics of its reservoirs and river systems, the purposes served, and the nature of drought. A second section, therefore, provides a regional assessment. It focuses on the reservoirs, purposes and droughts in the ten regional divisions of the Corps in the contiguous United States (Appendix 1). Conclusions and recommendations for future work are derived from the national and regional assessments. A third section of the report is the appendices. Here details are presented on the geographic boundaries of Corps' district and division offices, the individual reservoirs used in the analyses of the study, and the methodology for computation of the Palmer Drought Severity Index. This index is used to characterize and analyze regional drought.

Congressional Authorizations

The United States Congress authorizes the purposes served by Corps of Engineers' reservoirs at the time the authorizing legislation is passed. The Congress commonly authorizes a project "substantially in accordance with the recommendations of the Chief of Engineers", as detailed in a separate congressional document. Later, additional purposes are sometimes added, deleted, or original purposes modified, by subsequent congressional action. When the original purposes are not seriously affected, or structural or operational changes are not major, modifications may be made by the Chief of Engineers (Water Supply Act, 1958).

The Congress also passes general legislation that applies to many projects. The 1944 Flood Control Act, for example, authorizes recreational facilities at water resource development projects. This authority has made recreation a significant purpose at many reservoirs. Similar general legislation, for example, has been passed for fish and wildlife (1958) and wetlands (1976). The Water Resource Development Act of 1976 authorizes the Chief of Engineers, under certain conditions, to plan and establish wetland areas as part of an authorized water resource development project.

A chronology of the congressional legislation authorizing various purposes and programs is shown in Figure 1 and a brief description is presented in Table 1 (U.S. Army Corps of Engineers, 1989).

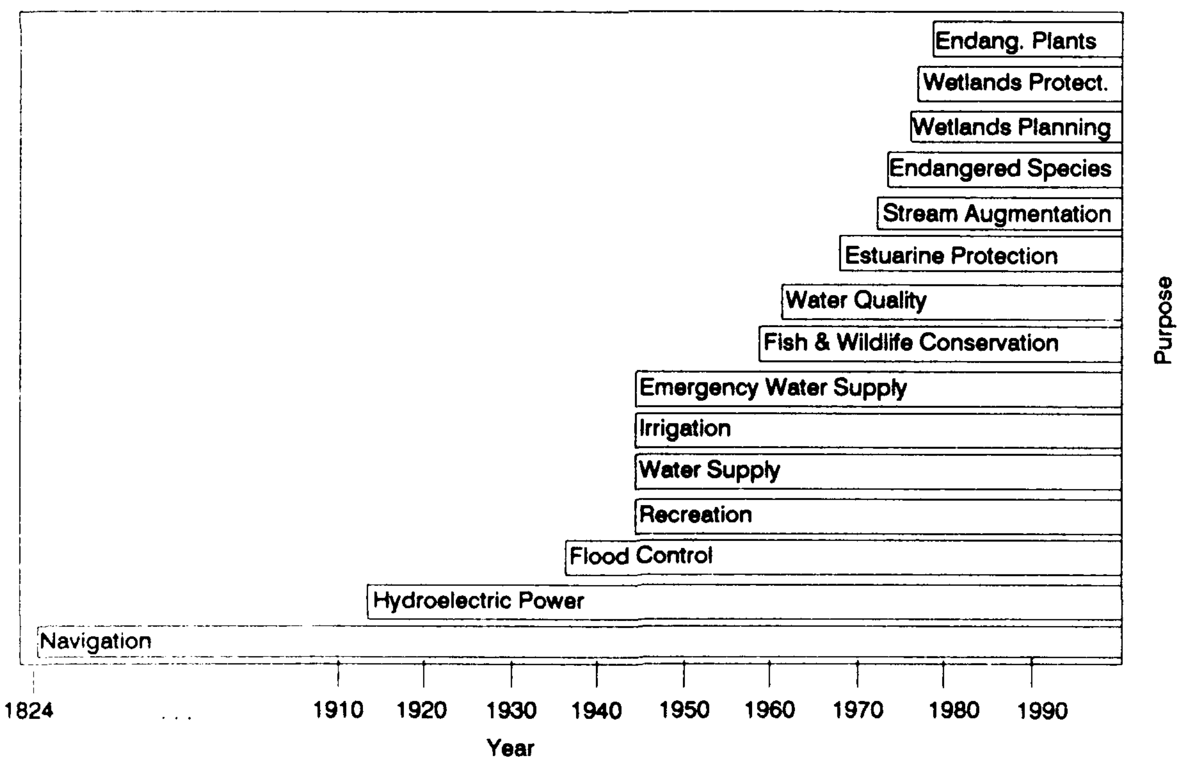

Figure 1. Purposes and Programs Authorized by Congress
Source: U.S Army Corps of Engineers, Digest of Water Resource Policies and Authorities, 1989

Table 1

Congressionally Authorized Purposes and Programs

1824 • Navigation: First appropriation by Congress for work in navigable waters was $75,000 for improving navigation over sand bars and for removing snags.

1912 • Power: River & Harbor Act (PL 62-241) Section 12, authorizes the Secretary of Army to provide, for dams authorized for navigation, such foundations, sluices, and other works as may be desirable for future water power development.

1919 • Navigation: River & Harbor Appropriations Act (PL 65-323) Section 1, states that at least one public terminal should exist, and be constructed, owned, and regulated by the municipality, or other public agency of the state and be open to the use of all on equal terms.

1932 • Navigation: "Fletcher Act" (PL 72-26) Federal interest in navigation is broadened to include within the term commerce: seasonal passenger craft, yachts, houseboats, fishing boats, etc.

1936 • Flood Control: Flood Control Act (PL 74-738) Section 1, declares flood control to be a proper Federal activity.

1938 • Power: Flood Control Act (PL 75-761) Section 4, authorizes the installation of facilities for future power use when approved by the Secretary of Army on recommendation of the Chief of Engineers and the Federal Power Commission.

1944 • Recreation: Flood Control Act (PL 78-534) Section 4, authorizes providing facilities for public use, including recreation and conservation of fish and wildlife.

• Power: Section 5, Secretary of the Interior is authorized to sell surplus electric power from Corps projects.

• Water Supply: Allows for contracts for surplus water with states, municipalities, and individuals, for domestic and M&I uses.

• Irrigation: Section 8, allows for irrigation with the recommendation from the Secretary of Interior.

• Emergency Water Supply: Section 6, allows USACE to be responsive to requests for water which may be generated by droughts or other emergency situations.

1958 • M&I Water Supply: Water Supply Act (PL 85-500) Federal water agencies may provide additional storage capacity for M&I water supply in reservoirs to be constructed primarily for purposes such as navigation, flood control, and irrigation. If already constructed and there are major structural or operational changes then Congressional approval is required.

• Fish and Wildlife Conservation: (PL 85-624) Provides that fish and wildlife conservation receive equal consideration and coordination with other project purposes.

• Aquatic Plant Control Program: (PL 85-500) Authorizes a comprehensive project for control and eradication of obnoxious aquatic plant growths in eight southern states.

1961 • Water Quality: Federal Water Pollution Control Act (PL 87-88) Provides for a more effective program of water pollution control. Establishes a policy on inclusion of storage for streamflow regulation in certain federal reservoir projects for the purpose of water quality control.

1965 • Recreation: Federal Water Project Recreation Act (PL 89-72) Requires consideration of opportunities for outdoor recreation and fish and wildlife enhancement in planning water resource projects.

1966 • Historic Preservation: National Historic Preservation Act (PL 89-665) Federal government is to provide leadership in preserving, restoring, and maintaining the historic and cultural environment of the Nation.

Table 1 (continued)

1968 • Estuaries: Estuarine Protection Act (PL 90-454) Section 4, requires all Federal agencies, in planning for the use or development of water or related land resources, to give consideration to estuaries and their natural resources.

• River Protection: Wild and Scenic Rivers Act (PL 90-542) Section 5 requires that plans for water resource development consider setting aside certain streams as wild, scenic or recreational rivers as an alternative to other uses.

1970 • Environmental Protection: National Environmental Policy Act (PL 91-190) Section 101 establishes a broad federal policy on environmental quality. Requires a five-point Environmental Impact Statement on proposed federal actions affecting the environment.

• Modifications: River & Harbor & Flood Control Act (PL 91-611) Authorizes USACE to review operations of completed projects and to report to Congress regarding recommendations for modifying the structures or their operations.

1972 • Stream Augmentation: Federal Water Pollution Control Act (PL 92-500) Section 102(B), provides that in the planning of any Corps reservoir consideration shall be given to the inclusion of storage for regulation of streamflow.

• Navigation: Section 511(A) provides that nothing in the Act is to be considered as affecting or impairing the authority of the Sec. of the Army to maintain navigation.

• Dam Safety: National Dam Safety Act (PL 92-367) Authorizes a national program of dam inspections and calls for an inventory of all dams located in the U.S. Recommends a comprehensive national program of dam inspection and regulation.

1973 • Endangered Species: Endangered Species Act (PL 93-205) All federal agencies must utilize their authorities in carrying out programs for conservation of endangered species protected by this act.

1974 • Water Quality Storage: Water Resources Development Act Section 65, under appropriate conditions water quality storage may be converted to other purposes.

• Emergency Supplies: Section 82, authorizes providing emergency supplies of clean drinking water from contamination due to floods.

• Emergency Supplies: Disaster Relief Act (PL 95-51) Allows USACE to construct wells and provide emergency water supplies during droughts.

1976 • Wetlands: Water Resources Development Act Section 150, authorizes the Chief of Engineers to plan and establish wetland areas as part of water resource development projects.

1977 • Wetlands Protection: (EO 11990) Directs federal agencies to provide leadership and take action to minimize the destruction, loss, or degradation of wetlands.

• Water Quality: Clean Water Act Section 404, COE retains primary responsibility for permits to discharge dredged or fill materials into waters of the U.S. Also defines conditions that must be met by Federal projects before they make any discharges into the Nation's waters.

1979 • Endangered Plants: (PL 96-159) Expands the Endangered Species Act to include protection for endangered plants.

1986 • Water Supply Storage: Water Resources Development Act Section 931, allows for the interim use of M&I water supply for irrigation until storage capacity is needed for M&I water supply.

• Emergency supplies: Section 917, authorizes emergency supplies of clean water, whether for drinking or other critical needs.

• Water Resources Development Act: WRDA, Army Corps will no longer develop projects for water quality. However, water quality enhancement provisions may be included if related benefits can be identified with basic project purposes.

1988 • Recreation: Water Resources development Act adds downstream recreation enhancement as an authorized project purpose for some projects.

Figure 1 illustrates how additional authorizations have increased the number of purposes for which the Corps is responsible both in planning and management of water resource development projects. The first authorizations were principally for navigation, hydroelectric power, and flood control. Later authorizations covered a variety of conservation purposes and programs. During drought when there is a water shortage, all purposes compete for the available water and are affected by the shortage. The more purposes and programs there are to serve, the greater the potential for conflict and the more complex the task of managing existing supplies.

Reservoir Purposes

A cross-section of a typical reservoir is shown in Figure 2. The storage capacity is divided into three zones: exclusive, multiple-purpose, and inactive. While each Corps' reservoir is unique both in its allocation of storage space and in its operation, the division of storage illustrated by Figure 2 is common for many Corps' reservoirs. The exclusive space is reserved for use by a single purpose. Usually this is flood control although navigation and hydroelectric power have exclusive space in some reservoirs. The exclusive capacity reserved for flood control is normally empty. Some reservoirs with exclusive flood control space have no multiple-purpose pool but have a nominal inactive pool that attracts recreational use. Recreational use is also common on pools originally established exclusively for navigation.

Multiple-purpose storage serves a variety of purposes. These purposes include both seasonal flood control storage, often in addition to exclusive storage, and conservation. Conservation purposes include: navigation, hydroelectric power, water supply, irrigation, fish and wildlife, recreation, and water quality. Other conservation purposes such as wetlands, ground water and endangered species, while not included in this study because of a lack of data, are nonetheless important in water control management.

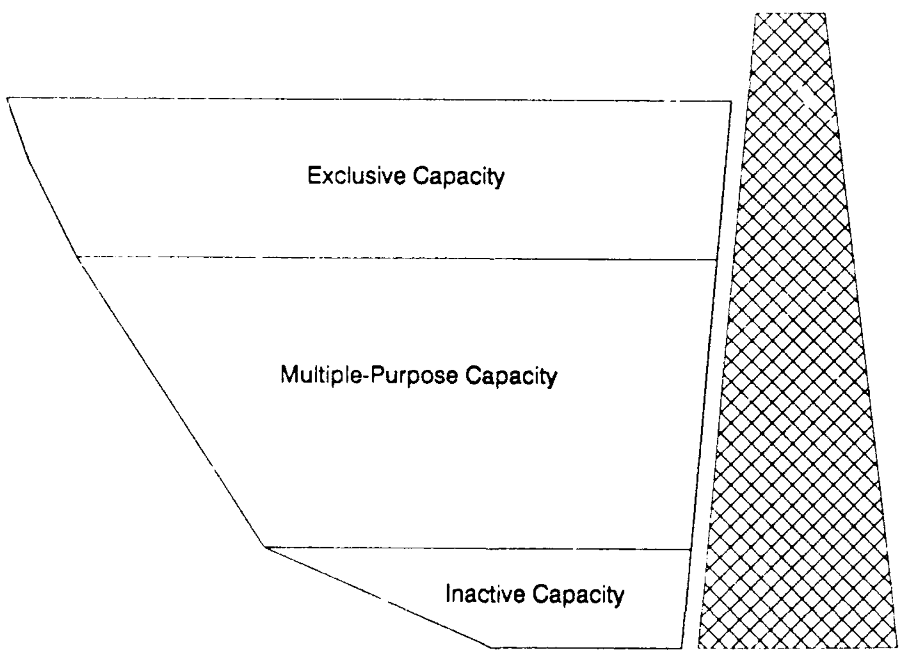

Figure 2. Typical Storage Capacities in Corps of Engineers Reservoirs

The inactive space is commonly used for sediment storage and is a significant purpose in some reservoirs. Also, inactive capacity not filled with sediment is sometimes used during drought when it can provide limited but important storage for water supply, irrigation, recreation, fish and wildlife, and water quality.

Reservoir storage space is not normally allocated to specific conservation purposes. Rather, reservoir releases are made that serve several purposes. However, the amount of water needed to serve each purpose varies. During drought, with limited multiple-purpose storage available, the purposes requiring greater releases begin to compete with purposes requiring less. For example, if the greater releases are not made, the storage would last longer for the purposes served by the lesser releases.

A brief description of each purpose discussed in this report is presented below. Additional detail, and a discussion of reservoir operating procedures, may be found in the Corps' Engineering Manual on Management of Water Control Systems (U. S. Army Corps of Engineers, 1987) from which the following sections are excerpts.

Flood Control. Reservoirs are usually capable of storing the entire runoff from minor or moderate flood events. Each reservoir's water control plan defines the basic goals of regulation. Usually a compromise is achieved to best utilize the storage space for control of both major and minor flood events. In special circumstances where reservoir inflows can be forecast several days or weeks in advance (for example, when the runoff occurs from snowmelt), the degree of control for a particular flood event may be determined on the basis of forecasts to best utilize the storage space. When runoff is seasonal, the amount of flood control storage space may be varied seasonally to utilize the reservoirs for multiple-purpose regulation.

Reservoir releases are based upon the overall objectives to limit the discharges at the downstream control points to predetermined damage levels. The regulation must consider the travel times caused by storage effects in the river system and the local inflows between the reservoir and downstream control points.

A multiple-reservoir system is generally regulated for flood control to provide flood protection both in intervening tributary areas and at downstream main stem damage areas. The extent of reservoir regulation required for protecting these areas depends upon local conditions of flood damage, uncontrolled tributary drainage, reservoir storage capacity, and the volume and time distribution of reservoir inflows. Either the upstream or downstream requirements may govern the reservoir regulation, and usually the optimum regulation is based on the combination of the two.

System control can incorporate the concept of a balanced reservoir regulation, with regard to filling the reservoirs in proportion to each reservoir's flood control capability, while also considering expected residual inflows and storage available. Evacuation of flood water stored in a reservoir system must also be accomplished on a coordinated basis. Each reservoir in the system is drawn down as quickly as possible to provide space for controlling future floods. The objectives for withdrawal of water in the various zones of reservoir storage are determined to minimize the risk of encroaching into the flood control storage and to conserve water for future requirements.

Navigation. Problems related to the management of water for navigation use vary widely among river basins and types of developments. Control structures at dams, reservoirs, or other facilities where navigation is one of the project purposes must be regulated to provide required water flows and/or to maintain project navigation depths. Navigational requirements must be integrated with other water uses where developments encompass multiple-purpose water resource systems. In the regulation of dams and reservoirs, the navigational requirements involve controlling water levels in the reservoirs and at downstream locations, and providing the quantity of water necessary for the operation of locks. There also may be navigational constraints in the regulation of dams and reservoirs with regard to rates of change of water surface elevations and outflows. There are numerous special navigational requirements that may involve water control, such as ice, undesirable currents and water flow patterns, emergency precautions, boating events, launchings, etc.

Navigation locks located at dams on major rivers generally have sufficient water from instream flows to supply lockage water flow requirements. Navigation requirements for downstream use in open river channels may require large quantities of water, metered out over a long period of time (from several months to a year), to achieve a significant, continuous increase in water levels for boat or barge transportation. Usually, water released from reservoirs for navigation is used jointly for other purposes, such as hydroelectric power, low-flow augmentation, water quality, enhancement of fish life, and recreation. Seasonal or annual water management plans are prepared which define the use of water for navigation. The amount of stored water to be released depends on the conditions of water storage in the reservoir system and downstream requirements or goals for low-flow augmentation, as well as factors related to all uses of the water in storage.

Navigational constraints are also important for short-term regulation of projects to meet all requirements. In some rivers, supply of water for lockage is a significant problem, particularly during periods of low flow or droughts. The use of water for lockage is generally given priority over hydropower or irrigation usages. In critical low-water periods, a curtailment of water use for lockage may be instituted by restricting the number of locks used, thereby conserving the utilization of water through a more efficient use of the navigation system. Water requirements for navigation canals are based on lockage and instream flows as necessary to preserve water quality in the canal.

Hydroelectric Power. Dam and reservoir projects which incorporate hydropower generally fall into two distinct categories: (a) storage reservoirs which have sufficient capacity to regulate streamflow on a seasonal basis and (b) run-of-river projects where storage capacity is minor relative to the volume of flow.

The storage projects are usually multiple-purpose. Normally, the upstream reservoirs include provisions for power production at the site, as well as for release of water for downstream control. Run-of-river hydropower plants are usually developed in connection with navigation projects.

Integration and control of a major power system involving hydropower resources is generally accomplished by a centralized power dispatching facility. This facility contains the equipment to monitor the entire power system operation, including individual plant generation, substation operation, transmission line operation, power loads and requirements by individual utilities and other bulk power users, and all factors related to the electrical system control for moment-to-moment operation. The dispatching center is manned on a continuous basis, and operations monitor and control the flow of power through the system, rectify outages, and perform all the necessary steps to ensure the continuity of power system operation in meeting system loads.

Regulation and management of hydropower systems involve two levels of control: scheduling and dispatching. The scheduling function is performed by schedulers who analyze daily requirements for meeting power loads and resources and all other project requirements. Schedules are prepared and thoroughly coordinated to meet water and power requirements of the system as a whole. Projections of system regulation, which indicate the expected physical operation of individual plants and the system as a whole, are prepared for one to five days in advance. These projections are updated on a daily or more frequent basis to reflect the continuously changing conditions of power and water requirements.

Irrigation. Irrigation water diverted from reservoirs, diversion dams, or natural river channels is controlled in a manner to supply water for the irrigation system as necessary to meet the water duty requirements. The requirements vary seasonally, and in most irrigated areas in the western United States, the agricultural growing season begins in the spring months of April or May. The diversion requirements gradually increase as the summer progresses, reaching their maximum amounts in July or August. They then recede to relatively low amounts by late summer. By the end of the growing season, irrigation diversions are terminated, except for minor amounts of water that may be necessary for domestic use, stock water, or other purposes.

Corps of Engineers' reservoir projects have been authorized and constructed primarily for flood control, navigation, and hydroelectric power. However, several major Corps of Engineers' multiple-purpose reservoir projects west of the Mississippi River include irrigation as a project purpose. Usually, water for irrigation is supplied from reservoir storage to augment the natural streamflow as required to meet irrigation demands in downstream areas. In some cases, water is diverted from the reservoir by gravity through outlet facilities at the dam which feed directly into irrigation canals. At some of the run-of-river power or navigation projects, water is pumped directly from the reservoir for irrigation purposes.

The general mode for regulation of water supply reservoirs to meet irrigation demands is to capture all runoff in excess of minimum flow demands during the spring and early summer. This usually results in refill of the reservoirs prior to the irrigation demand season. The water is held in storage until the natural flow recedes to the point where it is no longer of sufficient quantity to meet all demands for downstream irrigation. At that time, the release of stored water from reservoirs is begun and continued on a demand basis until the end of the growing season (usually September or October). During the winter, projects release water as required for instream flows, stock water, or other project purposes.

Municipal and Industrial Water Supply. Regulation of reservoirs for M&I water supply is performed in accordance with contractual arrangements. Storage rights of the user are defined in terms of acre-feet of stored water and/or the use of storage space between fixed limits of reservoir levels. The amount of storage space is adjusted to account for change in the total reservoir capacity that is caused by sediment deposits. The user has the right to withdraw water from the lake or to order releases to be made through the outlet works. This is subject to certain rights reserved for the government with regard to overall regulation of the project and to the extend of available storage space.

In times of drought, special considerations may guide the regulation of projects with regard to water supply. Adequate authority to permit temporary withdrawal of water from Corps' projects is contained in 31 U.S.C. 483a. Such withdrawal requires a fee that is sufficient to recapture lost project revenues, and a proportionate share of operation, maintenance and major replacement expenses.

Water Quality. Water quality encompasses the physical, chemical, and biological characteristics of water and the abiotic and biotic interrelationships. The quality of the water and the aquatic environment is significantly affected by management practices employed by the water control manager. Water quality control is an authorized purpose at many Corps of Engineers' reservoirs. However, even if not an authorized project purpose, water quality is an integral consideration during all phases of a project's life, from planning through operation. The goal is to, as a minimum, meet State and Federal water quality standards in effect for the lakes and tailwaters. The operating objective is to maximize beneficial uses of the resources through enhancement and nondegradation of water quality.

Water quality releases for downstream control have both quantitative and qualitative requirements. The quality aspects relate to Corps' policy and objectives to meet state water quality standards, maintain present water quality where standards are exceeded and maintain an acceptable tailwater habitat for aquatic life. The Corps has responsibility for the quality of water discharged from its projects. One of the most important measures of quality is quantity. At many projects authorized for water quality control, a minimum flow at some downstream control point is the water quality objective.

Coordinated regulation of multiple reservoirs in a river basin is required to maximize benefits beyond those achievable with individual project regulation. System regulation for quantitative aspects, such as flood control and hydropower generation, is a widely accepted and established practice, and the same principle applies to water quality concerns. Water quality maintenance and enhancement beyond the discernible effects of a single project are possible through coordinated system regulation. This applies to all facets of quality from the readily visible quantity aspect to traditional concerns such as temperature and dissolved oxygen.

System regulation for water quality is of most value during low-flow periods when available water must be used with greatest efficiency to avoid degrading lake or river quality. Water control decisions are formulated based on current and forecasted basin hydrologic, meteorologic and quality conditions, reservoir status, quality objectives and knowledge of water quality characteristics of component parts of the system. Required flows and qualities are then apportioned to the individual projects, resulting in a quantitatively and qualitatively balanced system. Computer programs capable of simulating reservoir system regulation for water quality provide useful tools for deriving and evaluating water control alternatives.

Fish and Wildlife. Project regulation can influence fisheries both in the pool and downs ' .am. One of the most readily observable influences of reservoir regulation is reservoir pool fluctuations. Periodic fluctuations in reservoir water levels present both problems and opportunities to the water control manager with regard to fishery management. The seasonal fluctuation that occurs at many flood control reservoirs, and the daily fluctuations that occur with hydropower operation often result in elimination of shoreline vegetation and subsequent shoreline erosion, water quality degradation and loss of habitat. Adverse impacts of water level fluctuations also include loss of shoreline shelter and physical disruption of spawning and nests.

Water-level management in fluctuating warm-water and cool-water reservoirs generally involves raising water levels during the spring to enhance spawning and survival of young predators. Pool levels are lowered during the summer to permit regrowth of vegetation in the fluctuation zone. Fluctuations may be timed to benefit one or more target species; therefore, several variations in operation may be desirable. In the central United States, managers frequently recommend small increases in pool levels during the autumn for waterfowl management.

Guidelines to meet downstream fishery management potentials are developed based on project water quality characteristics and water control capabilities. To do so, an understanding of the reservoir water quality regimes is critical for developing the water control criteria to meet the objectives. For example, temperature is often one of the major constraints of fishery management in the downstream reach, and water control managers must understand the temperature regime in the pool and downstream temperature requirements, as well as the capability of the project to achieve the balance required between the inflows and the releases. Releasing cold-water downstream where fishery management objectives require warm water will be detrimental to the downstream fishery. Conversely, releasing warm water creates difficulty in maintaining a cold-water fishery downstream.

Water control activities can also impact water temperatures within the pool by changing the volume of water available for a particular layer. In some instances, cold-water reserves may be necessary to maintain a downstream temperature objective in the late summer months, and therefore the availability of cold water must be maintained to meet this objective. For some projects, particularly in the southern United States, water control objectives include the maintenance of warm-water fisheries in the tailwaters. In other instances, fishery management objectives may include the maintenance of a two-story fishery in a reservoir, with a warm-water fishery in the surface water, and a cold-water fishery in the bottom waters. Such an objective challenges water control managers to regulate the project to maintain the desired temperature stratification while maintaining sufficient dissolved oxygen in the bottom waters for the cold-water fishery. Regulation to meet this objective requires an understanding of operational affects on seasonal patterns of thermal stratification, and the ability to anticipate thermal characteristics.

Minimum instantaneous flows can be beneficial for maintaining gravel beds downstream for species that require this habitat. However, dramatic changes in release volumes, such as those that result from flood control regulation, as well as hydropower, can be detrimental to downstream fisheries. Peaking hydropower operations can result in releases from near zero to \ ry high magnitudes during operations at full capacity.

Maintaining minimum releases and incorporating reregulation structures are two of the options available to mitigate this problem.

In some instances, tailwater fishing is at a maximum during summer weekends and holidays and this is a time when power generation may be at a minimum and release near zero. Maintaining minimum releases during weekend daylight hours may improve the recreational fishing, but may reduce the capability to meet peak power loads during the week because of lower water level (head) in the reservoir. In this instances, water control managers will be challenged to regulate the project with consideration of these two objectives.

Regulation for anadromous fish is particularly important during certain periods of the year. Generally, upstream migration of adult anadromous fish begins in the spring of each year and continues through early fall, and downstream migration of juvenile fish occurs predominantly during the spring and summer months. The reduced water velocities through reservoirs, in comparison with preproject conditions, may greatly lengthen the travel time for juvenile fish downstream through the impounded reach. In addition, storage for hydropower reduces the quantity of spill, and as a result, juvenile fish must pass through the turbines. The delay in travel time subjects the juvenile fish to greater exposure to birds and predator fish, and passage through the powerhouse turbines increases mortality. To improve juvenile survival, storage has been made available at some projects to augment river flows, and flows are diverted away from the turbine intakes and through tailraces where the fish are collected for transportation or released back into the river. Barges or tank truck can be used to transport juveniles from the collector dams to release sites below the projects. Other Corps' projects have been modified so the ice and trash spillways can be operated to provide juvenile fish passage.

Project regulation can influence wildlife habitat and management principally through water level fluctuations. The beneficial aspects of periodic drawdowns on wildlife habitat are well documented in wildlife literature. Drawdowns as a wildlife management technique can, as examples, allow the natural and artificial revegetation of shallows for waterfowl, permit the installation and maintenance of artificial nesting structures; allow the control of vegetation species composition, and ensure mast tree survival in greentree reservoirs. Wildlife benefits of periodic flooding include inhibiting the growth of undesirable and perennial plants, creating access and foraging opportunities for waterfowl in areas such as greentree reservoirs, and ensuring certain water levels in stands of vegetation to encourage waterfowl nesting and reproduction.

<u>Recreation.</u> Recreational use of the reservoirs may extend throughout the entire year. Under most circumstances, the optimum recreational use of reservoirs would require that the reservoir levels be at or near full conservation pool during the recreation season. The degree to which this objective can be met varies widely, depending upon the regional characteristics of water supply, runoff, and the basic objectives of water regulation for the various project purposes. Facilities constructed to enhance the recreational use of reservoirs may be designed to be operable under the planned reservoir regulation guide curves on water control diagrams, which reflect the ranges of reservoir levels that are to be expected during the recreational season.

In addition to the seasonal regulation of reservoir levels for recreation, regulation of project outflows may encompass requirements for specific regulation criteria to enhance the use of the rivers downstream from the projects, as well as to insure the safety of the general public. The Corps has the responsibility to regulate projects in a manner to maintain or enhance the recreational use of the rivers below projects to the extent possible. In the peak recreation season, streamflows are regulated to insure the safety of the public who may be engaged in water related activities, including boating, swimming, fishing, rafting, river drifting, etc. Also, the aesthetics of the rivers may be enhanced by augmenting streamflows in the low water period. Water requirements for maintaining or enhancing the recreational use of rivers are usually much smaller than other major project functional uses. Nevertheless, it is desirable to include specific goals to enhance recreation in downstream rivers in the water control plan. The goals may be minimum project outflows or augmented streamflows at times of special need for boating or fishing. Of special importance is minimizing any danger that might result from changing conditions of outflows which would cause unexpected rise or fall in river levels. Also, river drifting is becoming an important recreational use of rivers, and in some cases it may be possible to enhance the conditions of streamflow for relatively short periods of time for this purpose.

Profile of Corps of Engineers' Reservoirs

A map showing the geographic distribution of Corps of Engineers' reservoirs in the continental United States is presented in Figure 3. A profile of their year of completion, storage capacity, location, evaporation potential, and proximity to future population growth is presented below. A list of the individual reservoirs used in the analyses is included as Appendix 2.

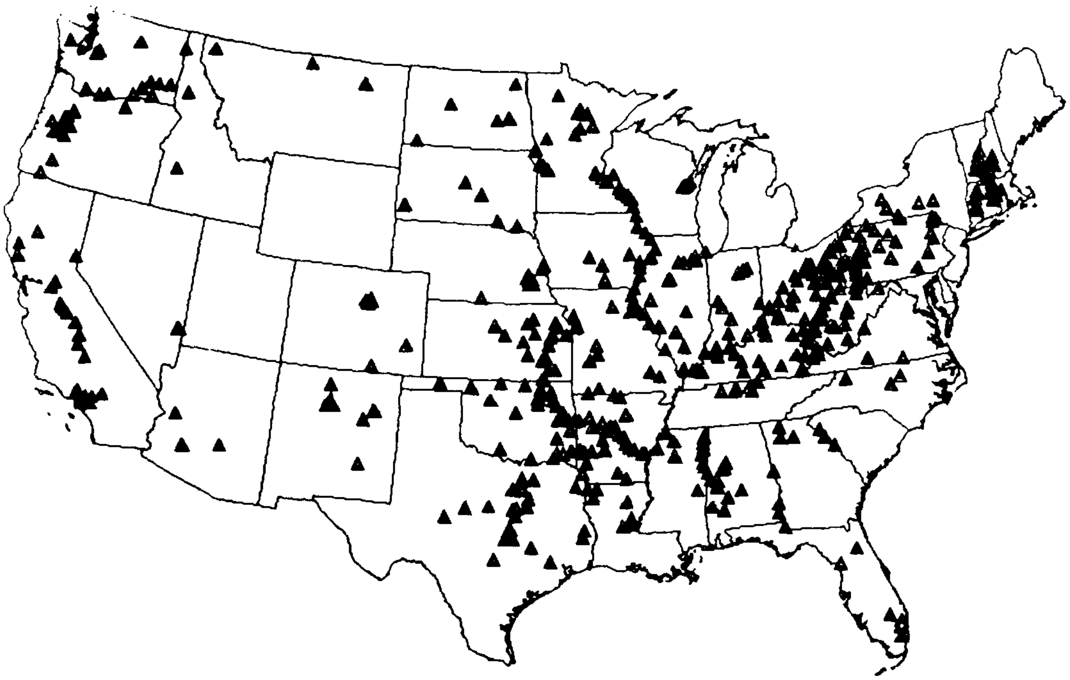

Figure 3. Corps of Engineers Reservoirs in the Continental United States (including locks and dams)

Time Line of Reservoir Construction. The number of Corps of Engineers' reservoirs completed each decade is shown in Figure 4. Approximately 46 percent were completed before 1960; by 1970, 75 percent were complete. Considering an average time between congressional authorization and the completion of construction (10-15 years at that time), it is clear that three-fourths of the projects were authorized, and construction begun, before the passage of most of the general congressional legislation that established the multiple purposes common today. Accommodating these additional purposes has become a major reservoir operations challenge. The competition between originally authorized purposes and purposes added later is evident from this historical analysis.

Time Line of Reservoir Capacity. Figure 5 shows a similar time line for completion of total reservoir capacity. The total capacity includes exclusive capacity for flood control, navigation, and hydroelectric power, and multiple-purpose capacity for

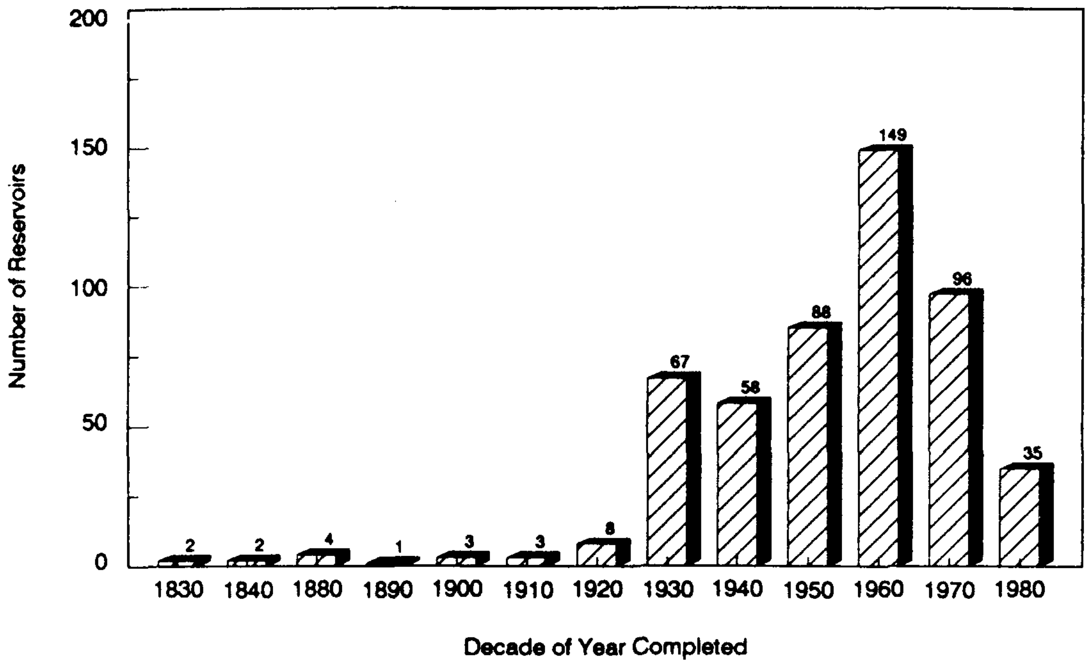

Figure 4. Number of Reservoirs Completed in Each Decade

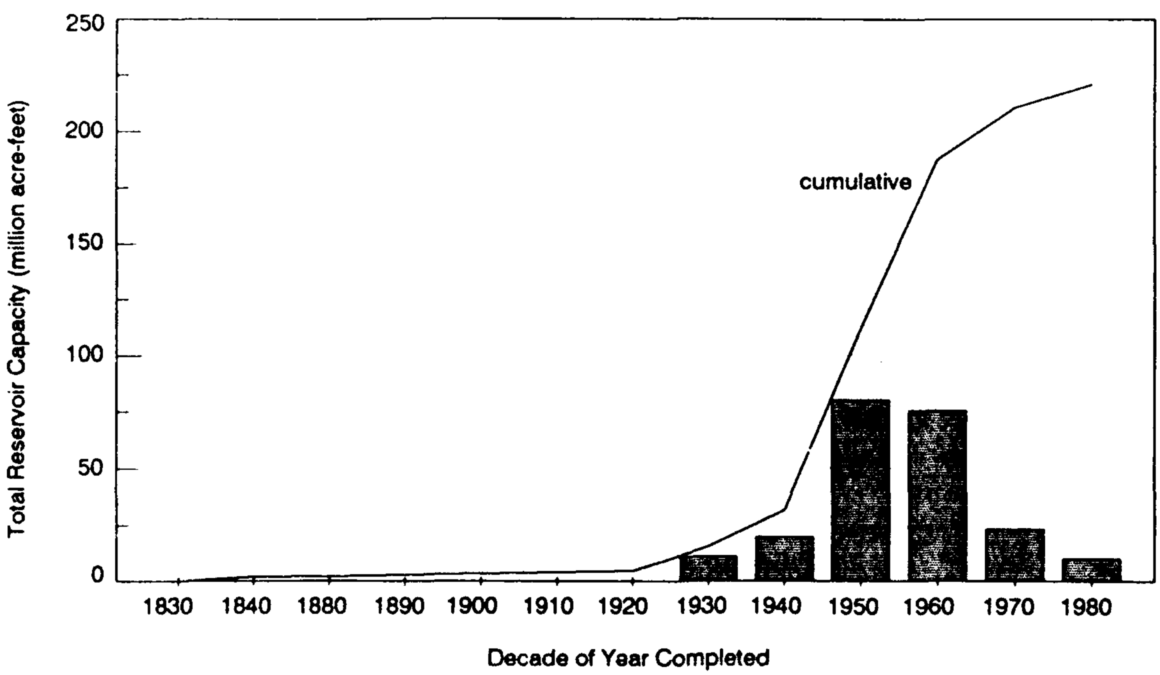

Figure 5. Reservoir Capacity and Cummulative Capacity by Decade

conservation purposes. Fifty-one percent of the total Corps' reservoir capacity was in place by 1960; by 1970, 85 percent was complete. Figure 6 shows a time line for completion of multiple-purpose capacity. Eighty-six percent of the multiple-purpose capacity was completed by 1970.

Multiple-purpose capacity is of primary importance during drought because within this capacity is stored the water needed for a variety of conservation purposes. Flood control is important during drought the extent that flood control space may be used to store seasonal runoff for conservation and to the extent that it provides an opportunity for storage reallocation. Figure 7 shows the distribution of reservoir capacity by use with multiple-purpose use accounting for nearly 123 million acre-feet, or nearly 56 percent of total capacity.

Reservoirs by Division. The number of completed reservoirs (including locks and dams) in each Corps of Engineers' division is shown in Figure 8. Figure 9 shows the distribution of locks and dams only. The Ohio River and Southwestern regions have the greatest number of reservoirs. In the Ohio River basin, the large number of locks and dams (49) contribute significantly to this total. Figure 10 shows the distribution of exclusive and multiple-purpose capacity by division. Some divisions have relatively small capacities for multiple purposes (NAD, NED), for others the capacity is large (MRD, SWD). Even small capacities, however, can be important to local interests in meeting conservation needs during drought.

Reservoir Systems. Some reservoirs, both large and small, are operated as part of a system. These reservoirs respond to extreme hydrologic events as a system rather than as a single reservoir. The influence of releases may extend hundreds of miles downstream as in the Columbia, Missouri, Ohio and Mississippi systems. Corps' reservoirs can also be tied to systems operated by others. In California, for example, the Central Valley Project is operated by the Bureau of Reclamation and the State Water Project is operated by the state of California. When a reservoir is part of a system, its response to drought must consider system purposes and storage as well as the purposes and storage of the individual reservoirs. In such cases the trade-offs between purposes are more complex and interrelated.

Reservoir Evaporation. In some regions evaporation is a significant loss of water from the multiple-purpose pool. This is of particular importance during drought for several reasons. First, drought means less water and more effort to conserve, consequently evaporation losses are undesirable. Second, drought is sometimes associated with higher than normal temperatures and below-average humidity; both increase evaporation. Third, because a drought may last many years, the cumulative net loss from evaporation can be much greater than during normal weather.

Figure 11 shows the estimated gross annual evaporation from the multiple-purpose pools of reservoirs in each division. The annual evaporation rates used in the calculations are from Farnsworth et al (1982). Three divisions have particularly high gross evaporation: South Atlantic, Missouri River, and Southwestern. All three have over 1 million acres of reservoir surface area. While the Southwestern region has the greatest number of reservoirs and highest average evaporation rate, and the South Atlantic region the fewer reservoirs and a lower average evaporation rate, the South Atlantic region has the greatest total evaporation because of an additional 400,000 acres

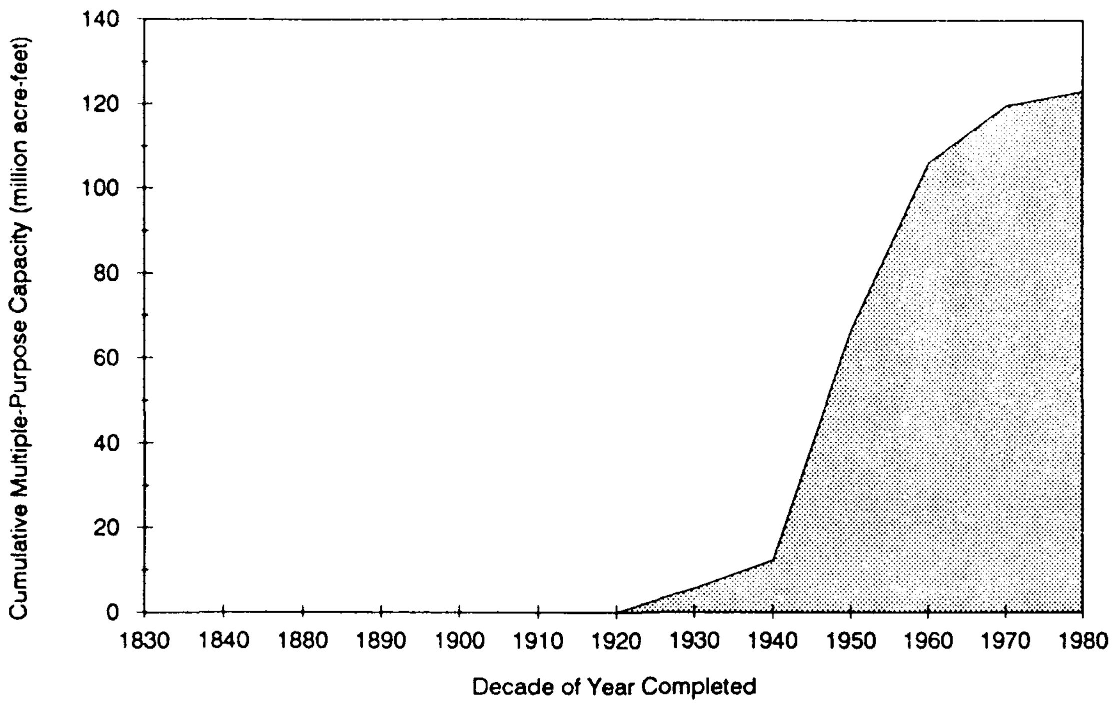

Figure 6. Growth of Reservoir Multiple-Purpose Capacity

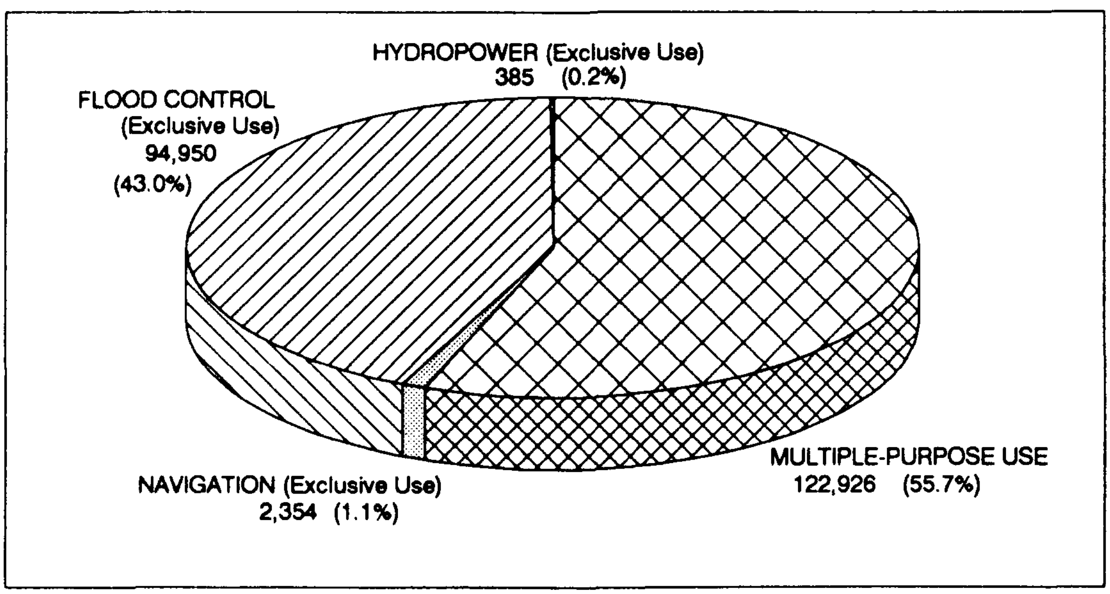

Figure 7. Reservoir Capacity for Exclusive and Multiple-Purposes (1000 acre-feet)

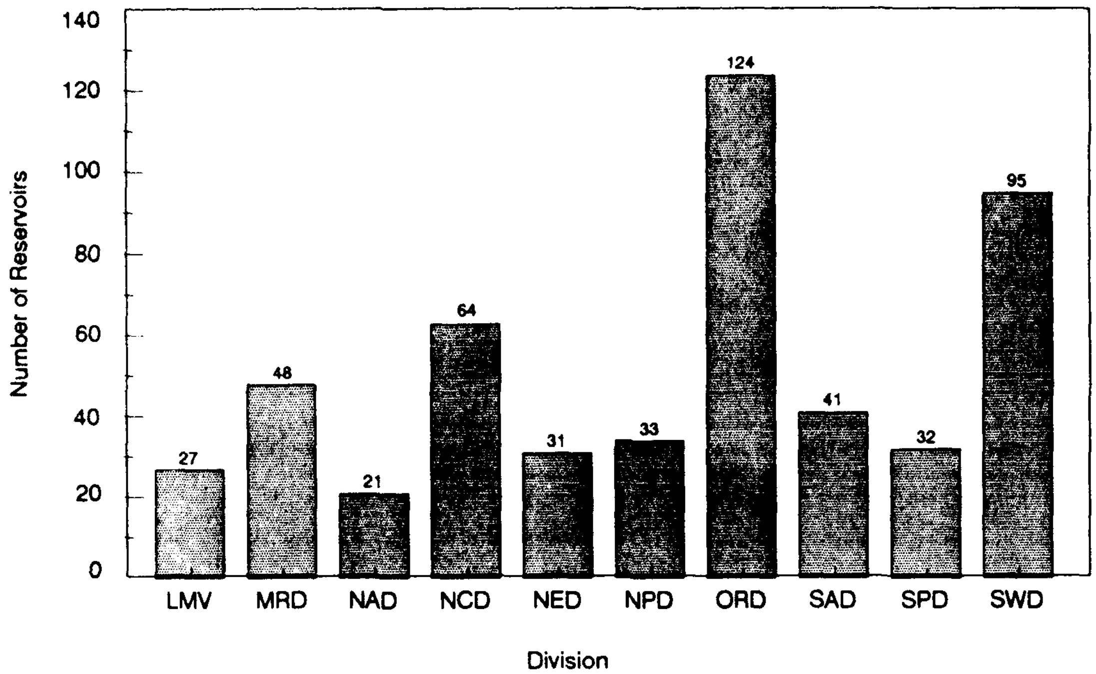

Figure 8. Number of Reservoirs (including locks and dams) by Division, 1989

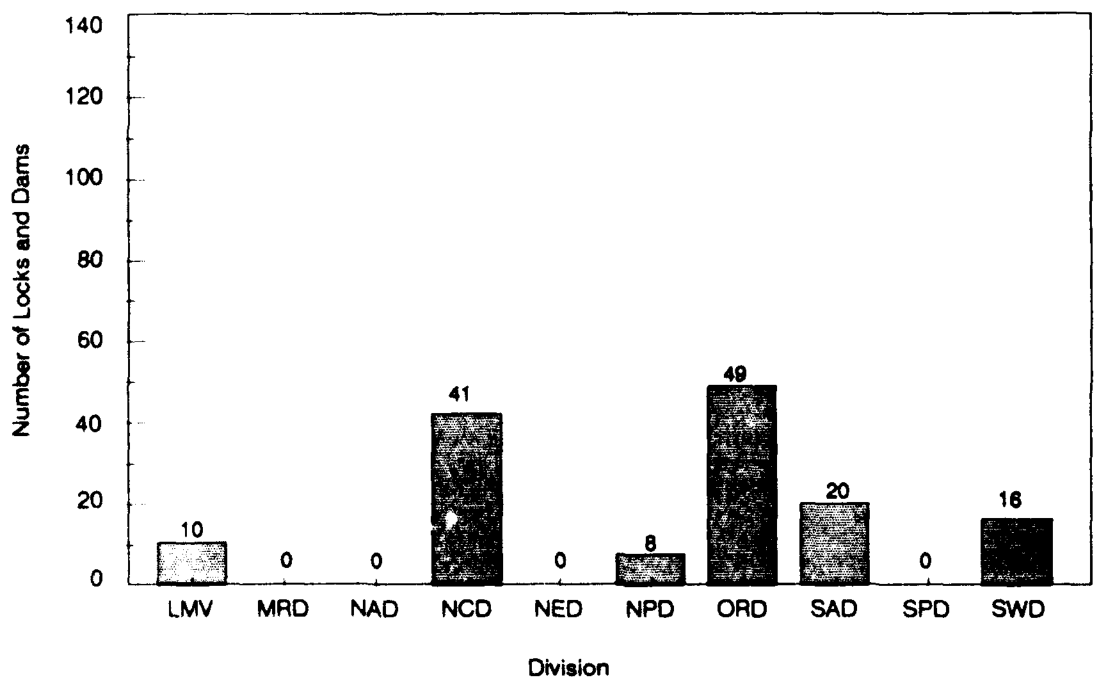

Figure 9. Number of Locks and Dams by Division, 1989

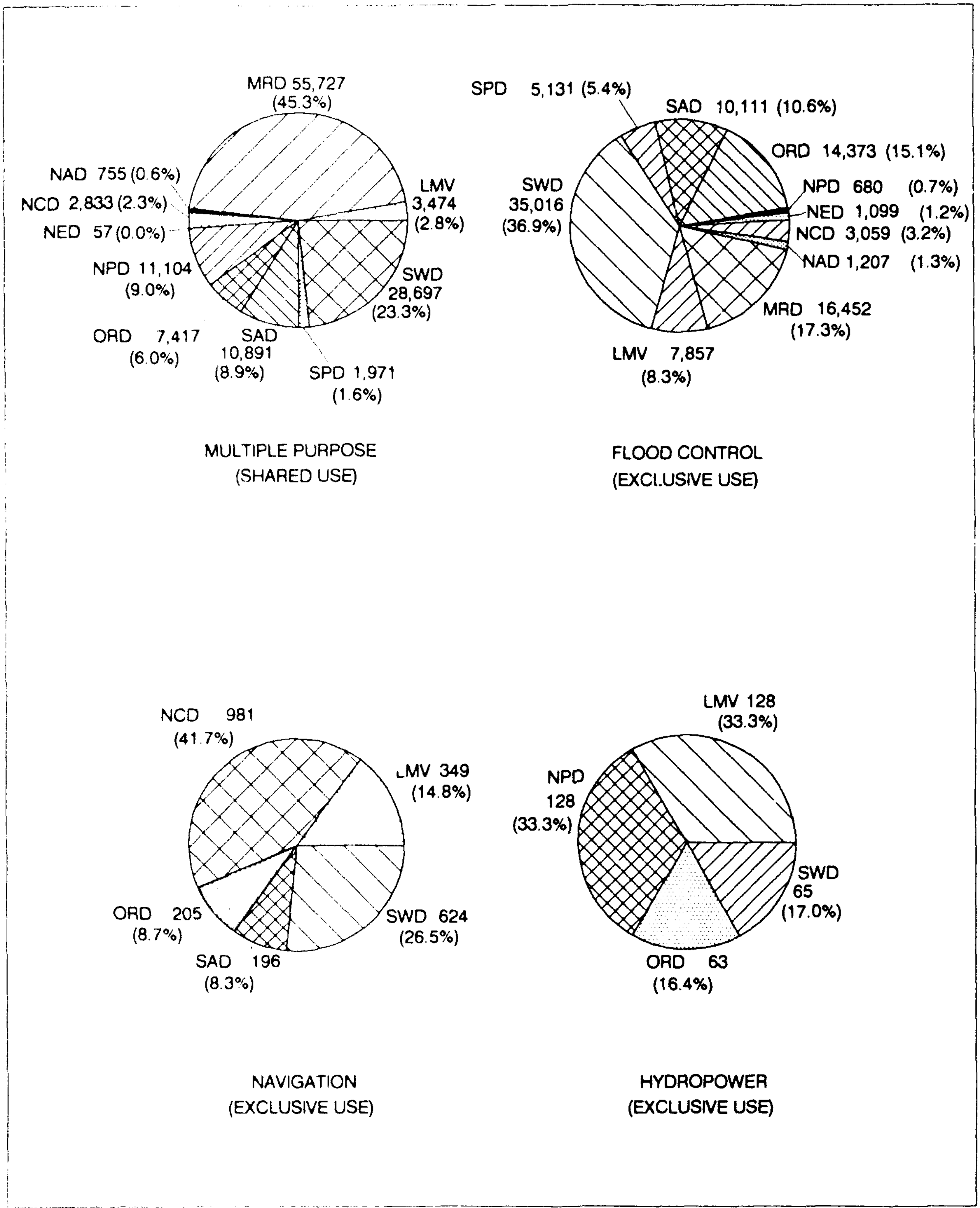

Figure 10. Reservoir Capacity for Exclusive and Multiple-Purposes by Division (1000 acre-feet). Percentages are of the total for all divisions

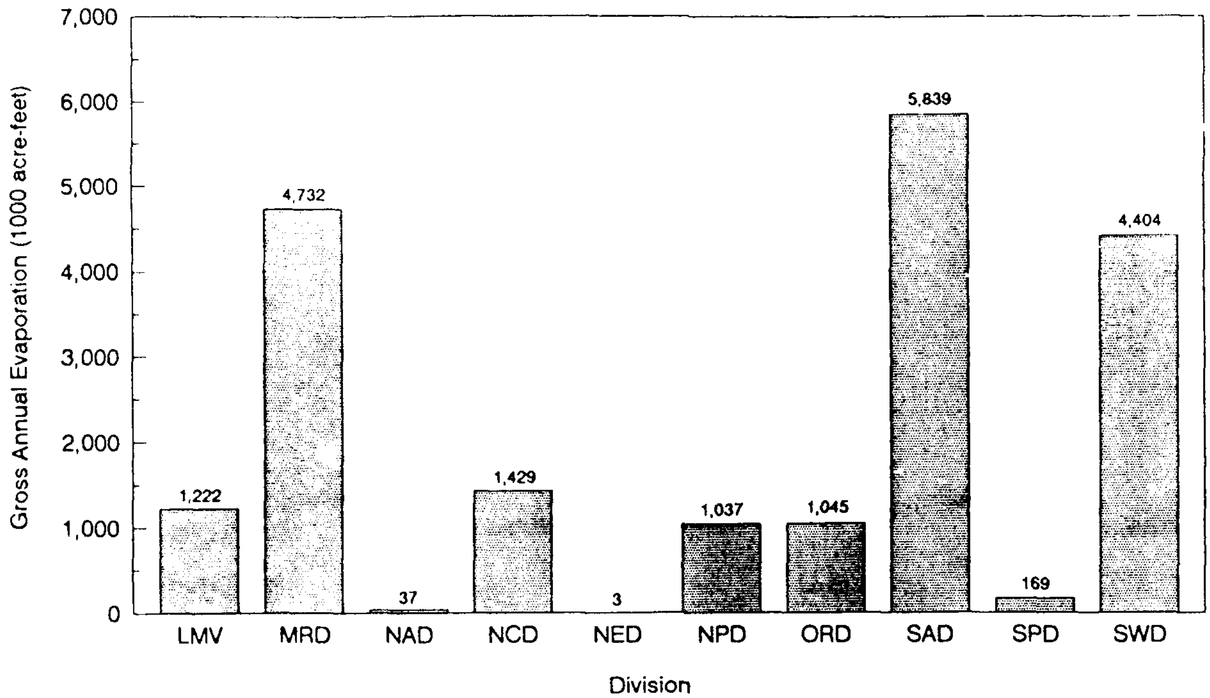

Figure 11. Gross Annual Reservoir Evaporation by Division

of reservoir surface area (one-third more). Seventy-five percent (4.3 million acre-feet) of the evaporation in the South Atlantic region comes from the million acres of surface area of Lake Okeechobee and the water conservation areas in Florida. In the Missouri River region, 84 percent of the evaporation occurs at the six main stem reservoirs.

During drought an effort is sometimes made to consolidate reservoir storage into fewer reservoirs to reduce surface area and evaporation. An example of this is described by Kelly (1986) at two California reservoirs operated by the U. S. Bureau of Reclamation.

Population Growth, 1990-2000. Population growth, whether in states, regions or cities, has the potential to affect the purposes served by Corps' reservoirs. The demand for recreation and water supply, for example, often increases as the population served increases. The relationship between population and water needs, however, is complex and influenced by many factors. Recreational use, for example, may be largely from out-of-state visitors, or water supply needs may depend upon the availability of alternative water sources and their costs. Hydroelectric power, navigation and irrigation are also affected by population growth, but the effect is often indirect because these purposes are part of larger regional systems. An exception is the growth of run-of-river hydropower additions at individual reservoirs. Fish and wildlife and instream water quality may be affected by the need for additional water to protect them from adverse impacts of growth.

Projected percentage change of population by state for the next ten years (1990-2000) is shown in Figure 12. The southwest (Nevada, Arizona, New Mexico) and Florida are projected to have the greatest increase. Parts of the upper Great Plains, midwest and Ohio River Valley are projected to have a decrease. Analysis of Corps' reservoirs shows that 30 percent are located in states with a greater than 5 percent change (Figure 13). Seventy percent of the reservoirs are in states with declining or low growth projections. This analysis is shown by division in Figure 14.

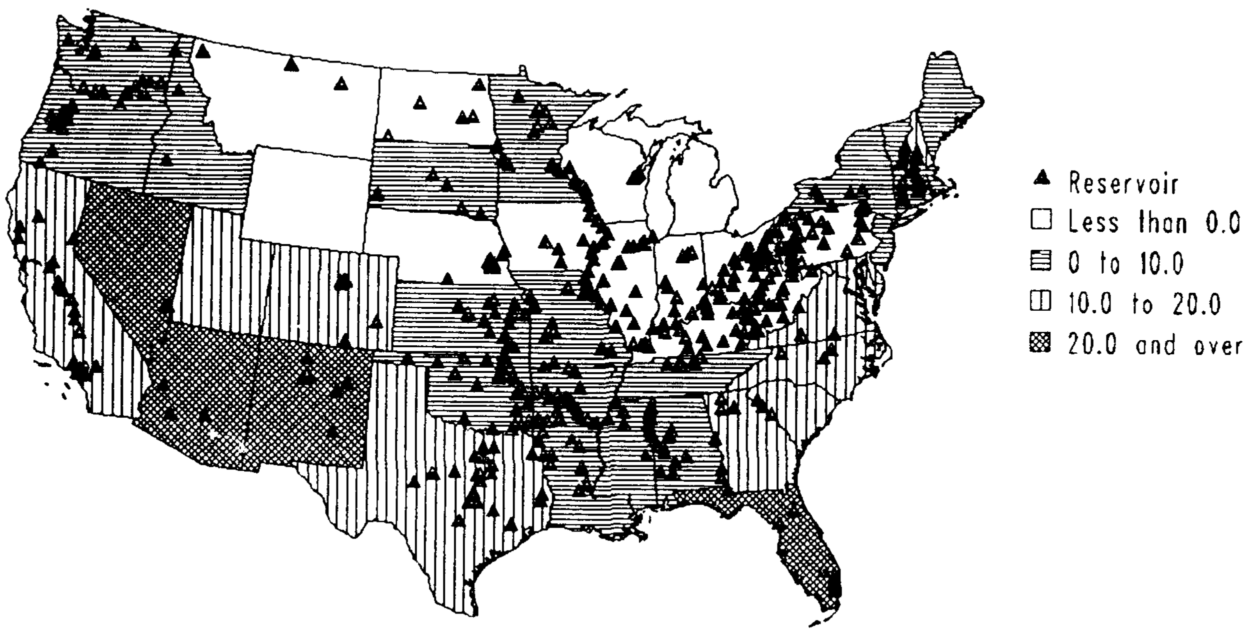

Figure 12. Projected Percent Change in State Populations, 1990 to 2000
Source: U.S. Bureau of Census, 1988

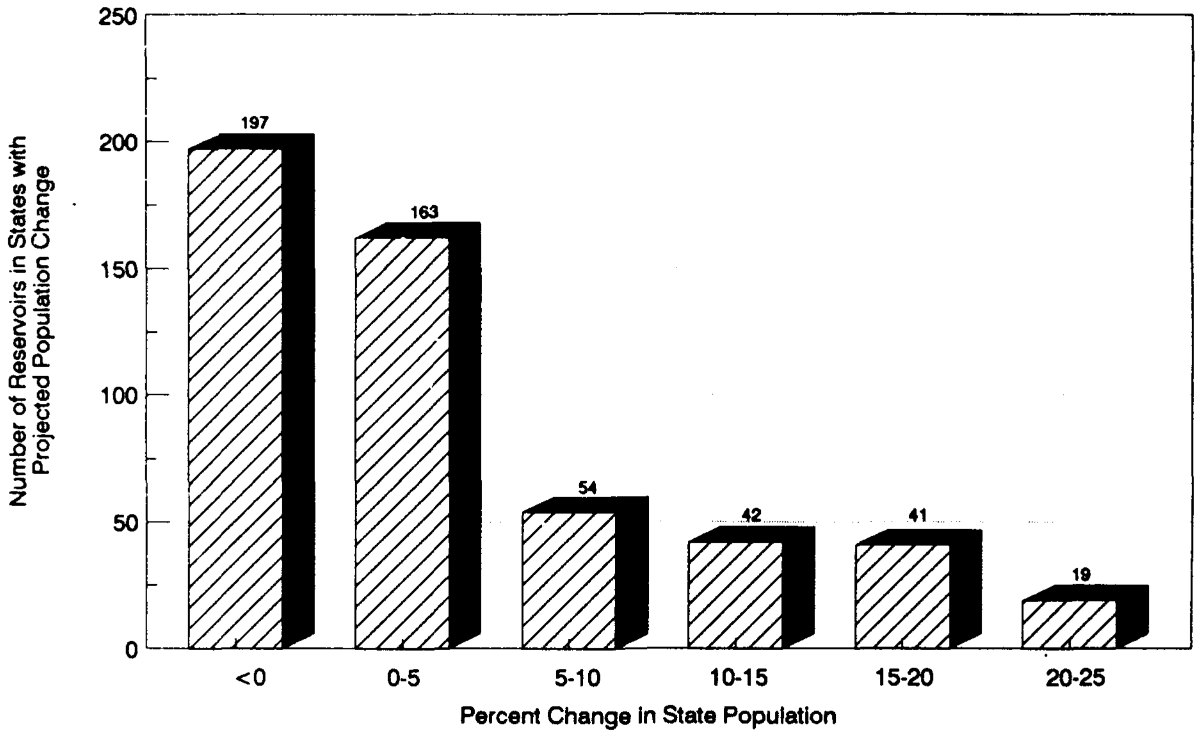

Figure 13. Number of Reservoirs by Projected Percent Change in State Populations, 1990-2000
Source: U.S. Bureau of Census, 1988

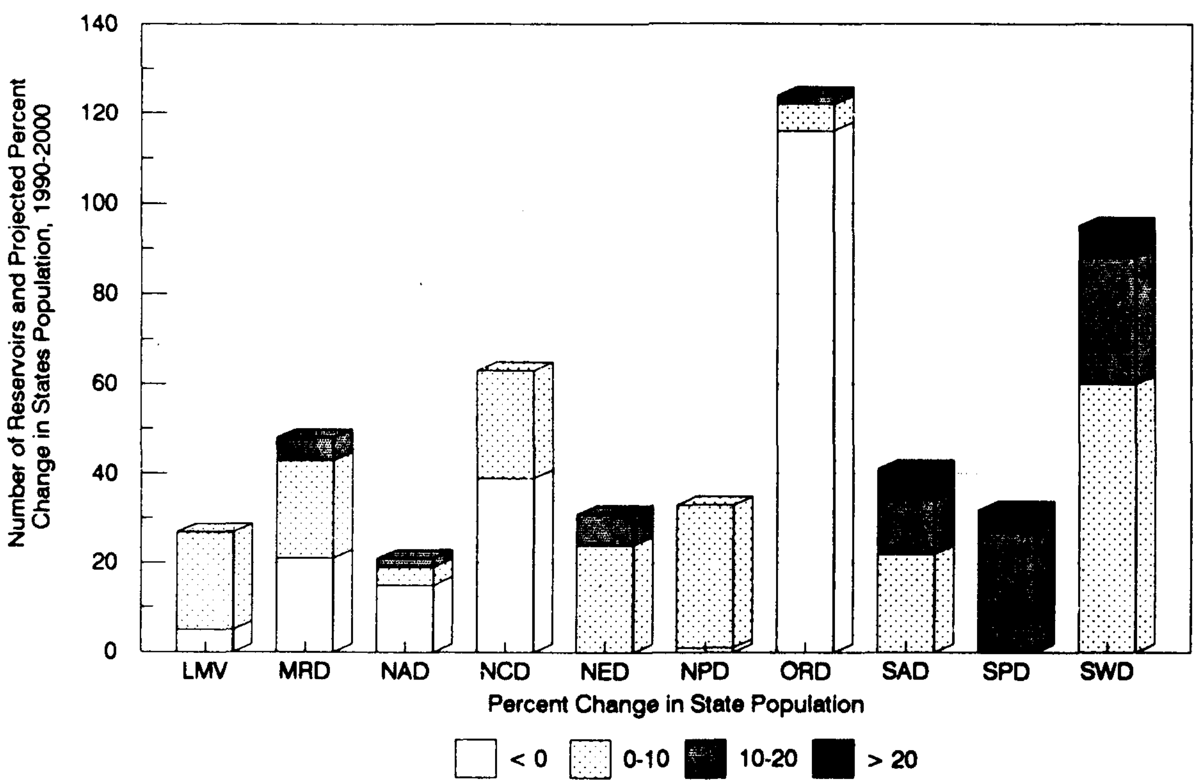

Figure 14. Number of Reservoirs by Division and Projected Percent Change in States Population, 1990-2000.
Source: U.S. Bureau of Census, 1988.

Growth of Water Use in the United States

While 86 percent of the Corps' multiple-purpose storage was in place by 1970, the nation's use of water resources for all purposes has continued to grow. This is illustrated in Figures 15 through 21. As the use of water has grown, the potential competition among purposes during drought has also increased. This is illustrated by the increase in requests to reallocate flood control storage capacity and in the growth of recreational use at reservoirs not originally authorized for recreation. While storage capacity authorized for flood control and conservation is fixed at the time the reservoir is constructed, growth and competition in water use will continue to influence the purposes served.

Flood Control. Figure 15 shows the growth of flood control storage capacity (exclusive and multiple-purpose) in Corps of Engineers' reservoirs. Flood storage has increased 55 million acre-feet since 1960. Although flood storage has been increasing annually, its rate of increase has slowed significantly. This decrease is due in part to the nation's environmental concerns, changes in project cost sharing, and changes from structural to non-structural measures to reduce flood damages (National Council on Public Works Improvements, 1987).

Navigation. Figure 16 shows a steady growth in inland waterway traffic, at an overall average annual rate of approximately 1.5 percent per year (U.S. Army Corps of Engineers, 1987). The tonnage transported has nearly doubled since 1960.

Hydroelectric Power. Instream withdrawals for hydroelectric power has increased more than three fold since 1950 (Figure 17). Instream use refers to water use taking place within the stream channel rather than water diverted and conveyed to the place of use. Some of the decrease in water use between 1980 and 1985 may be attributed to better estimating techniques that tend to produce estimates lower than previously reported (Solley et al, 1988).

Water Supply. Figure 18 shows the total surface and ground-water withdrawals between 1950 and 1980. The 10 percent decrease between 1980 and 1985 is attributed to waste treatment discharge restrictions mandated by the Clean Water Act of 1972 that made water reuse and conservation more cost effective. Water supplied from Corps of Engineers' multiple-purpose reservoirs to public water systems is approximately 9.5 million acre-feet (U.S. Army Corps of Engineers, 1987, 1988).

Irrigation. Figure 19 shows the offstream water withdrawals for irrigation in the United States between 1950 and 1985, as estimated by the U.S. Geological Survey. Offstream use represents water diverted or withdrawn from surface or ground-water sources and conveyed to the place of use. The reduction in withdrawals between 1980 and 1985 was mainly due to the decreased withdrawals from ground water, which resulted because of the increased cost of ground water, reduction and/or depletion of ground-water supplies, limited sites for new surface water developments, and the low value of the water used for irrigation compared to other offstream water uses (Solley et al, 1988).

Recreation. The Corps of Engineers administers over 4,400 recreation areas at 463 lakes and waterways across the United States. These projects provided over 550 million visitor-days of use in 1988. This is nearly a six-fold increase in the past 30 years. Figure 20 shows the growth of recreational use at Corps' reservoirs from 1952 to 1988.

Fish and Wildlife. Instream flow for fish and wildlife is a non-consumptive use, as is recreation, hydroelectric power, and navigation. Water is necessary to maintain the biophysical environment critical to fish and wildlife and does not require withdrawal from the stream, rather it requires assurance that a necessary and sufficient flow of water is maintained in the river. As concern over the habitat of fish and wildlife has grown, reservoir operations have responded by providing streamflows for this purpose. Changes in the magnitude and timing of reservoir releases are often sufficient to provide the needed water.

Water Quality. Concern for instream water quality has been a major national issue for about 20 years. The Administrator of the Environmental Protection Agency is authorized to determine the need for reservoir releases to maintain streamflows sufficient to maintain water quality. Efforts by the Corps of Engineers to develop effective management strategies to maintain adequate releases have increased in recent years (U.S. Army Corps of Engineers, 1982). This has made instream water quality an important purpose to be considered during drought.

Wetlands. Wetlands serve as both recharge and discharge areas in the hydrologic cycle. They are important habitat for fish and wildlife and offer a possible way to treat stormwater. The disappearance of wetlands may eventually lead to depletions in ground-water resources as the recharge capability of the surface-ground water system falls due to less recharge. In regions such as New England, many wetlands are underlain by a impermeable layer which causes infiltrating water to be discharged to adjacent streams and lakes. A recent trend has been toward the prevention of further wetlands development and toward creating new wetlands (U.S. Department of the Interior, 1984).

Ground Water. The nation's use of ground water has, for the most part, steadily risen since 1950 as shown in Figure 21 (Solley et al, 1988). Between 1950 and 1980, total ground-water withdrawals for all purposes increased approximately 162 percent. The cause for the more recent declines in ground-water withdrawals are discussed above under irrigation.

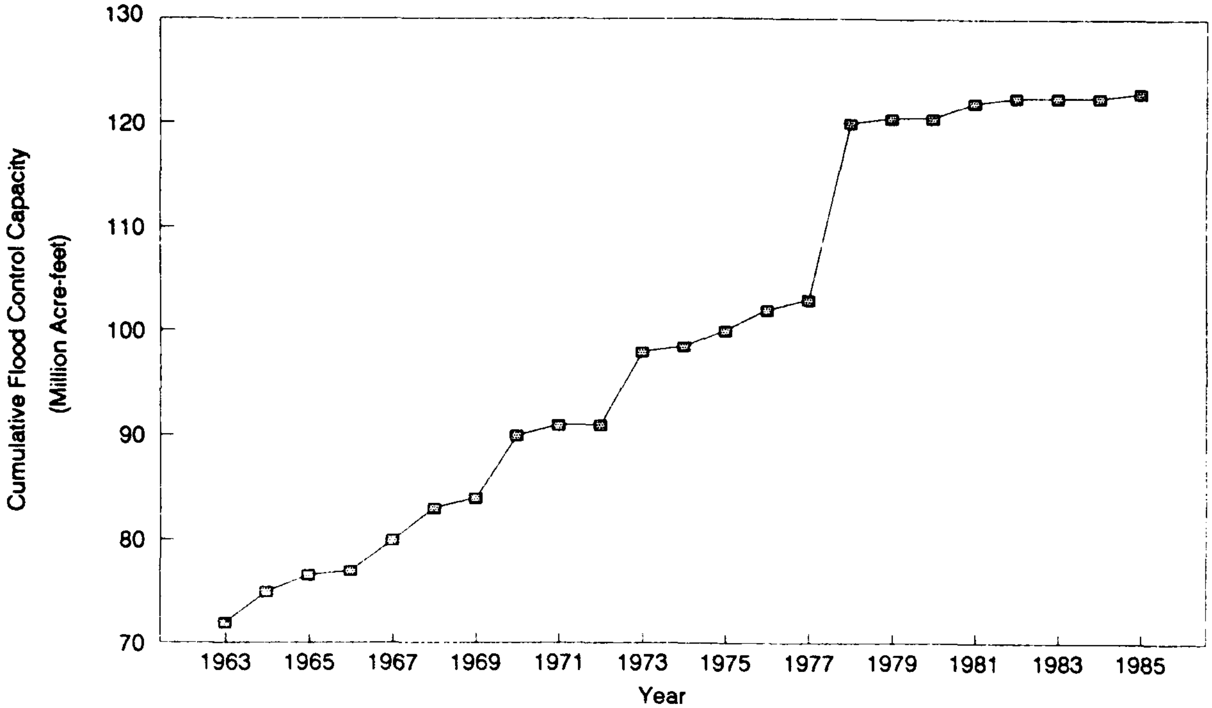

Figure 15. Cumulative Flood Control Capacity in Corps of Engineers' Reservoirs
Source: U. S. Army Corps of Engineers, Annual Reports of the Chief of Engineers for Civil Works

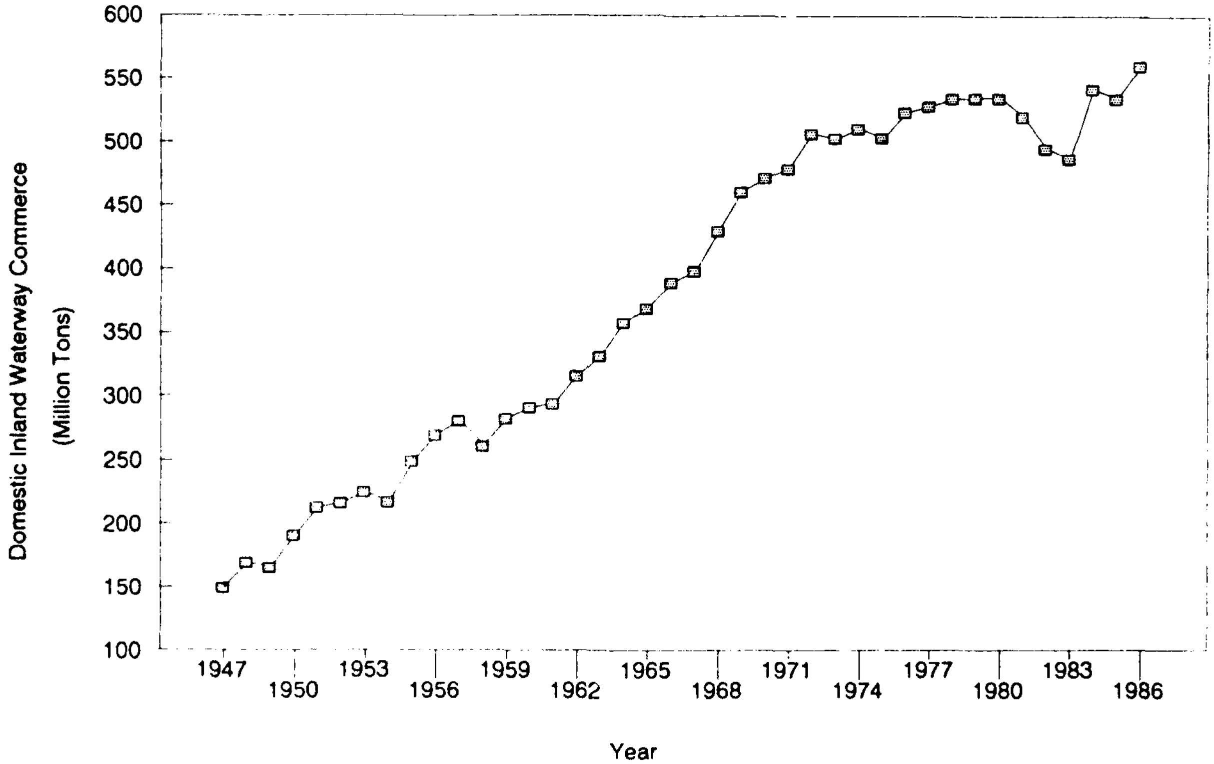

Figure 16. U.S. Inland Waterway Traffic
Source: Corps of Engineers, Waterborne Commerce of the United States, Annual Report 1987

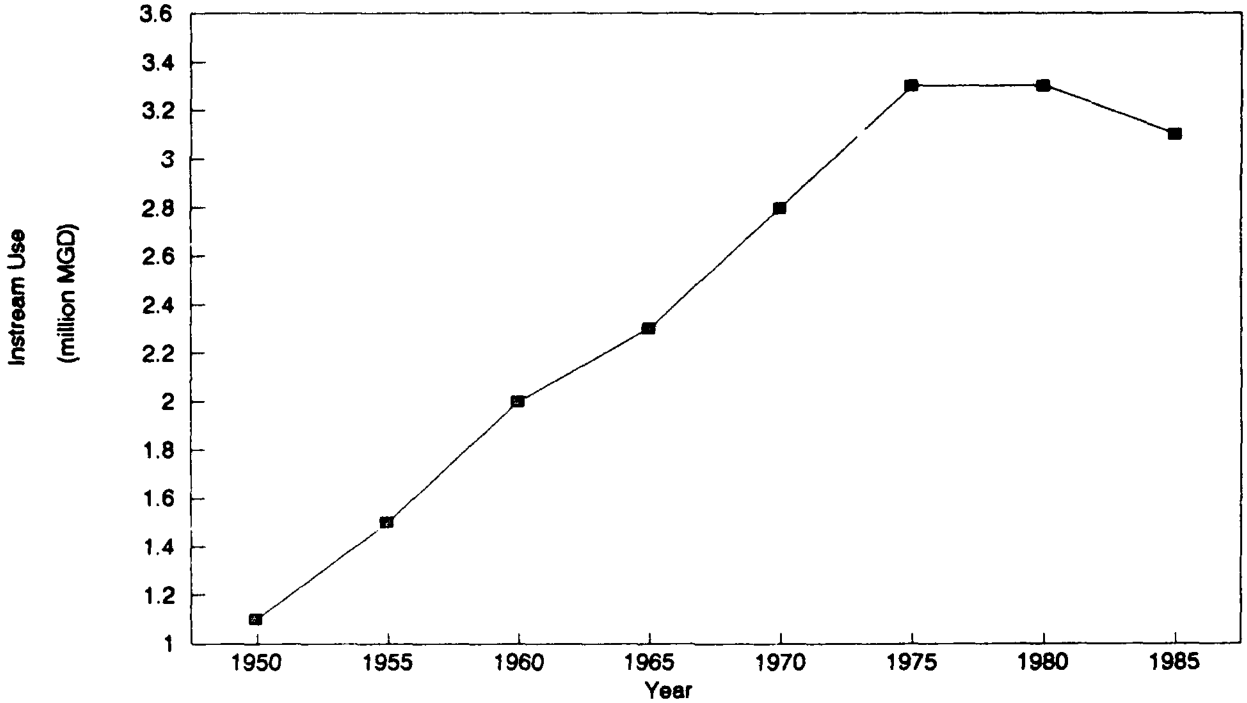

Figure 17. Hydroelectric Instream Use
Source: Solley et al, 1988

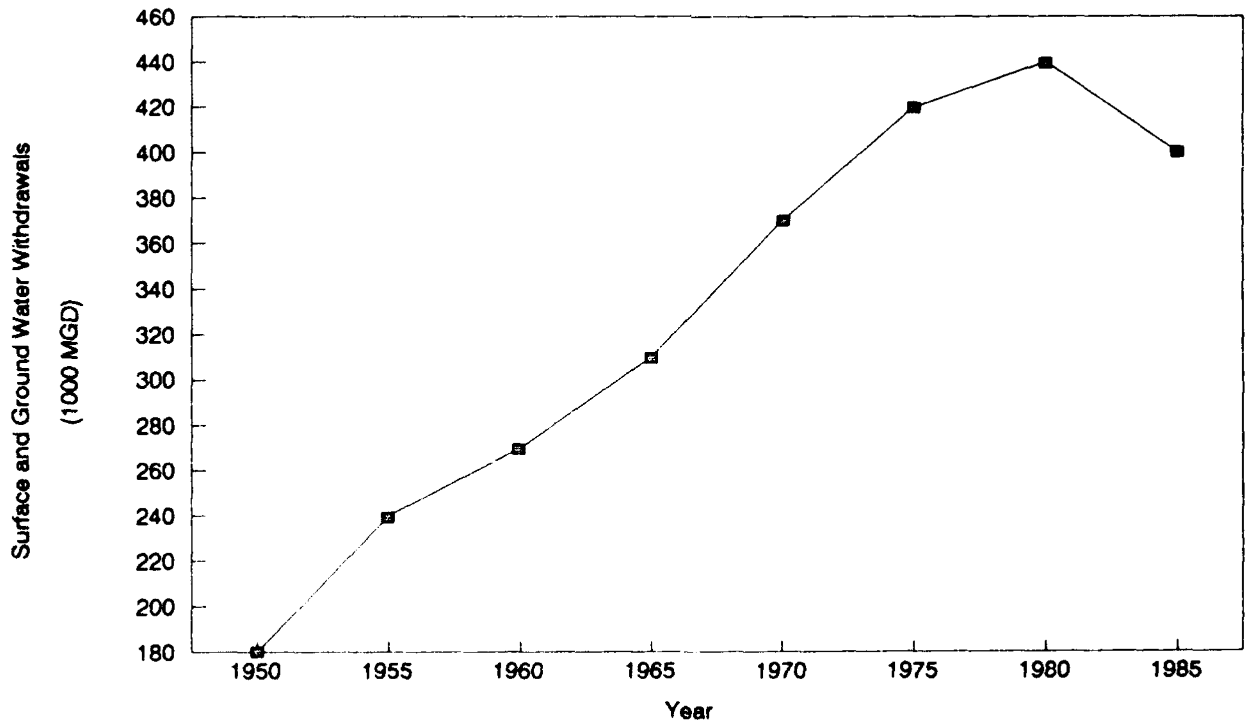

Figure 18. Surface and Ground Water Withdrawals in the United States
Source: Solley et al, 1988

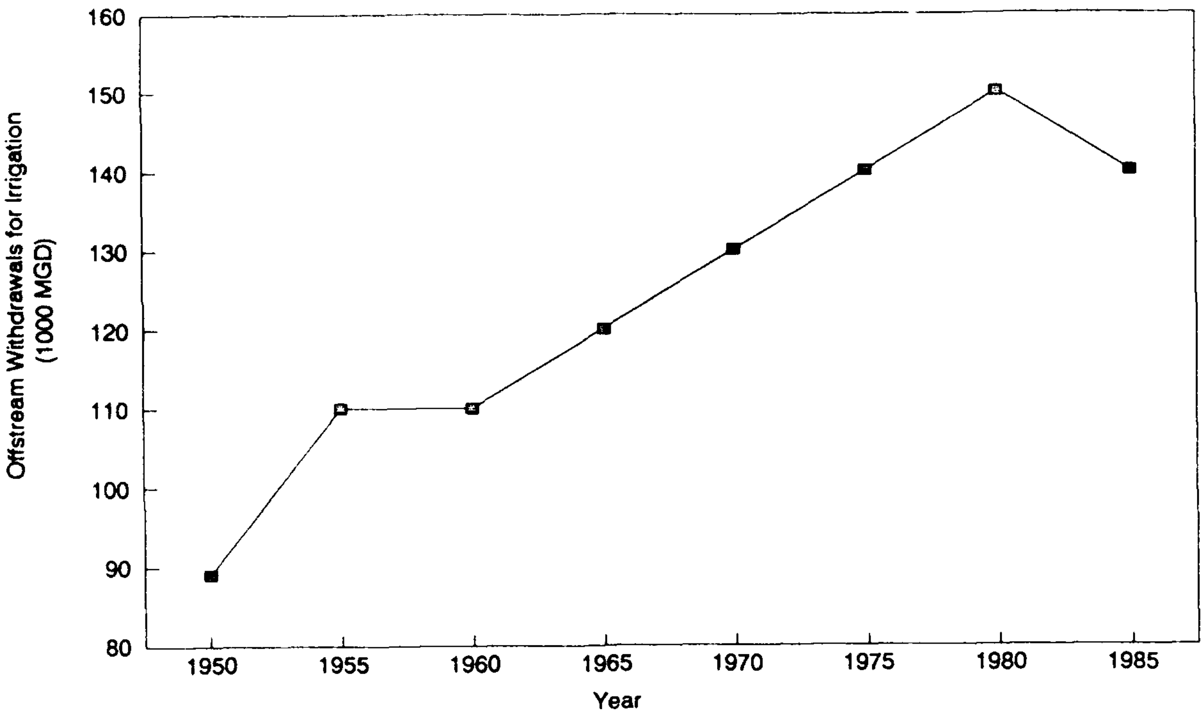

Figure 19: Irrigation Offstream Water Withdrawals
Source: Solley et al, 1988

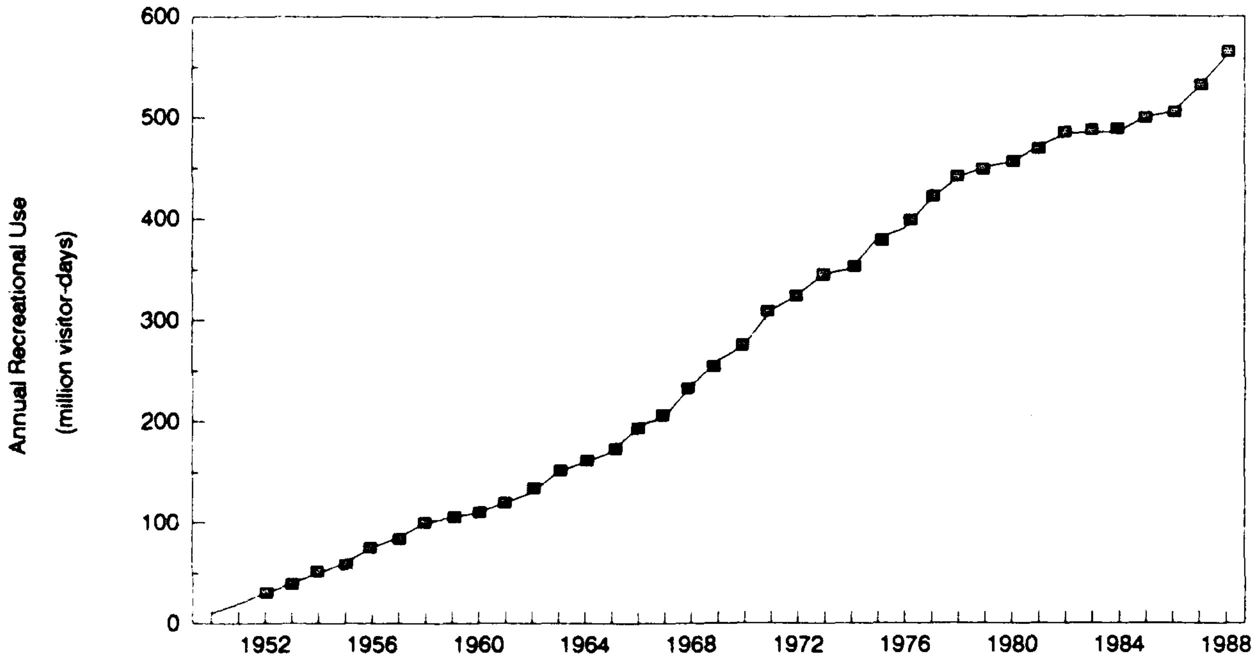

Figure 20. Recreational Use at Corps of Engineers Facilities
Source: U.S. Army Corps of Engineers, Natural Resources Management Branch, Washington D.C., 1989.

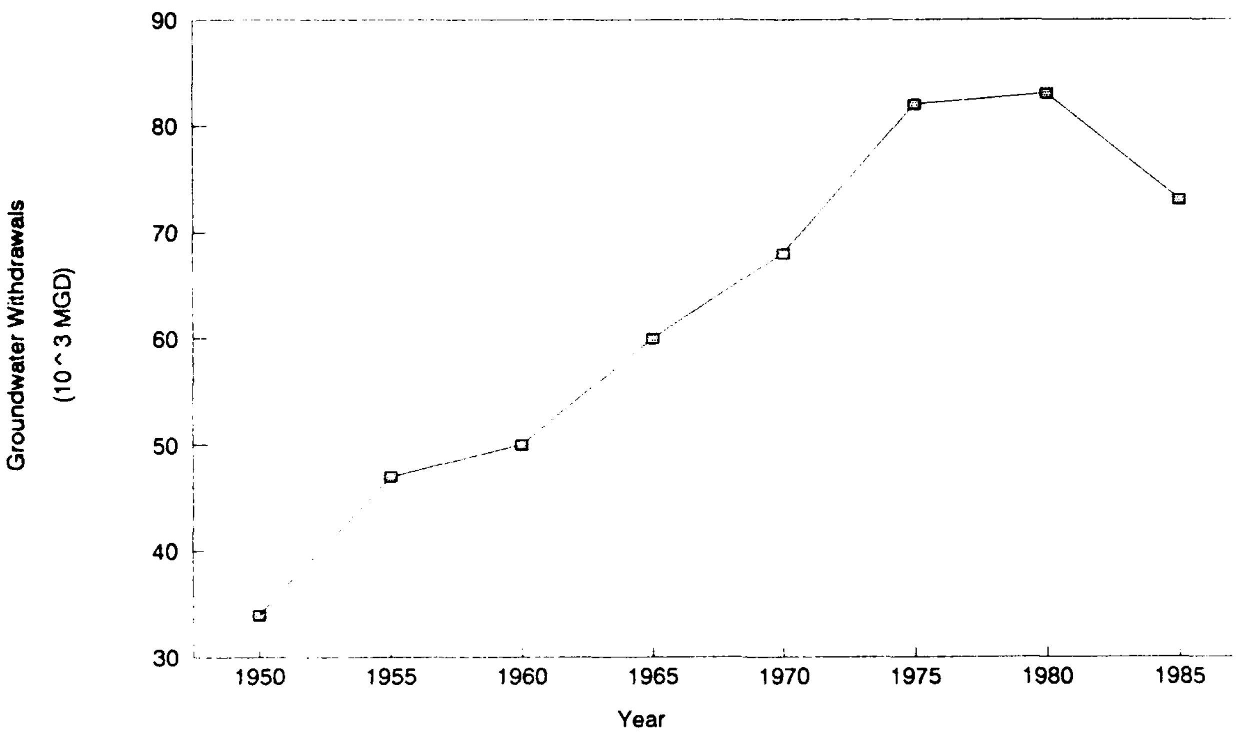

Figure 21. Groundwater Withdrawals
Source: Solley et al, 1988

Droughts and Reservoirs

Characteristics of Drought. Drought is defined in the *Glossary of Meteorology* as, "A period of abnormally dry weather sufficiently prolonged for the lack of water to cause a serious hydrologic imbalance (i.e. crop damage, water-supply shortage, etc.) in the affected area" (Huschke, 1959). This classical definition communicates the essential elements of drought but does not describe the complexities encountered in planning for drought (Dracup et al, 1980; Wilhite and Glantz, 1985). Drought, for example, can be characterized by less than normal precipitation, lack of soil moisture, low streamflow, below normal reservoir levels, or reduced ground-water storage. The lack of water that is implicit in each of these conditions, and the effects of this shortage, must both be considered when analyzing drought. A drought characterized by less than normal precipitation does not mean there is a water supply shortage, the reservoir is low, or even streamflow is low. Many hydrologic features need to be examined and each in a site specific way. Streamflow, for example, may originate from several sources such as natural runoff, ground-water, springs, or regulated flow. Reservoir levels are subject to operating rules and the size and nature of the watershed, in addition to the amount of precipitation. And water supply shortages require consideration of the source of supply, management measures, and demand.

Drought may be characterized by its duration, magnitude, severity, frequency, and areal extent (Dracup et al, 1980). Duration refers to the length of drought. Long-term droughts of ten years are likely to have a greater impact on reservoir storage than short-term droughts of one or two years. Drought magnitude is measured by the amount of shortage. For example, the inches of precipitation below normal, or the streamflow below the period of record mean. Severity is defined by Dracup (1980) as duration times magnitude. Severity is useful because it draws attention to the role both magnitude and duration play in drought. A drought of long duration and moderate magnitude may be as severe as one of short duration and a large magnitude. The frequency of drought is the number of occurrences of a given duration that are likely in a given period of time. For example, short duration droughts are more frequent in the historical record than those of long duration. The areal extent of drought is important because it determines the geographic extent of resources and uses affected. Droughts over large regions limit the transfer of water and may affect more uses than local droughts.

Historical Droughts. All regions of the country have experienced drought at some time. When drought is severe and causes a significant water shortage it is often identified by the years it occurred. For example, the "Dust Bowl" drought of the 1930's, the drought of the northeast during 1964-67, or the California drought of 1976-77. Table 2 lists the principal historical droughts in the contiguous United States from 1895 to 1989. They were identified by examining the drought literature, for example, Diaz (1983), Matthai (1979), Nace and Pluhowski (1965), Rosenberg (1978), Thomas (1962); by reviewing the monthly Palmer Hydrological Drought Index for the period (Karl and Knight, 1985); and through discussions with Corps' water control personnel in selected regions. They are designated "principal" droughts because of their significant duration, magnitude, and/or areal extent. Each drought serves as a reminder of the reality of water shortage in a historical context and of the need to plan for future occurrences. Many of the Corps' reservoirs did not exist during the earlier droughts, so the experience of reservoir operation during these events is not available.

Table 2

Principal Droughts in the Contiguous United States, 1895-1989

Region	Drought Periods			
New England	1908-1917	1925	1930	1947-1950
	1963-1967			
North Atlantic	1908-1911	1925-1926	1930-1931	1963-1967
South Atlantic	1895-1898	1903-1907	1925-1927	1954-1955
	1980-1981			
Ohio River	1899-1901	1930-1935	1939-1942	1952-1954
	1962-1964	1988		
North Central	1910-1911	1922-1924	1930-1931	1933-1934
	1952-1954	1962-1964	1976-1977	1988-1989
Lower Mississippi Valley	1896-1898	1924-1926	1933-1934	1952-1955
	1962-1963	1980-1981		
Southwestern	1899-1905	1909-1911	1924-1925	1933-1935
	1950-1957	1962-1964	1977-1978	
Missouri River	1897-1901	1910-1911	1931	1934-1937
	1939-1941	1954-1957	1959-1961	1976-1977
	1988-1989			
North Pacific	1922-1932	1973	1976-1977	1987
South Pacific	1897-1905	1924-1934	1954-1956	1959-1960
	1976-1977	1987-1989		

Palmer Hydrological Drought Index (PHDI). The Palmer Drought Severity Index (PDSI) is a widely used indicator of meteorological drought that standardizes soil moisture surplus and deficiency for different regions and from month to month. The National Weather Service and most Corps of Engineers' offices use the PDSI as a regional indicator. Some Corps' offices use the PDSI together with other indices, for example, streamflow and reservoir levels, to measure drought and develop appropriate responses. A discussion of the equations used to compute the PDSI and a review of the technical literature discussing its theory and evaluation and application in climatology and water resources is presented in Appendix 3.

A variation of the PDSI is the Palmer Hydrological Drought Index (PHDI). This is the index used in the analyses of this report. The PHDI uses the same principles of moisture supply and demand as the PDSI and during the maximum severity of a drought or wet spell it is identical to the PDSI (Karl and Knight, 1985). However, at the beginning and ending of droughts or wet periods the PHDI responds more slowly to change in weather. The advantage of this delayed response is that while the weather may return to normal, there may still exist a deficiency in soil moisture, streamflow and lake levels. A slower response time allows for the recovery of these hydrologic features and is a better index of hydrologic drought.

The PHDI is used in this study as a first look at the susceptibility of Corps of Engineers' reservoirs to drought. For each geographic region, it is used to examine the historical droughts, identify differences in drought duration, analyze the frequency of occurrence, and to provide a preliminary assessment of the nature of drought affecting purposes served by Corps' reservoirs. While the PHDI is a useful index of drought, it is not a direct measure of streamflow or other hydrologic features. However, because it accounts for moisture supply and demand, it does reflect, qualitatively, water deficiencies in these hydrologic features. To illustrate this, correlations between PHDI, precipitation, and runoff data were analyzed at stream gages in each of the ten Corps' divisions in the continental United States. These correlations are discussed under the regional assessments of this report. Sufficient correlation exists to justify use of the PHDI for this study and its objectives.

Susceptibility of Reservoirs to Drought. The Palmer Hydrological Drought Index (PHDI) is shown monthly from 1895 to 1983 on maps of the contiguous United States by Karl and Knight (1985). It is also available in digitized form from the National Climatic Data Center for the 344 climate divisions in the contiguous United States from 1895 to the present. In this study the monthly PHDI, 1895 to 1989, is used to assess the susceptibility of Corps of Engineers' reservoirs to drought. Following Karl and Knight (1985), three drought categories are used: mild to moderate drought (PHDI=-1.5 to -3.0), severe drought (PHDI=-3.0 to -4.0), and extreme drought (PHDI<-4.0). Using these categories the historical occurrence of drought is examined. While the extreme category represents the greater moisture deficiency, there are few occurrences. The mild to moderate category will occur more often because it is nearer to normal, however, it represents only a moderate water shortage. The analyses and figures of this report use the severe and extreme categories (PHDI<-3.0). These categories were selected because they are more likely to represent a corresponding decrease in streamflow, lower reservoir levels, and have a potentially greater impact on reservoir operations. However, the number of consecutive months in this range will be less than if the mild to moderate droughts are included (PHDI<-1.5). For comparison purposes, the duration of droughts in the mild to extreme range are also discussed.

The PHDI values are not linear and, therefore, should not be averaged. A month with a PHDI equal to -4.0 is not twice as deficient as a month with a PHDI of -2.0. Similarly, three consecutive months with PHDI's of -2.0, -3.0 and -4.0 should not be understood as having an average PHDI of -3.0. Also, two PHDI's of the same value, but in different regions of the country, do not represent the same deficiency in moisture. For example, a PHDI of -4.0 in Arizona where the average precipitation is 14 inches, does not represent the same inches of moisture shortage as a -4.0 in North Carolina where the average precipitation is 50 inches. The climate divisions were created by state climatologists and are used by the National Weather Service for collecting, storing and referencing climatological data (Appendix 3). Each division represents a reasonably homogeneous climate area within a state.

Figures 22 through 26 show droughts of different durations in the climate divisions of the contiguous United States. Figure 22 shows those areas where drought in the severe or extreme range has not exceeded 12 consecutive months. Figure 26 shows the climate divisions where severe or extreme droughts of 48 consecutive months or longer have occurred. Each shaded climate division in Figure 26 has had, during the period 1895 to 1989, at least one period when the PHDI was in the severe or extreme range for 48 consecutive months or longer. Figure 25 shows climate divisions where severe or extreme droughts as long as 36 to 48 consecutive months have occurred. Figure 25 does not show the climate divisions covered by Figure 26 even though those climate divisions shaded in Figure 26 include droughts of lesser duration. Figures 22 through 26 are incremental, not cumulative displays.

Overlaying Figures 25 and 26 illustrates the findings of climatologists that the interior portions of the United States, in this case predominately the Great Plains, are more susceptible to prolonged drought than the coastal areas (Diaz, 1983). Also, it is not unusual to have climate divisions adjacent to one another with different physical geographies and drought durations. The Sacramento Valley and North Coast of California, for example, are an interior valley and a coastal mountain range which have very different physical features.

The frequency of droughts of different durations is also analyzed. One difficulty with computing frequency of drought, however, is the small record sample available. Unlike floods where a peak value is selected for each year, droughts of duration longer than a single year have fewer potential occurrences. A 95 year record, for example, will have 95 annual peak flood values but only 19 possible drought periods if a duration of 60 months is considered. A 120 month drought will have a maximum of 9 values in a 95 year record. This, together with the problem of distinguishing independent events, makes the computation of drought frequency from gaged records difficult at best and statistically questionable at worst. In this study the number of occurrences of drought as described by the PHDI is examined for different durations in the 95 year record. It is found that for the longer duration droughts (>48 consecutive months) in the severe or extreme range, the record has only one occurrence. As the duration gets shorter the number of occurrences increases. For 36 months, the number of occurrences increases to two in a handful of climate divisions, one in most. For a 24 month drought, the number of occurrences in the record increases to four for a few divisions, less than four for most. At 12 months, the number of occurrences increases to a maximum of eight. When drought in the mild to moderate range (<-1.5 PHDI) is considered, the number of occurrences in the record increases by approximately 50 percent.

Using the PHDI, the susceptibility of reservoirs to drought is investigated by determining the maximum number of consecutive months of severe or extreme drought at each reservoir location. Figure 27 shows the results of this analysis. Only 14 percent, or 52 multiple-purpose reservoirs with a multiple-purpose capacity of 5,007,000 acre-feet, are susceptible to severe or extreme drought longer than 36 consecutive months. There are 152 multiple-purpose reservoirs (39 percent) susceptible to durations of severe or extreme drought longer than 24 months. Twenty-seven reservoirs with a multiple-purpose capacity of 6,832,000 acre-feet are in climate divisions that historically (1895-1989) have not exceeded 12 consecutive months of severe or extreme drought according to the PHDI. All of the other reservoirs represented by Figure 27, however, have had durations greater than 12 months. This analysis is described in greater detail for each division of the Corps under the regional assessments of this report.

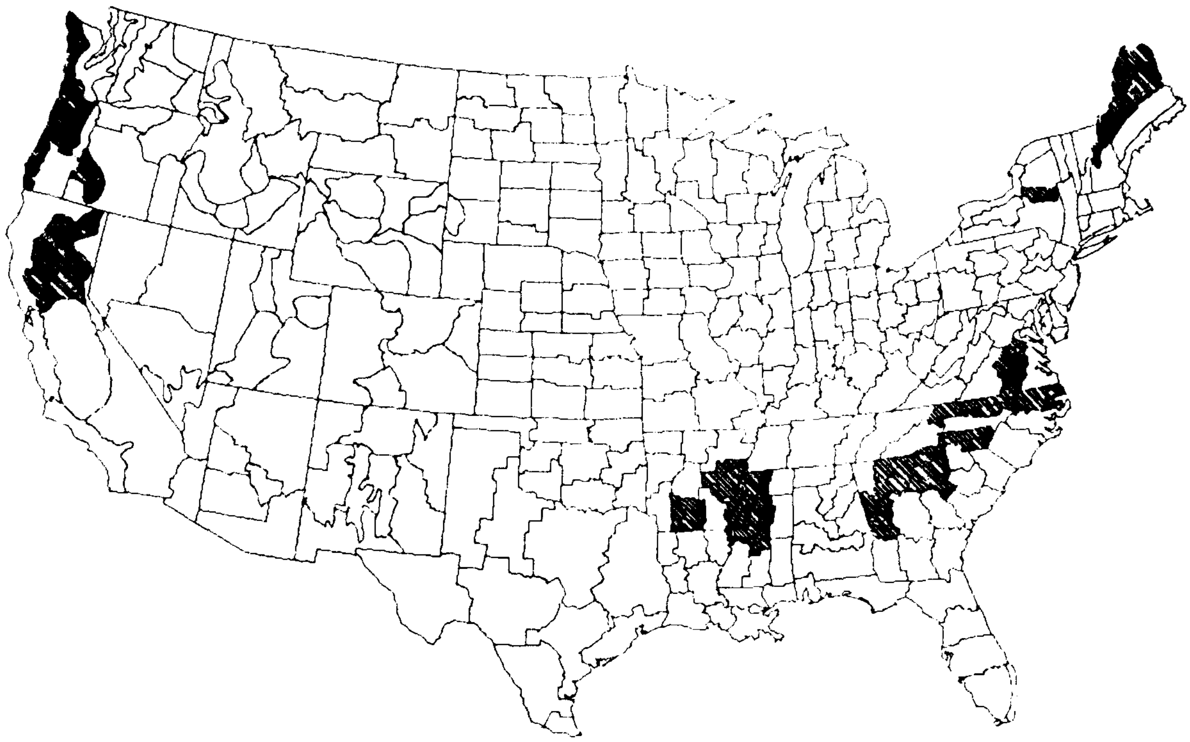

Figure 22. Climate Divisions with Severe or Extreme Droughts of <12 Consecutive Months Duration (PHDI)

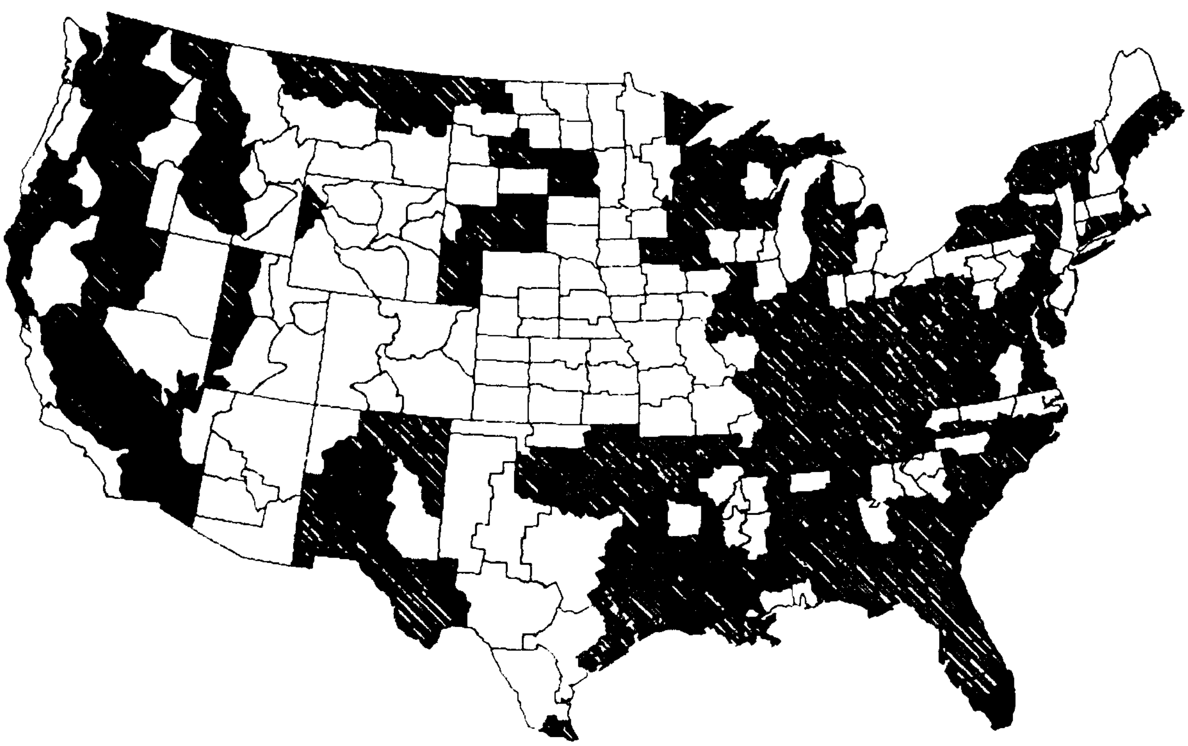

Figure 23. Climate Divisions with Severe or Extreme Droughts of 12 to 24 Consecutive Months Duration (PHDI)

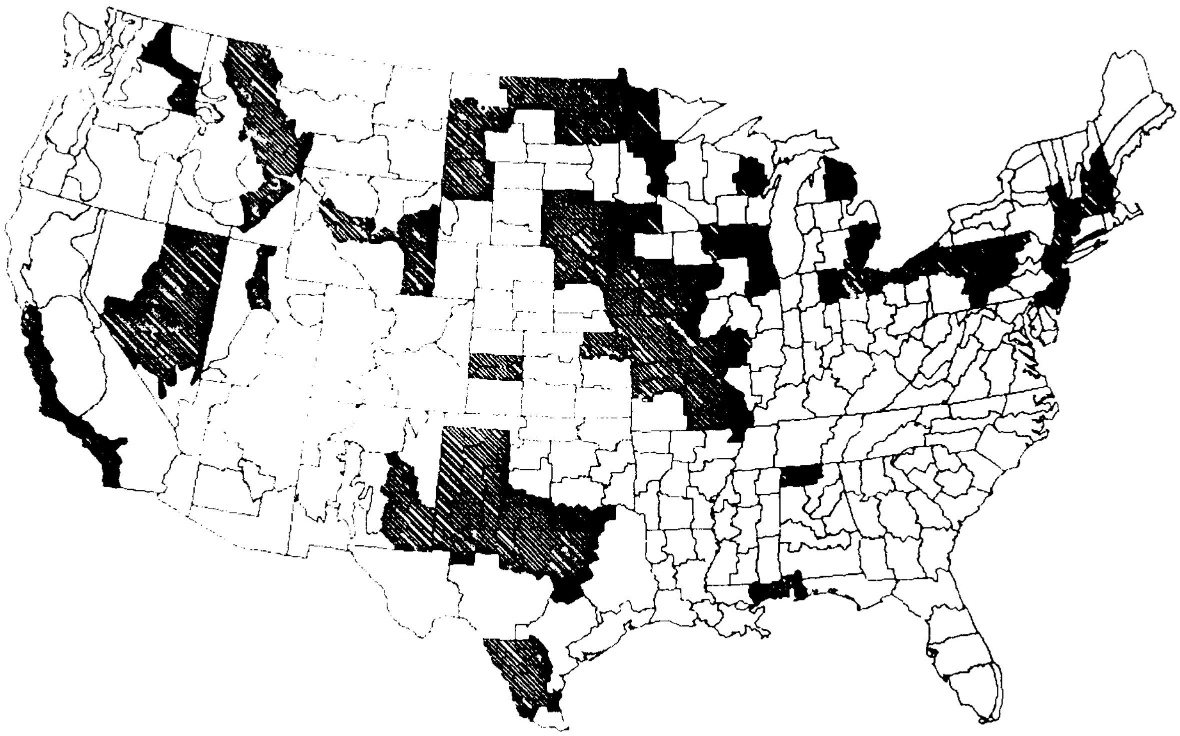

Figure 24. Climate Divisions with Severe or Extreme Droughts of 24 to 36 Consecutive Months Duration (PHDI)

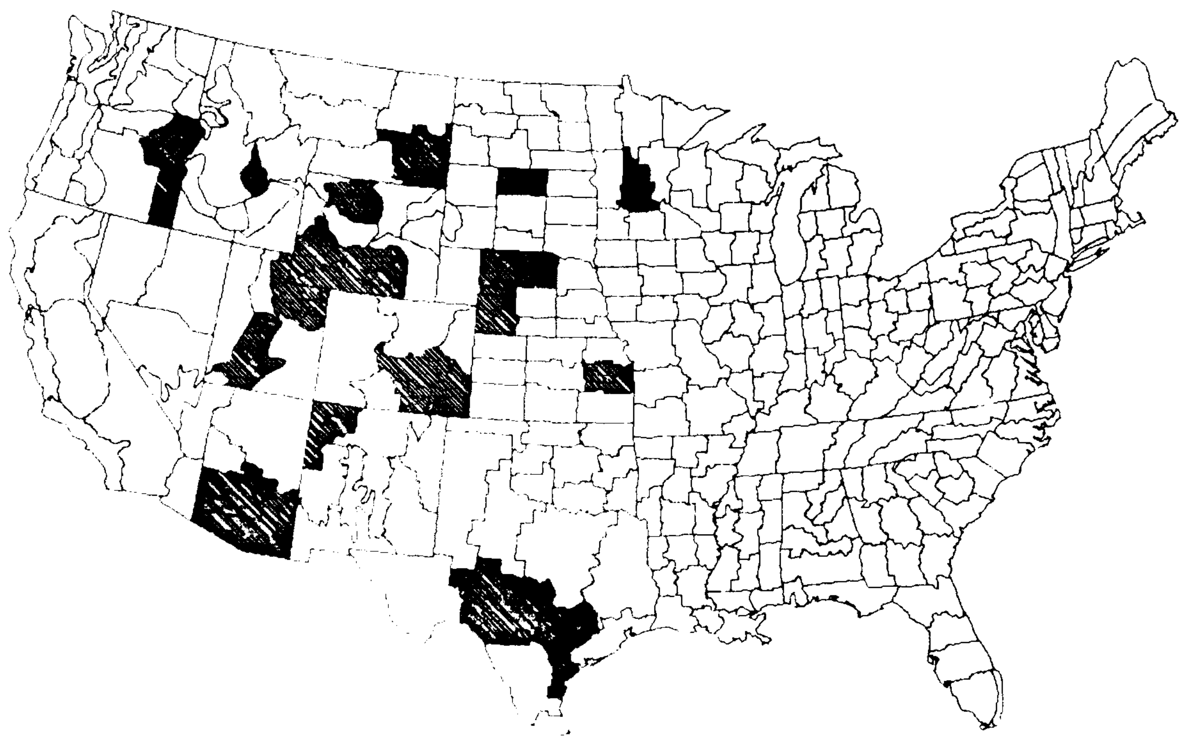

Figure 25. Climate Divisions with Severe or Extreme Droughts of 36 to 48 Consecutive Months Duration (PHDI)

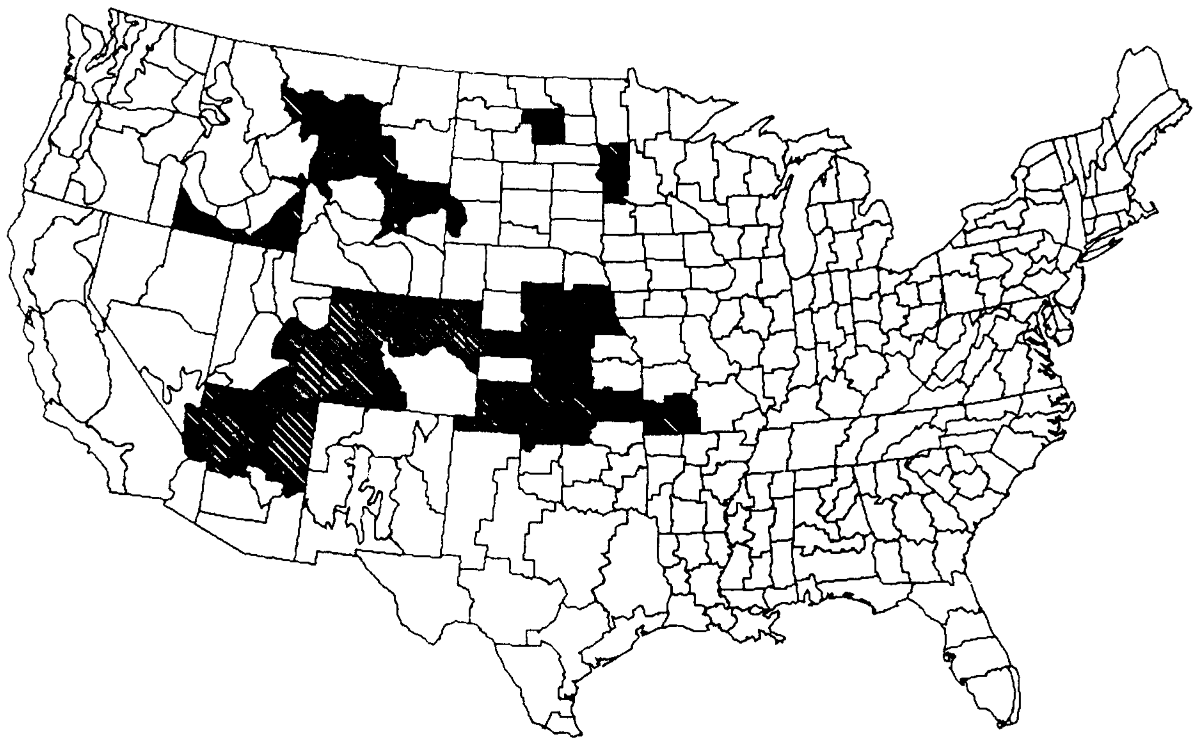

Figure 26. Climate Divisions with Severe or Extreme Droughts of >48 Consecutive Months Duration (PHDI)

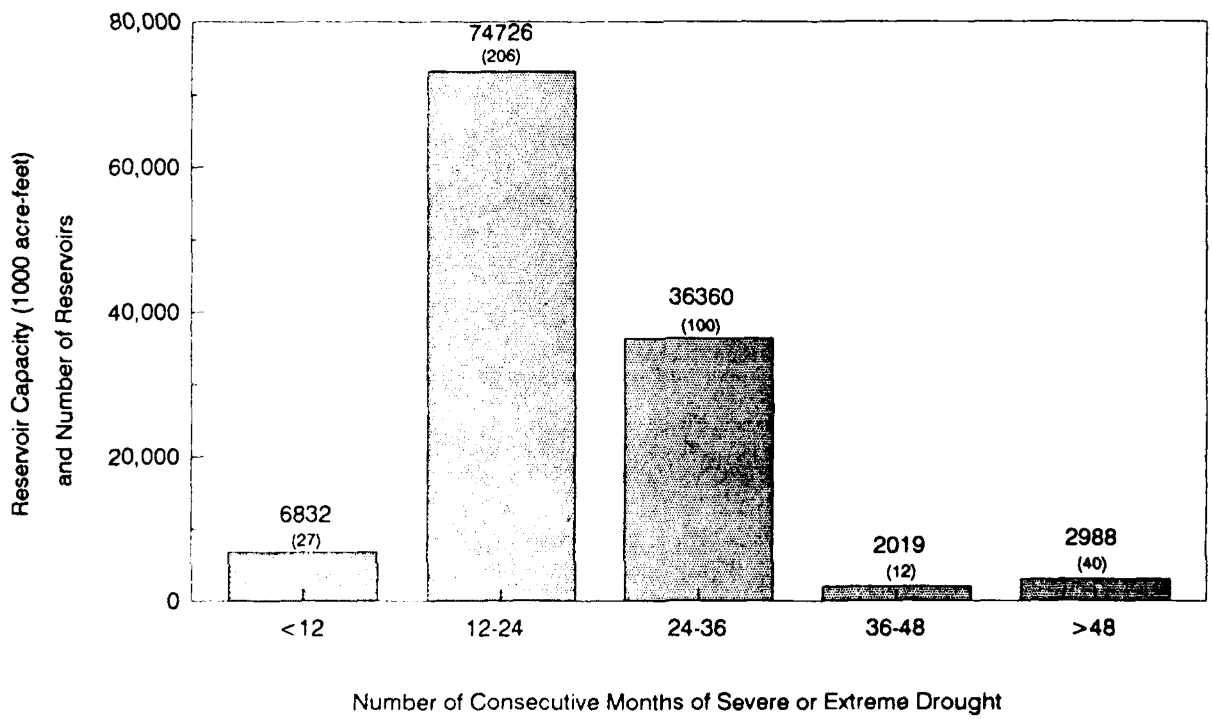

Figure 27. Multiple-Purpose Reservoirs in Climate Divisions with Severe or Extreme Droughts of Different Duration (PHDI) During the Period 1895-1989

Reservoir Management for Drought

This preliminary assessment using the Palmer index provides a national and regional perspective on Corps of Engineers' reservoirs and drought. There are, however, many factors that are important to improving reservoir management that are not included in this study because of its regional nature. These can be considered by examining individual reservoirs, their purposes, and drought in the specific context in which each reservoir operates. While such an examination is beyond the scope of this study, some of the tasks are briefly described below.

Defining Drought. The duration, magnitude, severity, frequency, and areal extent have been identified as five common characteristics of drought. They are applicable to drought whether measured by the Palmer index, precipitation, streamflow, or reservoir level. Part of the task of improving the response to drought is to define drought for the reservoir being examined. This may involve looking at several measures of drought, extending short-record data, using stochastic analysis, and considering the effects of drought on the region. As the areal extent becomes greater, additional reservoirs, interconnections, purposes and institutions are affected. An accurate description of drought is necessary to assess its impact on reservoir purposes.

Reservoir and Streamflow Requirements. Each reservoir purpose, with the exception of in-reservoir recreation, fish and wildlife, and slack water navigation pools, has associated with it releases or downstream flow requirements. Each purpose often has several target levels, for example, desirable, minimum, and maximum streamflow. If the flow requirement is entirely dependent upon releases from a reservoir, as with hydroelectric power, then a reduction in release will directly affect that purpose. Some purposes are met from joint releases, for example, downstream withdrawals for water supply, instream water quality, and river recreation and fishery. Other requirements are seasonal, for example, fish spawning, which may only last a few weeks during certain times of the year. It is important in planning for drought to consider the streamflow requirements of each purpose from minimum to maximum, how they compete with or complement other purposes, their seasonal variation, their timing, and their required storage capacity.

Reservoir Capacity. Streamflow requirements must not only be established but they must also be converted into reservoir storage space to evaluate the capability of the reservoir to meet project needs during drought. Translating streamflow to storage requires consideration of the characteristics of historical droughts and the flow requirements necessary to serve each purpose. This is normally done at the time a reservoir is designed by considering the authorized purposes and droughts of record. A re-evaluation may be undertaken when the purposes change or more severe droughts occur. Such analyses commonly use a reservoir simulation model with drought hydrology. To accurately simulate low-flow conditions, other hydrologic features such as reservoir evaporation, return flow and stream gains and losses must be taken into account. Simulation effectively performs an accounting of water in the reservoir and river downstream and establishes the adequacy of reservoir capacities to meet the purposes. This is an essential part of drought planning.

Flexibility of Operation. Individual reservoirs, or systems of reservoirs, can respond more effectively to drought if they have the flexibility of operation to adapt to uncertain conditions. Flexibility of releases and reservoir levels, seasonal changes, system operation, and cooperation between Corps' offices and other agencies provides this needed capability. More socially desirable purposes are less vulnerable when maximum flexibility is available because changes can be made to meet those purposes. Conversely, purposes viewed as less desirable by the public will be more vulnerable because flexibility allows these purposes to be given lower priorities. Flexibility of operation can be developed by examining alternative operating plans before a drought occurs. Computer simulation provides the necessary analytical tool to do this.

Alternative Sources. Reservoir purposes that have alternative sources of supply are less vulnerable to drought than those that do not. Alternatives to hydroelectric power, for example, include hydropower at other sites, integrated power networks, thermal and nuclear power. Alternatives to navigation include rail and highway transportation. Water supply and irrigation needs are often met by other surface storage sources or ground water. Recreation may shift from water-based or river recreation to other forms of recreation not water based, or may temporarily shift from the drought area to other areas. Fish and wildlife and instream water quality are most vulnerable because of their dependence upon instream flow. A natural supply system of ground water inflow, springs, and tributaries can reduce these impacts, however, they may also be low during drought. An important task of drought planning is the identification and evaluation of alternative sources of water for each reservoir and its purposes.

Consequences of Shortage. Water supply shortages are serious because they have the potential to threaten human life, disrupt business and commerce, reduce industrial output, and adversely affect social well-being and the environment. Some purposes feel direct economic consequences of water shortage; hydroelectric power is an example. While it may be possible to purchase substitute power from alternative sources, there is usually an increased economic cost. Other purposes may be adversely effected, however, the impact is not easily translated into economic terms. It is necessary to assess the consequences of water shortage to identify the economic, environmental and social trade-offs between purposes.

Data and Decision Criteria. Good data, a knowledge of the important decision determinants, and the availability of appropriate decision criteria all aid in effective decision-making. Such information is not as readily available for low-flow conditions as it is for flood flows. Water intake elevations along rivers, for example, have only recently been obtained by some offices. Such elevations and corresponding minimum low-flow requirements are necessary to determine releases to meet downstream withdrawals for water supply. Return flows, ground-water inflows and other elements of low-flow hydrology are often not known. Water losses along river reaches and from reservoirs are also important elements. Water rights is a major determinant in meeting water needs in many regions. The riparian system of the east, the appropriative system of the west, and the joint system of some states affect the extent and way in which the needs of various purposes are met. The availability of calibrated and verified computer simulation models can contribute significantly to the decision-making process. The work of developing good data, methods of analysis, and decision criteria for low-flow conditions remains to be done in many Corps' offices.

REGIONAL ASSESSMENTS

New England (NED)

Reservoir Capacities and Purposes. Corps' reservoirs in this region store water primarily fo· flood control with only a small volume stored for municipal water supply, recreation, and hydroelectric power (Tables 3 and 4). Approximately 1.1 million acre-feet are reserved for flood control with the largest reservoir having a flood control capacity of 150,000 acre-feet. In addition to the 31 reservoirs with exclusive flood control storage (Table 3), there are four reservoirs, not included in this analysis, that were built by the Corps but have been turned over and are maintained by the state. Including the four reservoirs maintained by the state, fourteen of the flood control reservoirs are dry bed.

The multiple-purpose capacity of the reservoirs is small; less than 60,000 acre-feet. The principal purposes served are flood control and river and reservoir recreation. Table 4 identifies the purposes served by the 31 reservoirs in the region.

Drought Effects. The effects of drought are limited to the small storage reserved for recreation, hydroelectric power, and water supply. Both river and reservoir recreation are harmed by reduced streamflow during drought. Less release also reduces generated power for local power companies. Most cities in the region depend upon reservoir storage for water supply, thus the possible use of existing flood control capacity for water supply is attractive to municipalities and water agencies. The Corps regularly receives inquiries about the feasibility of reallocating storage and this is likely to increase in the future as the population of the northeast continues to grow. The population of New England is currently about 13 million people. Projections for the next 10 years are for a 5 percent increase for most states except New Hampshire with a 16.7 percent increase. Current authorization of Corps' projects, however, is for flood control. A reallocation of storage from flood control to water supply requires an assessment of the impact of that change and where the impact is significant the reallocation requires Congressional approval.

Susceptibility of Reservoirs to Drought. Climate divisions with severe or extreme drought of various durations are shown in Figure 28. All reservoirs (exclusive and multiple-purpose) are located in climate divisions with severe or extreme droughts that have not exceeded 36 months duration according to the Palmer Hydrological Drought Index (PHDI). Figure 29 shows the number and capacity of the 21 multiple-purpose reservoirs susceptible to droughts of 12 to 24 and 24 to 36 consecutive months duration. The six multiple-purpose reservoirs with zero conservation storage are flood control reservoirs with recreation at the bottom of the flood pool. The 15 multiple-purpose reservoirs with 57,000 acre-feet capacity are in climate divisions where historically (1895-1989) severe or extreme droughts have been of less than 36 consecutive months duration.

If droughts in the mild to moderate range are included in the analysis, durations greater than 36 consecutive months are found. The 1960's for example, show a duration of over 60 months where the PHDI was in the mild to extreme range.

Comparison of PHDI, Precipitation, and Runoff. Figure 30 compares PHDI, cumulative monthly precipitation deficit and annual runoff at a gage in Connecticut for the 1960's drought. The purpose of the comparison is to show the correlation between the three measures of drought. The top figure shows a plot of monthly PHDI for the 1960's drought in New England. The center figure is the cumulative precipitation deficit for the same period. A deficit is computed for each month as the difference between the long-term average for the month and the actual precipitation for the month. These deficits are then summed from the beginning of the drought to the end. The bottom figure shows the annual runoff for each water year (October 1 to September 30) summed from daily values. A comparison of these figures shows the PHDI is in the severe or extreme range (<-3.0 PHDI) 1964 to 1967, about 28 months. At the same time the region experienced a cumulative precipitation deficit and lower annual runoff. One aspect of drought which can be illustrated from these figures is recovery. While runoff may return to normal in the years following a drought (1968-71 in Figure 30), this does not mean the region and its storage facilities have recovered to pre-drought levels. The cumulative precipitation deficit, for example, increases during the drought years, however, when precipitation returns to near normal (indicated by the leveling off, 1967-72), the deficit does not return to zero. This would take several particularly wet years. The significance of recovery is that unless a reservoir recovers to the top of conservation soon after a drought, it may remain down even though runoff is normal. Should another drought occur, it could be more critical than the first because the reservoir begins with less storage.

TABLE 3

NEW ENGLAND (NED)
RESERVOIR STORAGE

Purpose	Number of Reservoirs	Storage Capacity (Acre-Feet)
Flood Control (Exclusive)	31	1,099,000
Navigation (Exclusive)	0	0
Hydroelectric Power (Exclusive)	0	0
Multiple-Purpose	21	57,000
TOTAL	31	1,156,000

TABLE 4

NEW ENGLAND (NED)
NUMBER OF RESERVOIRS SERVING EACH PURPOSE
WITH EXCLUSIVE OR MULTIPLE-PURPOSE STORAGE

Purpose	Number of Reservoirs
Flood Control	31
Navigation	0
Hydroelectric Power	2
Irrigation	0
Water Supply	3
Fish and Wildlife	1
Recreation	21
Low-Flow Augmentation	0

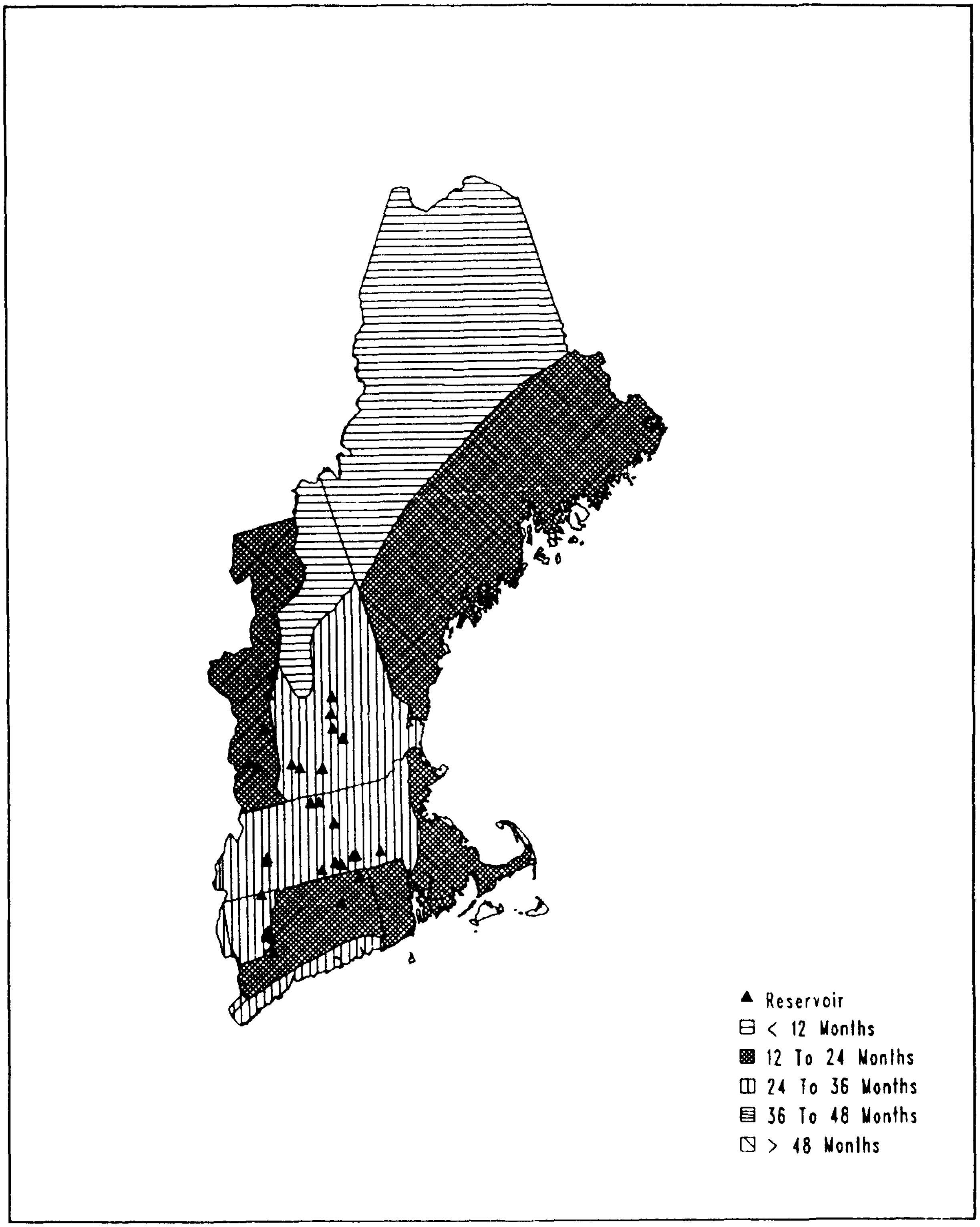

Figure 28. New England Division. Climate Divisions with Severe or Extreme Drought of Different Durations (PHDI)

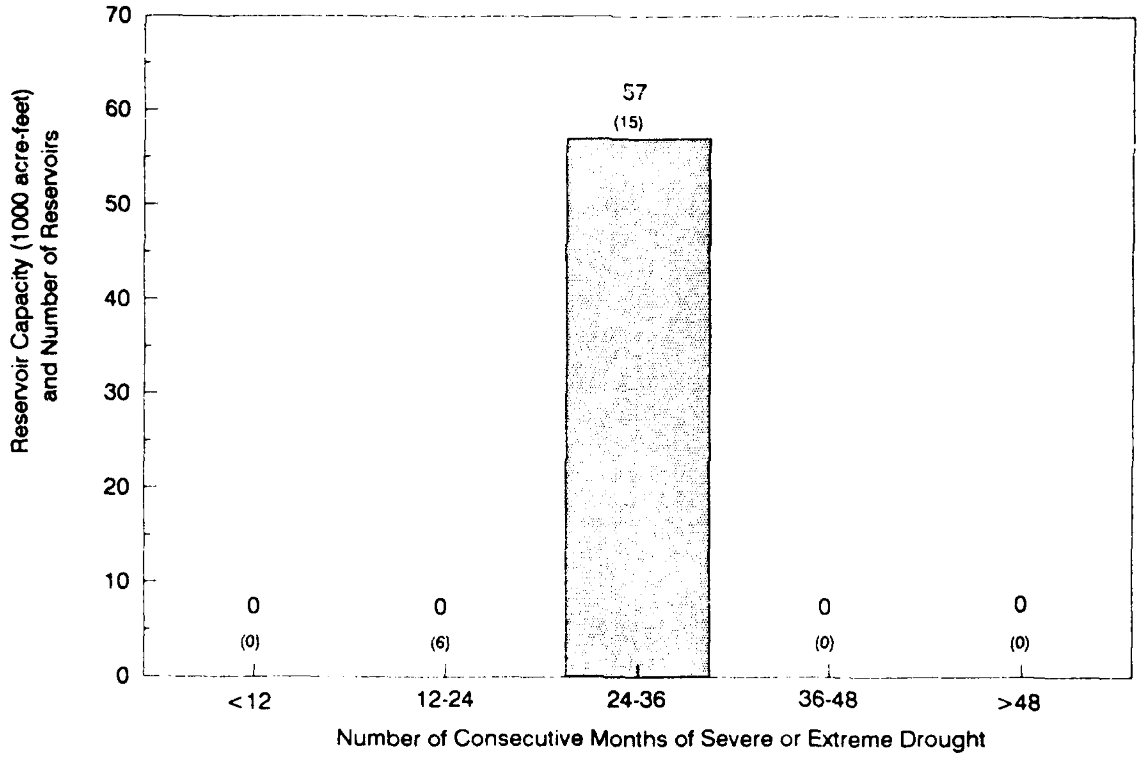

Figure 29. New England Division. Multiple-Purpose Reservoirs Susceptible to Severe or Extreme Droughts of Different Durations (PHDI)

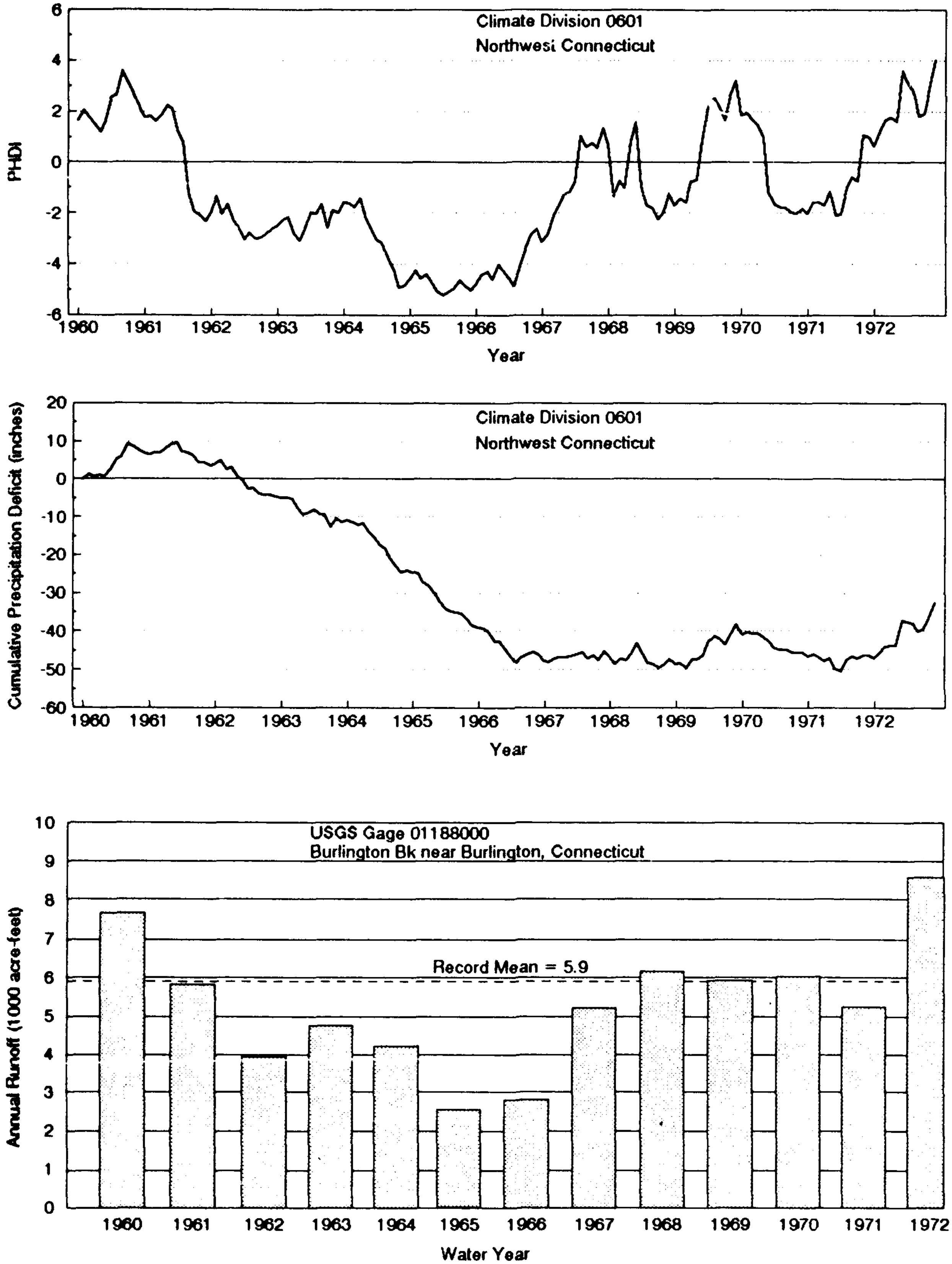

Figure 30. Comparison of PHDI, Precipitation, and Runoff for 1961-67 Drought

North Atlantic (NAD)

Reservoir Capacities and Purposes. All 21 reservoirs in this region have exclusive flood control storage as a project purpose. Total flood control capacity is 1.2 million acre-feet (Table 5). When drought conditions are anticipated, the conservation pool is sometimes raised 0.5 to 1.0 feet to store additional water for water supply and instream water quality. The pool may also be raised to provide additional storage for whitewater recreation downstream. In both cases, this requires small volumes of flood control capacity to be used temporarily to serve conservation purposes.

While flood control is the principal purpose served by these projects, they also have multiple-purpose capacity to serve reservoir recreation, whitewater recreation, instream water quality, and water supply (Table 6). Seventeen reservoirs have reservoir recreation activities. Blue Marsh and Jennings Randolph Lakes have the greatest visitation with over 1.4 million visitor-days annually. Recreation at each of the other reservoirs is more than 500,000 visitor-days. Water supply is stored at five reservoirs with a total conservation capacity of about 180,000 acre-feet.

Drought Effects. While the storage capacity for water supply is relatively small, and only five reservoirs provide storage, water supply is important during drought because of the dependence of the region upon surface water. Relatively small quantities of water supply storage can be effective in reducing the affects of drought for municipalities and water purveyors. Recreation and instream water quality are affected as the pool elevation is drawn down and less water is released.

Susceptibility of Reservoirs to Drought. In this region, all reservoirs (exclusive and multiple-purpose) are located in climate divisions with durations less than 36 months for severe or extreme drought (Figure 31). Figure 32 shows this graphically for the multiple-purpose reservoirs. Eight reservoirs with a multiple-purpose capacity of 540,000 acre-feet are in climate divisions where severe or extreme drought, as determined by the Palmer index, has been greater than 24 consecutive months but less than 36 consecutive months.

When mild to moderate droughts are examined, drought duration increases to about 40 consecutive months over most of the area, but up to 62 consecutive months in eastern New York. The drought of the 1960's is the predominate drought in the region although there was a major drought in the 1930's of shorter duration.

Comparison of PHDI, Precipitation, and Runoff. Figure 33 compares PHDI, cumulative precipitation deficit and annual stream runoff for a location in south central Pennsylvania. The comparison shows that the drought of the 1930's is accompanied by a significant precipitation deficit and corresponding low annual runoff. As the PHDI returns to near normal in 1932-33, the precipitation deficit decreases although it is not eliminated, and the annual runoff at the stream gage increases.

TABLE 5

NORTH ATLANTIC (NAD)
RESERVOIR STORAGE

Purpose	Number of Reservoirs	Storage Capacity (Acre-Feet)
Flood Control (Exclusive)	21	1,207,000
Navigation (Exclusive)	0	0
Hydroelectric Power (Exclusive)	0	0
Multiple-Purpose	18	755,000
TOTAL	21	1,962,000

TABLE 6

NORTH ATLANTIC (NAD)
NUMBER OF RESERVOIRS SERVING EACH PURPOSE
WITH EXCLUSIVE OR MULTIPLE-PURPOSE STORAGE

Purpose	Number of Reservoirs
Flood Control	21
Navigation	0
Hydroelectric Power	1
Irrigation	0
Water Supply	5
Fish and Wildlife	0
Recreation	17
Low-Flow Augmentation	4

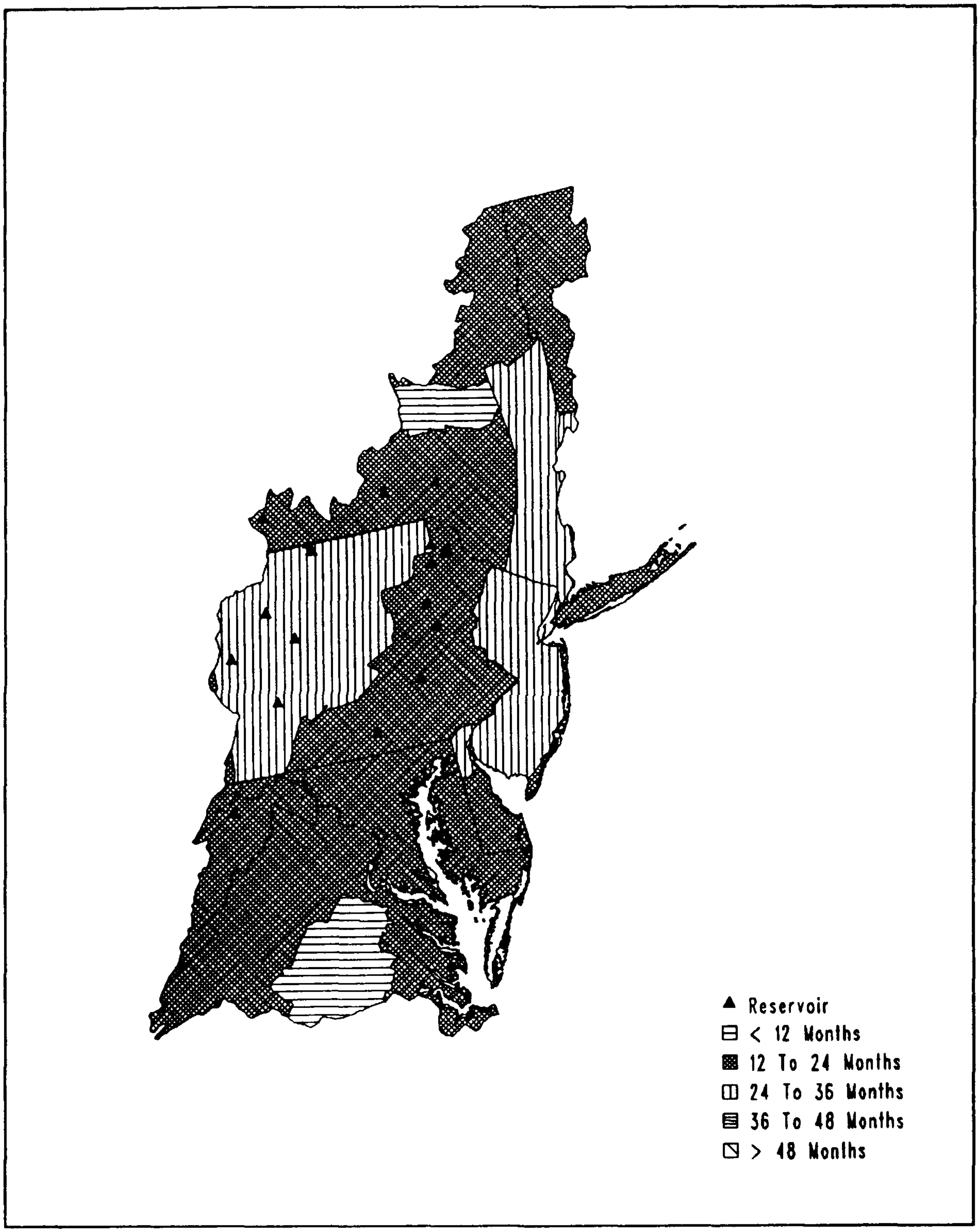

Figure 31. North Atlantic Division. Climate Divisions with Severe or Extreme Drought of Different Durations (PHDI)

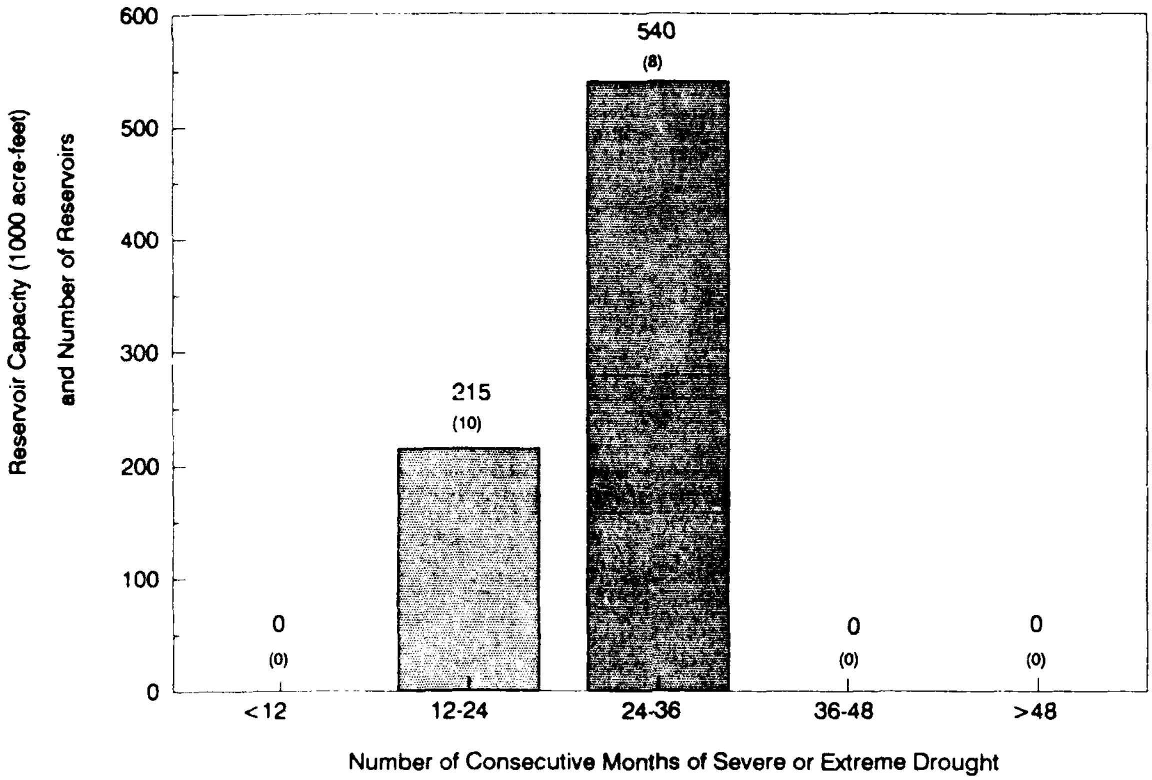

Figure 32. North Atlantic Division. Multiple-Purpose Reservoirs Susceptible to Severe or Extreme Droughts of Different Durations (PHDI)

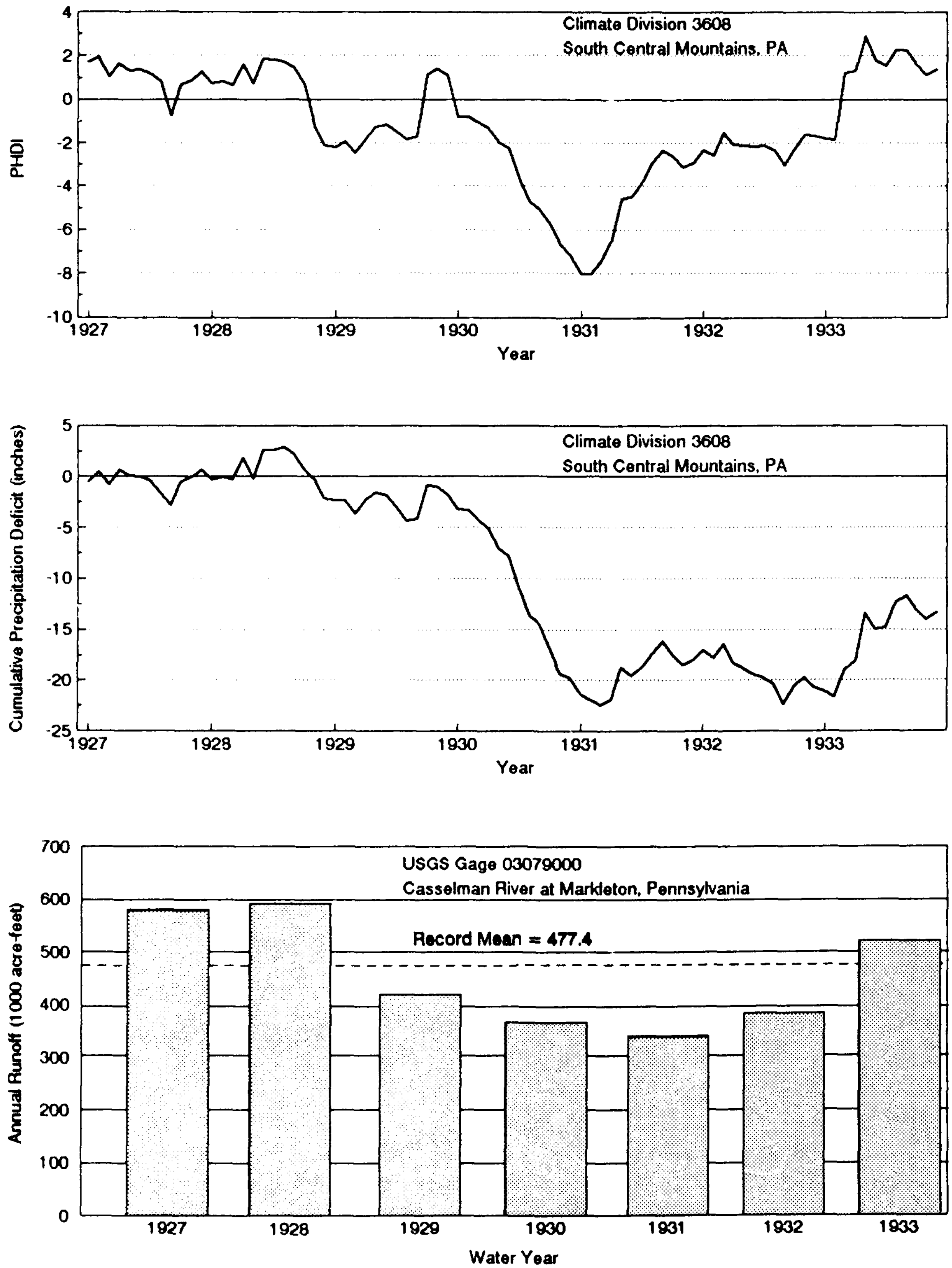

Figure 33. Comparison of PHDI, Precipitation, and Runoff for 1930-33 Drought

South Atlantic (SAD)

Reservoir Capacities and Purposes. Projects in this region serve all purposes. Tables 7 and 8 present the number and storage capacities of the reservoirs and their purposes. Navigation is a principal purpose in the Tennessee-Tombigbee and Apalachicola-Chattahoochee-Flint river basins. Fifteen of the 18 exclusive navigation projects in the region are on the Tennessee-Tombigbee waterways. In addition, there are nine multiple-purpose projects with navigation as one of the purposes. While thermal electric is the principal source of power generation in the region, hydroelectric still plays an important role in peaking operations. Fifteen Corps' projects generate hydroelectric power which is marketed by the Southeastern Power Administration (SEPA). Reservoir recreation is an important purpose with eight of the twelve most visited reservoirs in the nation located in the southeast. They provide over 80 million visitor-days annually. Lake Lanier, near Atlanta, Georgia, has over 17 million visitor-days each year. Irrigation is a project purpose in southeast Florida. Water supply, fish and wildlife, and water quality are an important part of reservoir operations at most storage projects in the region.

Drought Effects. Drought affects all purposes in this region either because of less water being available in storage or because of the timing of demand. Hydropower, for example, has a high energy demand during the summer, and reservoir releases made to meet that demand conflict with reservoir recreation, also a high summer demand. Releases to meet hydropower schedules make less storage available for fall season navigation and water quality. Various areas of the region experience water supply problems even during near normal water years. When droughts create seasonal low-flow periods, often coupled with higher demands, the water supply is stressed. Adequate river flows are critical for the nuclear power plant on the Savannah River. To maintain water quality and manage fish and wildlife, releases from various reservoirs are needed. This includes increased flow on the Savannah River to prevent saltwater intrusion. Reservoir recreation is affected by lower lake levels which prevent use of boat ramps and docks and expose tree stumps and sandbars creating hazards.

Susceptibility of Reservoirs to Drought. This region is characterized by droughts of less than 24 consecutive months in the severe or extreme range. This is shown in Figure 34. Figure 35 displays the number and capacity of multiple-purpose reservoirs for different durations. Twenty-two multiple-purpose reservoirs are in climate divisions with durations greater than 12 consecutive months but less than 24, based upon the Palmer index for the historical period 1895-1989. Seven multiple-purpose reservoirs with 5,003,000 acre-feet are in climate divisions with durations that have not exceeded 12 consecutive months.

Mild to extreme droughts have lasted longer than 24 consecutive months. When mild to moderate droughts are included in the analysis, droughts of up to 56 consecutive months are indicated in some climate divisions. Droughts near the beginning of this century and in the 1950's were generally the most severe. For North Carolina the mid-1920's drought was particularly severe and of long duration (36 months).

Comparison of PHDI, Precipitation, and Runoff. Figure 36 shows a comparison between PHDI, cumulative precipitation deficit, and annual runoff in north central Georgia. The drought period selected is the 1950's. The PHDI was in the mild to extreme range (<-1.5 PHDI) for about 34 consecutive months beginning in 1954. The duration for the severe or extreme drought (<-3.0 PHDI) was 10 months in 1954-55. The cumulative precipitation deficit steadily increased during the drought and even in 1958, the last year shown, there was not sufficient precipitation to begin a significant recovery. The lowest annual runoff occurred when the PHDI dipped into the severe and extreme range (1955).

TABLE 7

SOUTH ATLANTIC (SAD)
RESERVOIR STORAGE

Purpose	Number of Reservoirs	Storage Capacity (Acre-Feet)
Flood Control (Exclusive)	17	10,111,000
Navigation (Exclusive)	18	196,000
Hydroelectric Power (Exclusive)	0	0
Multiple-Purpose	29	10,891,000
TOTAL	41	21,198,000

TABLE 8

SOUTH ATLANTIC (SAD)
NUMBER OF RESERVOIRS SERVING EACH PURPOSE
WITH EXCLUSIVE OR MULTIPLE-PURPOSE STORAGE

Purpose	Number of Reservoirs
Flood Control	17
Navigation	27
Hydroelectric Power	15
Irrigation	4
Water Supply	11
Fish and Wildlife	8
Recreation	23
Low-Flow Augmentation	6

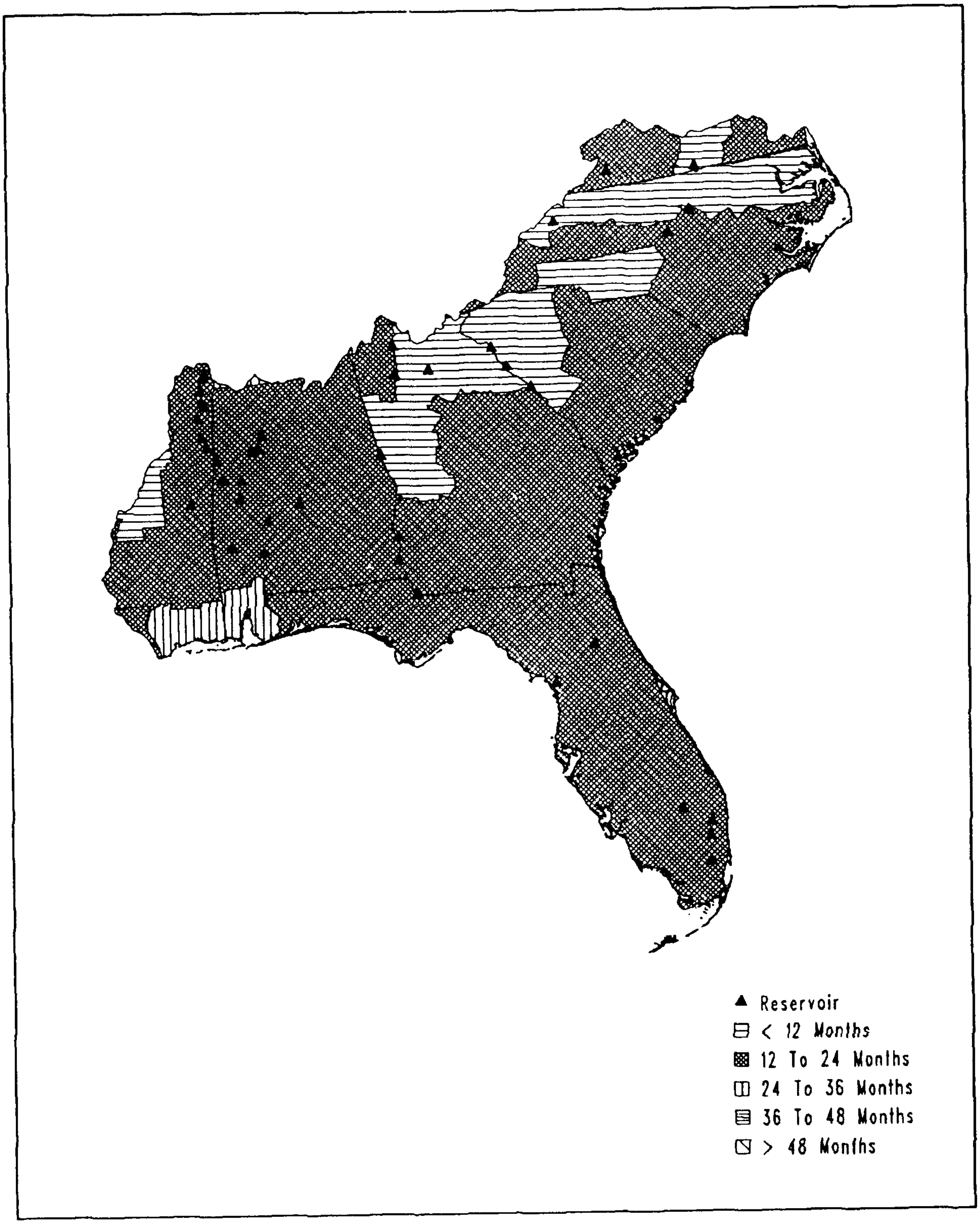

Figure 34. South Atlantic Division. Climate Divisions with Severe or Extreme Drought of Different Durations (PHDI)

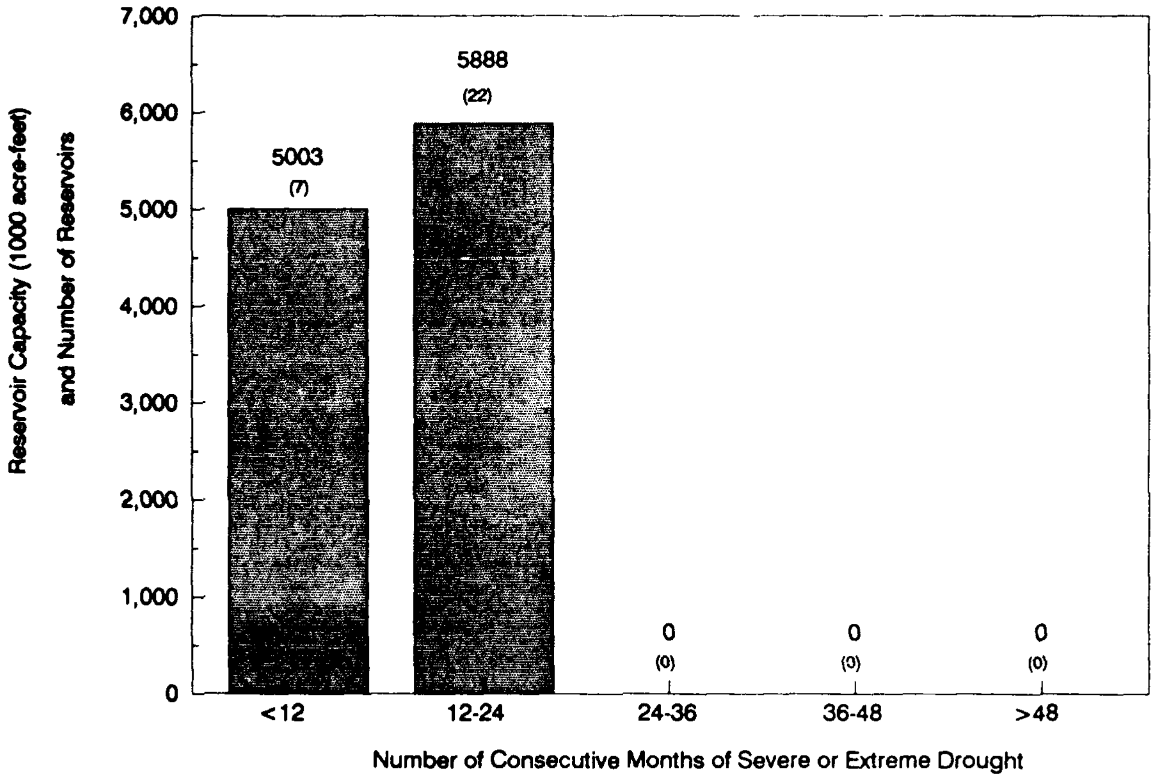

Figure 35. South Atlantic Division. Multiple-Purpose Reservoirs Susceptible to Severe or Extreme Droughts of Different Durations (PHDI)

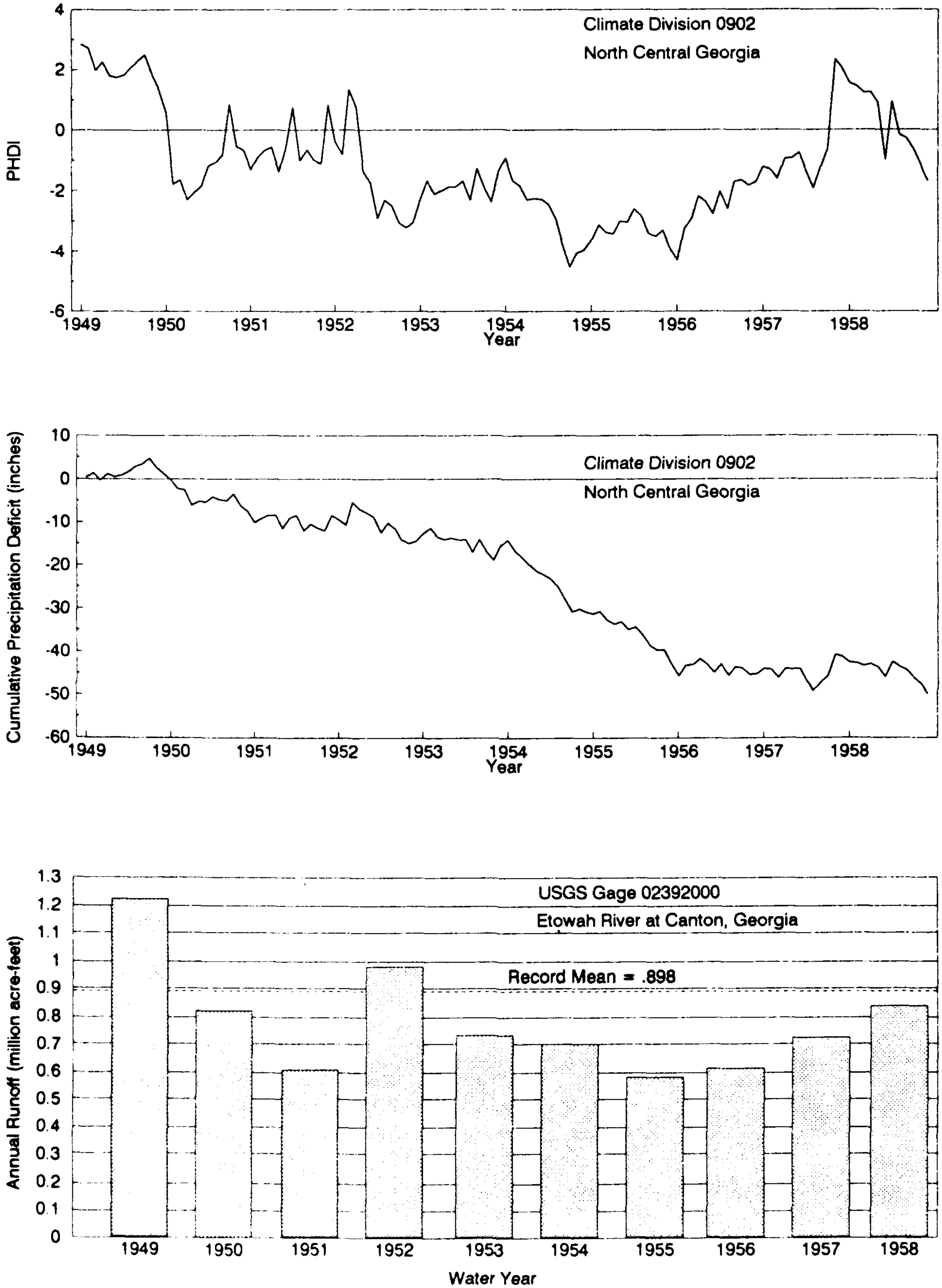

Figure 36. Comparison of PHDI, Precipitation, and Runoff for 1954-56 Drought

Ohio River (ORD)

Reservoir Capacities and Purposes. This region is characterized by a large number of reservoirs, including locks and dams, that serve both flood control and navigation. Of the 124 projects, 74 have 1.5 million acre-feet of storage exclusively for flood control and 48 serve navigation exclusively (Table 9). The Ohio, Cumberland, Kentucky, Allegheny and Monongahela rivers are the principal inland navigation waterways. Conservation purposes include: navigation, instream water quality, recreation, fish and wildlife, water supply, and hydroelectric power (Table 10). Total conservation storage for these purposes is over 7.5 million acre-feet. Reservoir recreation is a purpose at 72 projects, and instream quality and fish and wildlife is a purpose at about half that number. There are nine projects with hydroelectric power as a purpose and 12 with water supply contracts.

Drought Effects. During drought conditions, water supply and water quality are of major concern. Early filling to summer pool and minimizing reservoir outflow helps to provide additional storage. Storage is needed to meet water supply contracts at Corps' reservoirs and low-flow augmentation keeps stream dissolved oxygen levels above the required minimum. It is sometimes necessary for navigation to maintain channel depths within the Ohio River system and to assist in keeping the channel open on the Mississippi River. By reducing peak fluctuations in hydropower releases, water is released more uniformly which is desirable for navigation and water conservation. Hydropower generation is also reduced when only water quality releases are made. Additional power purchases are made by the Southeastern Power Administration to make up for the lost generation. Reservoir recreation and downstream whitewater rafting are also affected by drought conditions.

Susceptibility of Reservoirs to Drought. Figure 37 illustrates that droughts of less than 24 consecutive months in the severe or extreme range are most common in the Ohio River region. Longer durations occur in several climate divisions around the perimeter of the region. Figure 38 shows that there are nine multiple-purpose reservoirs (856,000 acre-feet) that are susceptible to severe or extreme droughts of 24 to 36 consecutive months duration.

Longer duration droughts are common throughout the region when mild to moderate droughts are considered. Droughts of about 78 consecutive months in the mild to extreme range have occurred in Ohio and droughts of 54 months duration in Tennessee. The longest in most other states is about 38 months. These long duration droughts occurred in the 1930's, 1940's and 1960's.

Comparison of PHDI, Precipitation, and Runoff. A comparison of PHDI, cumulative precipitation deficit, and annual runoff for a location in western Kentucky is shown in Figure 39 for the 1940-43 drought. The PHDI is in the mild to extreme range (PHDI <-1.5) from 1939 to 1945. A corresponding deficit in monthly precipitation, computed from the period of record average for each month, increases throughout this period and only begins to level off as the monthly precipitation returns to normal and there is no monthly deficit. The severe or extreme drought period (PHDI <-3.0) begins in 1940 and continues for about 20 months. This period has corresponding low annual runoff.

TABLE 9

OHIO RIVER (ORD)
RESERVOIR STORAGE

Purpose	Number of Reservoirs	Storage Capacity (Acre-Feet)
Flood Control (Exclusive)	74	14,373,000
Navigation (Exclusive)	48	205,000
Hydroelectric Power (Exclusive)	1	63,000
Multiple-Purpose	72	7,417,000
TOTAL	124	22,058,000

TABLE 10

OHIO RIVER (ORD)
NUMBER OF RESERVOIRS SERVING EACH PURPOSE
WITH EXCLUSIVE OR MULTIPLE-PURPOSE STORAGE

Purpose	Number of Reservoirs
Flood Control	74
Navigation	52
Hydroelectric Power	10
Irrigation	0
Water Supply	12
Fish and Wildlife	38
Recreation	72
Low-Flow Augmentation	34

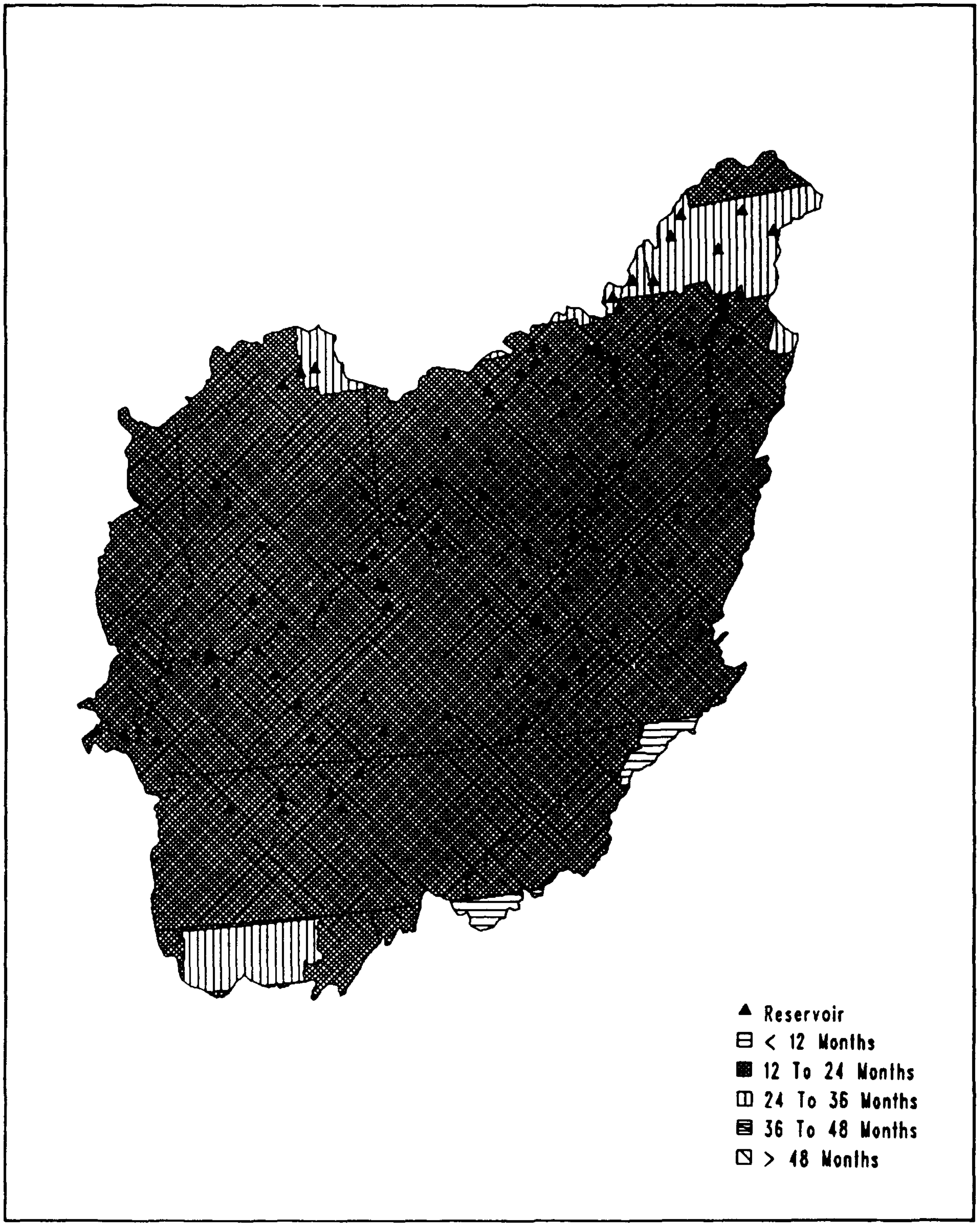

Figure 37. Ohio River Division. Climate Divisions with Severe or Extreme Drought of Different Durations (PHDI)

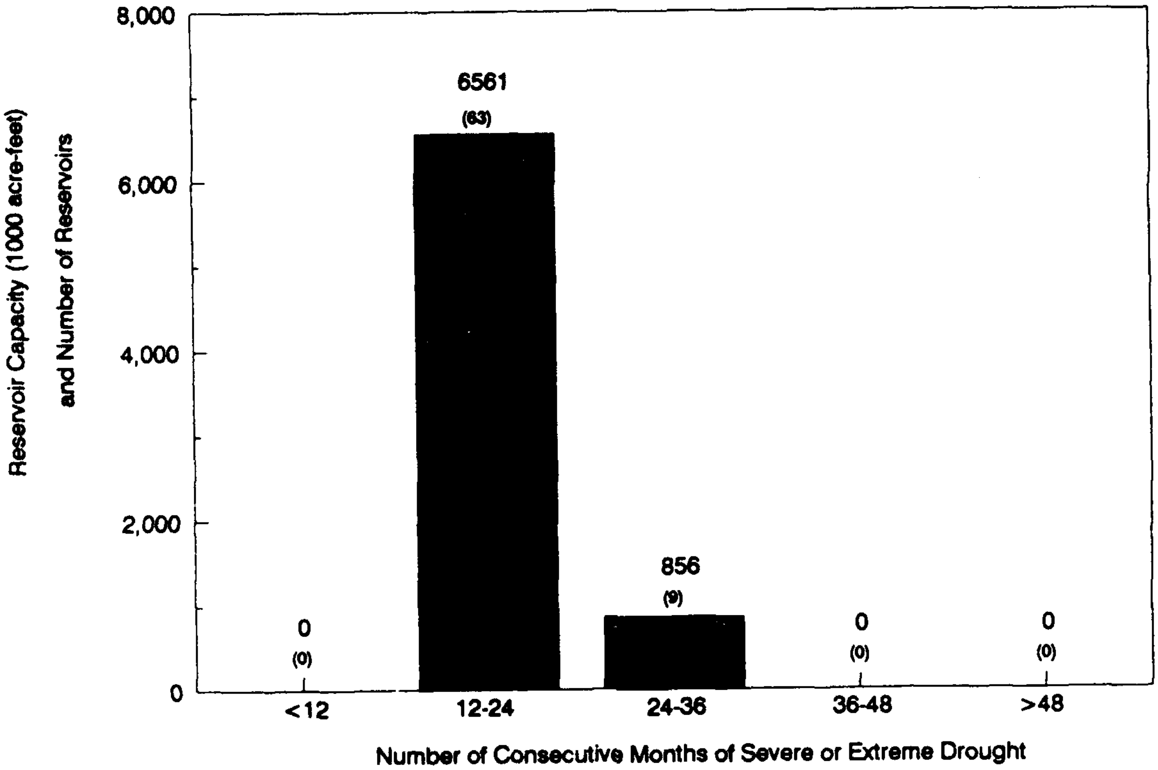

Figure 38. Ohio River Division. Multiple-Purpose Reservoirs Susceptible to Severe or Extreme Droughts of Different Durations (PHDI)

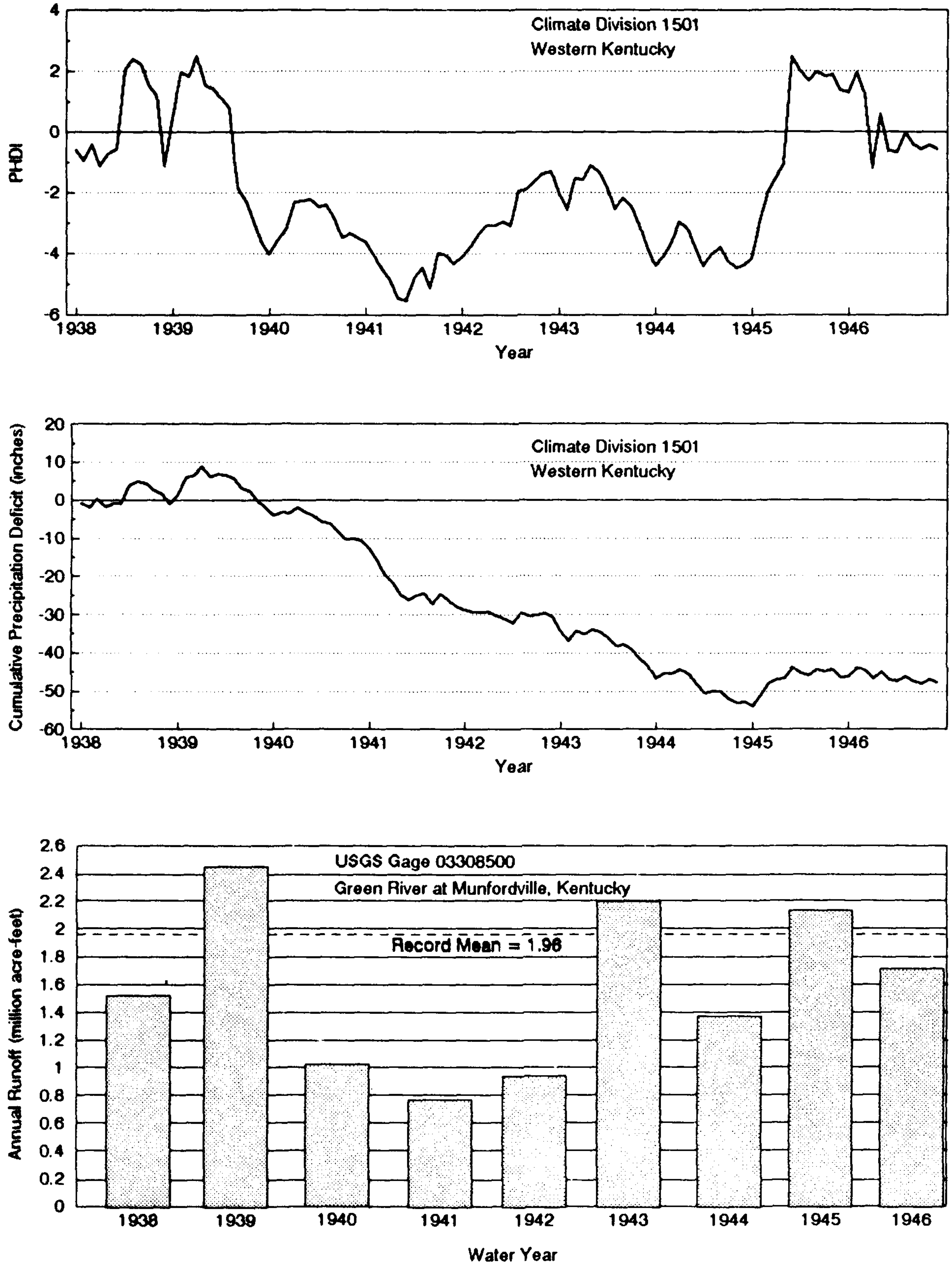

Figure 39. Comparison of PHDI, Precipitation, and Runoff for 1939-42 Drought

North Central (NCD)

Reservoir Capacities and Purposes. Navigation is the major purpose served by the 64 reservoirs in this region. There are 46 locks and dams with navigation as an exclusive purpose (Table 11). They create navigation pools for commercial and recreational traffic on the Fox, Illinois, and Mississippi Rivers. Many of these pools are also used for recreation. Hydroelectric power is generated at some sites. Flood control is an exclusive purpose at seven reservoirs with 3 million acre-feet of storage capacity. Multiple-purpose reservoir capacity in the region is nearly 3 million acre-feet. A variety of purposes are served, with navigation and recreation the most common (Table 12).

A major influence on the region is the Great Lakes. Their water level not only affects purposes served directly by the lakes, but also affects some of the rivers and their purposes. When the Great Lakes decline below long-term levels, river navigation, run-of-the-river hydropower, and fish and wildlife are all affected. In addition, the Corps has partial ownership in one control structure at Sault Ste. Marie, Michigan that is operated for navigation and hydroelectric power.

Drought Effects. Drought affects on the purposes varies. Water provided to cities for municipal and industrial use is susceptible to shortage during drought. Fish and wildlife may suffer the loss of marsh habitat; increases in fall pool levels for waterfowl may not be possible; river water quality may have higher sediment and pollutant loads; reservoir recreation may have lower water levels for boating; hydropower generation could be reduced; and navigation may have difficulty providing adequate channel depths for commercial and recreational traffic. Both municipalities and thermal electric plants along the river system withdraw river water for municipal, industrial and cooling purposes. Releases from reservoirs during drought are often necessary to meet these uses.

Susceptibility of Reservoirs to Drought. An analysis using the Palmer Hydrological Drought Index (PHDI) indicates that most of the region is characterized by severe or extreme droughts of less than 36 consecutive month duration. Drought durations and the Corps' reservoirs (exclusive and multiple-purpose) are shown in Figure 40. Figure 41 shows the distribution of multiple-purpose reservoirs by drought duration. Thirty-one reservoirs representing 2,379,000 acre-feet of multiple-purpose capacity are in climate divisions with severe or extreme drought of greater than 24 consecutive months. There are six multiple-purpose reservoirs in climate divisions of severe or extreme drought durations of greater than 48 consecutive months.

Droughts of longer duration are found in the region when mild to moderate severity is considered. The 1930's, 1950's and 1960's brought long dry spells with durations as long as 50 to 90 consecutive months.

Comparison of PHDI, Precipitation, and Runoff. The 1930's drought is illustrated in Figure 42. A comparison of PHDI, precipitation, and annual runoff shows many ups and downs during this period. Increases and decreases in one indicator generally shows corresponding increases and decreases in the others. Severe and extreme drought conditions (PHDI <-3.0) occurred in 1931 and 1934. These were also the years of lowest annual runoff.

TABLE 11

NORTH CENTRAL (NCD)
RESERVOIR STORAGE

Purpose	Number of Reservoirs	Storage Capacity (Acre-Feet)
Flood Control (Exclusive)	7	3,059,000
Navigation (Exclusive)	46	981,000
Hydroelectric Power (Exclusive)	0	0
Multiple-Purpose	44	2,833,000
TOTAL	64	6,873,000

TABLE 12

NORTH CENTRAL (NCD)
NUMBER OF RESERVOIRS SERVING EACH PURPOSE
WITH EXCLUSIVE OR MULTIPLE-PURPOSE STORAGE

Purpose	Number of Reservoirs
Flood Control	18
Navigation	48
Hydroelectric Power	1
Irrigation	0
Water Supply	5
Fish and Wildlife	10
Recreation	36
Low-Flow Augmentation	6

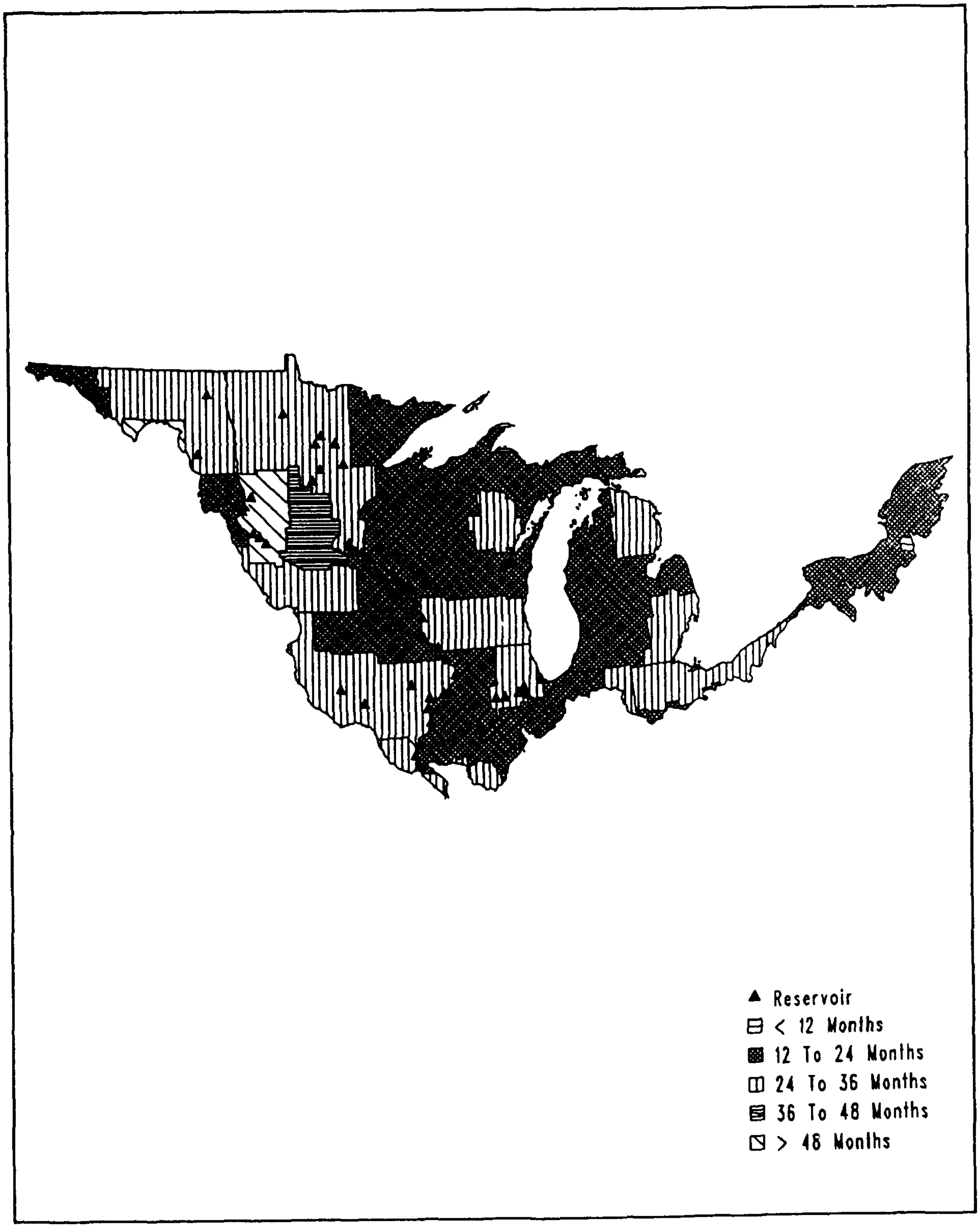

Figure 40. North Central Division. Climate Divisions with Severe or Extreme Drought of Different Durations (PHDI)

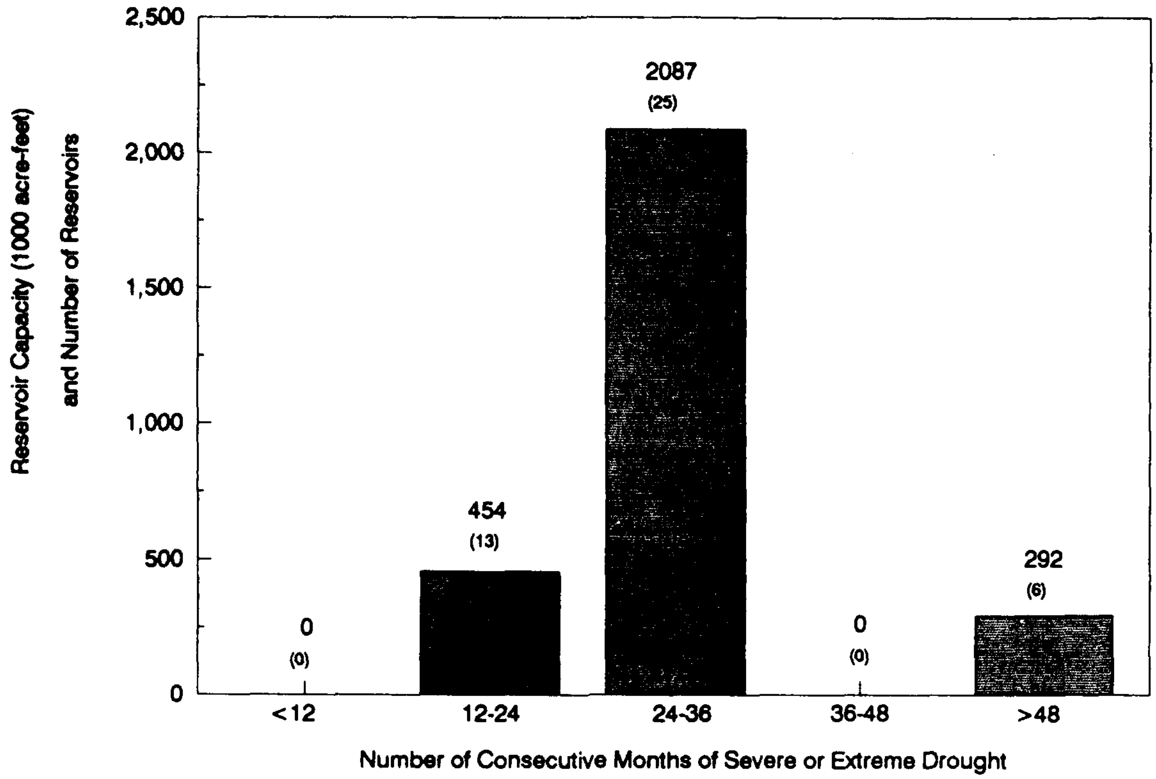

Figure 41. North Central Division. Multiple-Purpose Reservoirs Susceptible to Severe or Extreme Droughts of Different Durations (PHDI)

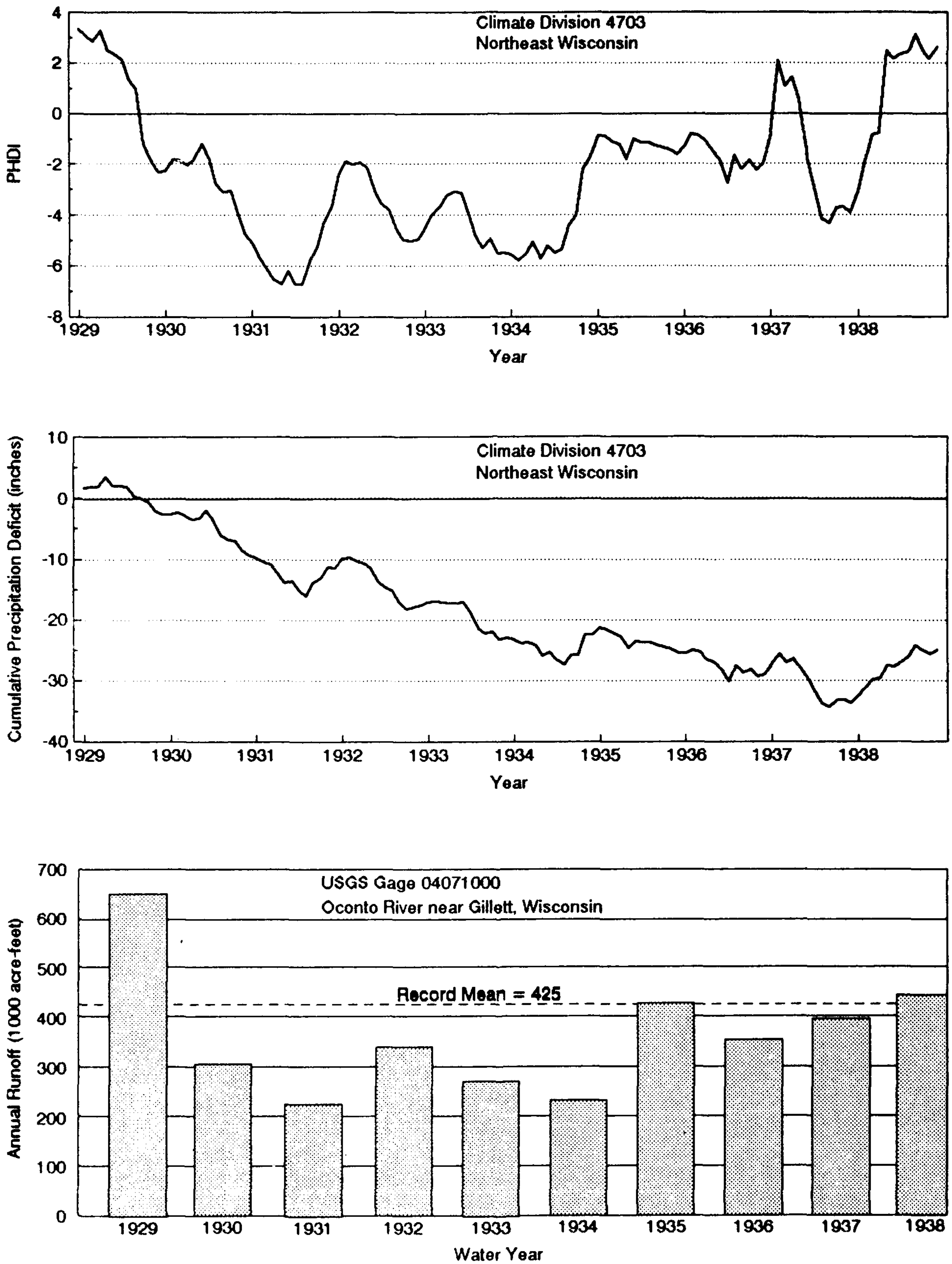

Figure 42. Comparison of PHDI, Precipitation, and Runoff for 1930-34 Drought

Lower Mississippi Valley (LMV)

Reservoir Capacities and Purposes. Two-thirds of the reservoir storage capacity in this region is allocated to flood control (Table 13). Multiple-purpose storage accounts for most of the remaining one-third and this represents nearly 3.5 million acre-feet. The principal conservation purposes include: recreation, hydroelectric power, water supply, fish and wildlife, and water quality (low flow augmentation). Of the 23 multiple-purpose reservoirs, recreation occurs at all of them. Water supply is provided from storage at six reservoirs and instream water quality, fish and wildlife, navigation, hydroelectric power are served at fewer sites (Table 14).

Drought Effects. A major concern during drought is navigation on the middle and lower Mississippi River. Low flows and stages on the river cause problems keeping the navigation channel open for traffic. The low flows, however, are not solely the result of drought in the Lower Mississippi Valley. Streamflow is also significantly affected by drought in the major tributaries: the Upper Mississippi, Missouri, Ohio, and Arkansas-White River Basins. Shoaling, narrower and shallower channels, and bank stability are common problems during low flow. During the drought of 1988 emergency dredging was required on the lower end of some tributaries, and in some harbors because the record low water caused unprecedented shoaling. During low-flow periods a saltwater wedge advances up the mouth of the Mississippi River threatening water supplies that use the river as a source. This is particularly critical in the vicinity of New Orleans.

Susceptibility of Reservoirs to Drought. In this region, severe or extreme droughts, as measured by the Palmer Hydrological Drought Index (PHDI), have durations of less than 24 consecutive months except in the upper most part of the region (southeast Missouri). In this area severe or extreme droughts of up to 36 consecutive months have occurred. Figure 43 shows the drought durations for the region together with the exclusive and multiple-purpose reservoirs. Figure 44 shows the distribution of multiple-purpose reservoirs by drought duration. Six multiple-purpose reservoirs, with a total capacity of 494,000 acre-feet, are in areas that historically (1895-1989) have experienced severe or extreme droughts of up to 24 to 36 consecutive months. Fifteen of the reservoirs (2,795,000 acre-feet) are susceptible to droughts in the severe or extreme range of greater than 12 consecutive months.

When droughts in the mild to moderate range are considered, the duration of drought increases up to 45 consecutive months. Historically these longer duration droughts occurred in 1953 in Arkansas and 1963 in Louisiana.

Comparison of PHDI, Precipitation, and Runoff. A comparison of PHDI, cumulative precipitation, and annual runoff at a location in central Arkansas is shown in Figure 45. The severe or extreme period (PHDI <-3.0) occurred between 1953 and 1955. The cumulative precipitation deficit increased during these years, indicating generally dry conditions. The deficit decreased as above average monthly precipitation occurred in 1957. The low runoff years, 1954-56, correspond to the severe or extreme drought period.

TABLE 13

LOWER MISSISSIPPI VALLEY (LMV)
RESERVOIR STORAGE

Purpose	Number of Reservoirs	Storage Capacity (Acre-Feet)
Flood Control (Exclusive)	13	7,856,000
Navigation (Exclusive)	11	349,000
Hydroelectric Power (Exclusive)	1	128,000
Multiple-Purpose	23	3,474,000
TOTAL	27	11,807,000

TABLE 14

LOWER MISSISSIPPI VALLEY (LMV)
NUMBER OF RESERVOIRS SERVING EACH PURPOSE
WITH EXCLUSIVE OR MULTIPLE-PURPOSE STORAGE

Purpose	Number of Reservoirs
Flood Control	14
Navigation	11
Hydroelectric Power	4
Irrigation	0
Water Supply	6
Fish and Wildlife	3
Recreation	23
Low-Flow Augmentation	4

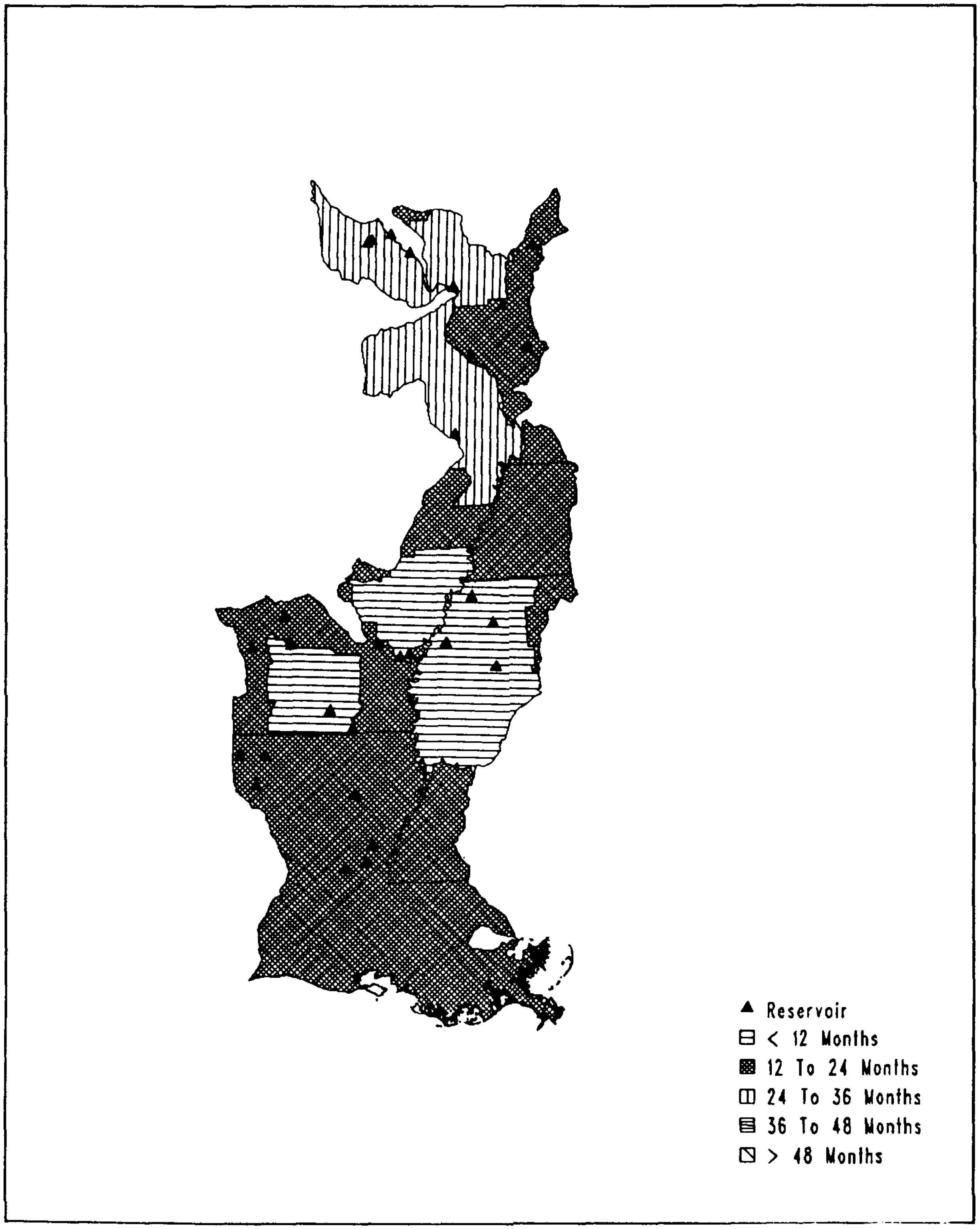

Figure 43. Lower Mississippi Valley Division. Climate Divisions with Severe or Extreme Drought of Different Durations (PHDI).

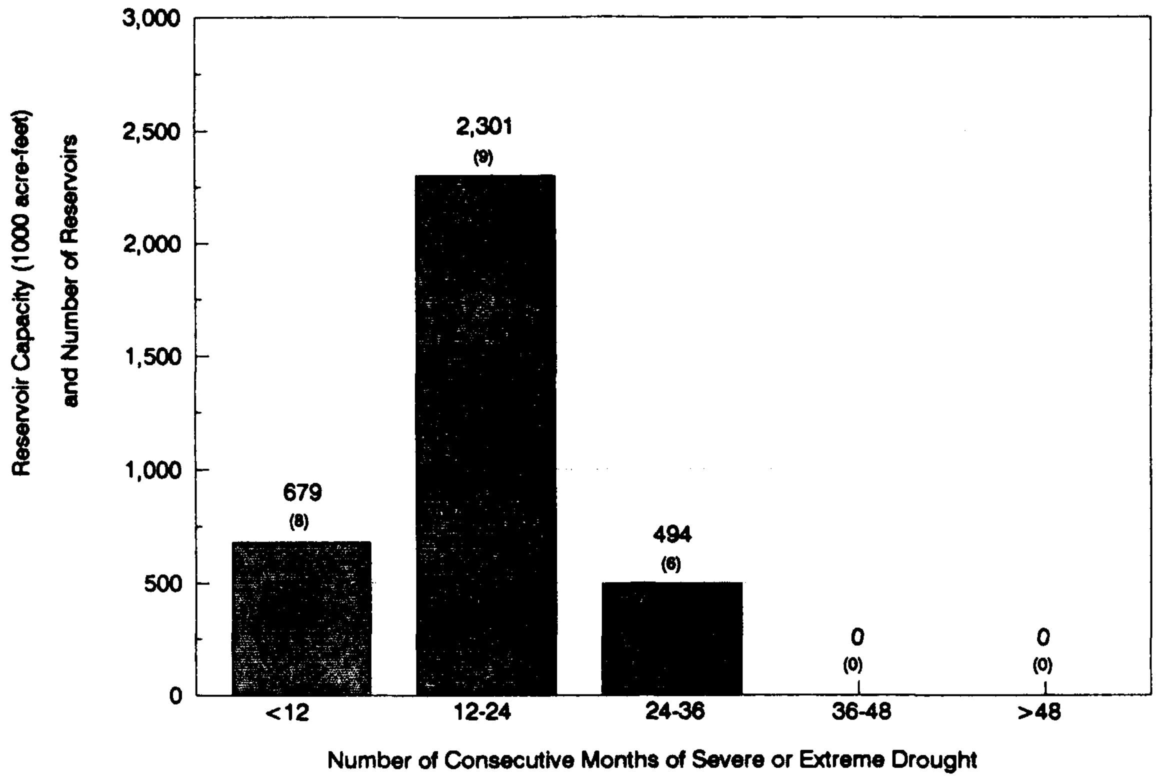

Figure 44. Lower Mississippi Valley Division. Multiple-Purpose Reservoirs Susceptible to Severe or Extreme Droughts of Different Durations (PHDI)

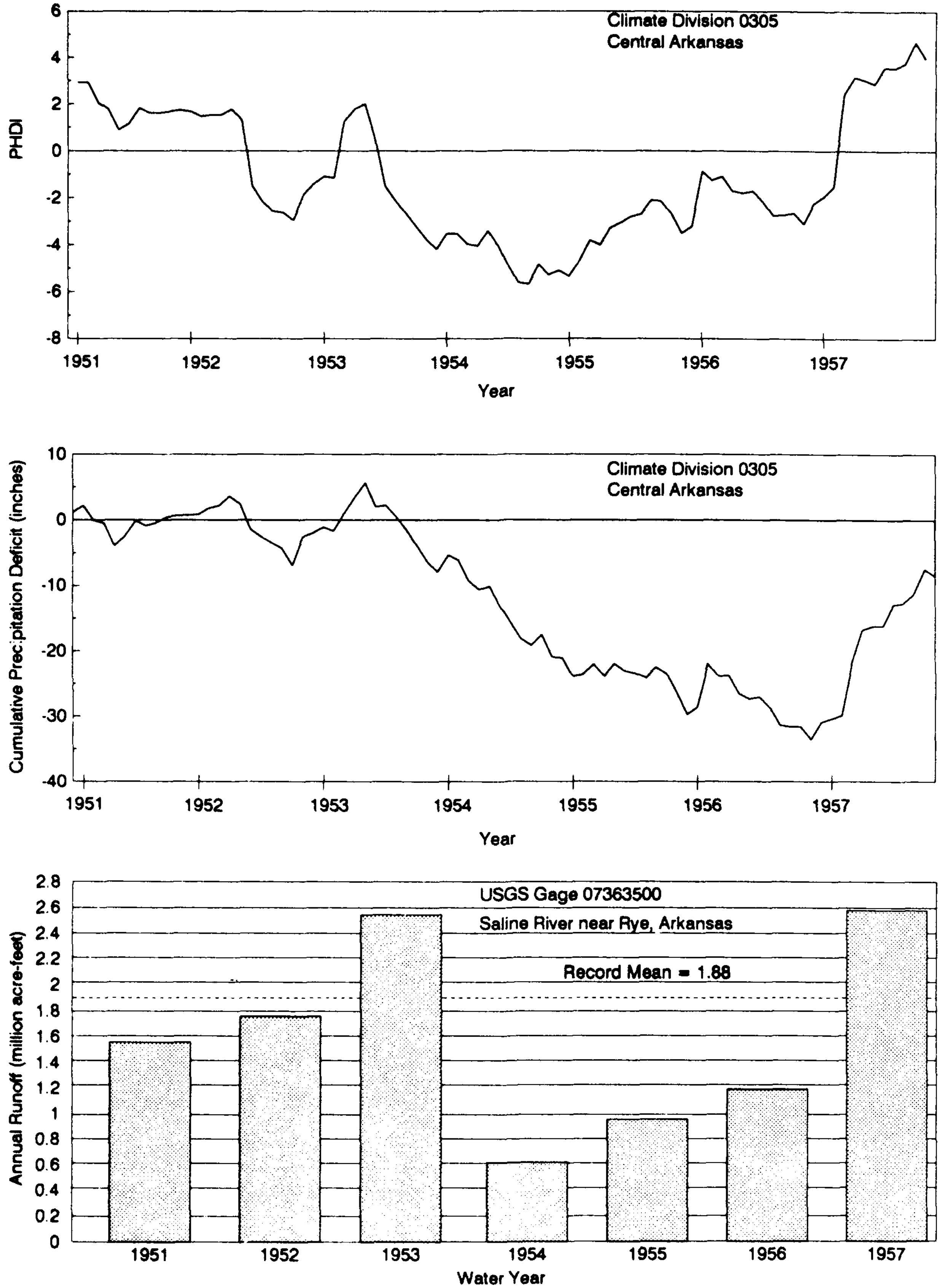

Figure 45. Comparison of PHDI, Precipitation and Runoff for 1953-56 Drought

Southwestern (SWD)

Reservoir Capacities and Purposes. This region has a large number of reservoirs with both exclusive flood control and multiple-purpose capacity; over 35 million and 28 million acre-feet respectively (Table 15). While all multiple purposes are served, water supply and recreation are particularly common (Table 16). Of all the regions, the Southwestern has the greatest storage capacity allocated to water supply contracts (U. S. Army Corps of Engineers, 1988). Reservoir recreation is equally significant. Over 140 million visitor-days, or 30 percent of the total Corps of Engineers' recreation visitation occurs at reservoirs in this region. Lake Texoma has the highest visitation with over 8 million annual visitor-days. Overall water management activities are dependent upon releases for hydroelectric power production. Nineteen reservoirs generate energy primarily for peaking operations.

Drought Effects. Because both water supply and recreation are present at most multiple-purpose reservoirs, they are the most common purposes affected by drought. Drought increases the risk that water supply contracts will not be met and recreation is directly impacted by lower reservoir pools and lower downstream releases. Fish and wildlife and water quality are similarly affected by lower releases. Navigation on the Arkansas River is affected when low stages on the Mississippi River reduce the channel depth of the White River Entrance Channel which connects the Arkansas with the Mississippi. To maintain navigable depths, heavy dredging is often necessary. Tow size and draft restrictions are also imposed and remain in effect through the end of the summer. Hydroelectric power generation is reduced both by lower heads and less water through the turbines.

Susceptibility of Reservoirs to Drought. Drought in the region is of relatively long duration. Figure 46 shows the climate divisions with severe or extreme drought of different durations and Corps' exclusive and multiple-purpose reservoirs. Approximately two-thirds of the region has experienced drought of greater than 24 consecutive months during the record 1895-1989 according to the Palmer Hydrological Drought Index. This is most noticeable in the northern portion (southern Kansas and southeast Colorado). The distribution of multiple-purpose reservoirs by drought durations is presented in Figure 47; all are in climate divisions of greater than 12 consecutive month duration. Examining multiple-purpose storage capacity, 23 percent of the capacity, or 6,458,000 acre-feet, is susceptible to drought greater than 24 consecutive months in the severe or extreme range. The ten reservoirs susceptible to severe or extreme drought of greater than 48 consecutive months are located in northern Oklahoma and southern Kansas.

When mild to moderate droughts are considered, the duration is greater. In northern Oklahoma and southern Kansas the 1930's drought had durations mild to extreme of 80 and 102 consecutive months respectively. In central Texas the drought beginning in 1950 had a duration of about 80 consecutive months in the mild to extreme range as measured by the PHDI.

Comparison of PHDI, Precipitation, and Runoff. A comparison of the PHDI, cumulative precipitation, and annual runoff in north central Texas is shown in Figure 48 for the 1950's drought. The mild to extreme period (<-1.5 PHDI) occurs between 1950-1957. Corresponding precipitation deficits and low annual runoff occur during this same period.

TABLE 15

SOUTHWESTERN (SWD)
RESERVOIR STORAGE

Purpose	Number of Reservoirs	Storage Capacity (Acre-Feet)
Flood Control (Exclusive)	78	35,016,000
Navigation (Exclusive)	12	624,000
Hydroelectric Power (Exclusive)	1	65,000
Multiple-Purpose	90	28,697,000
TOTAL	95	64,402,000

TABLE 16

SOUTHWESTERN (SWD)
NUMBER OF RESERVOIRS SERVING EACH PURPOSE
WITH EXCLUSIVE OR MULTIPLE-PURPOSE STORAGE

Purpose	Number of Reservoirs
Flood Control	78
Navigation	19
Hydroelectric Power	20
Irrigation	8
Water Supply	58
Fish and Wildlife	23
Recreation	89
Low-Flow Augmentation	16

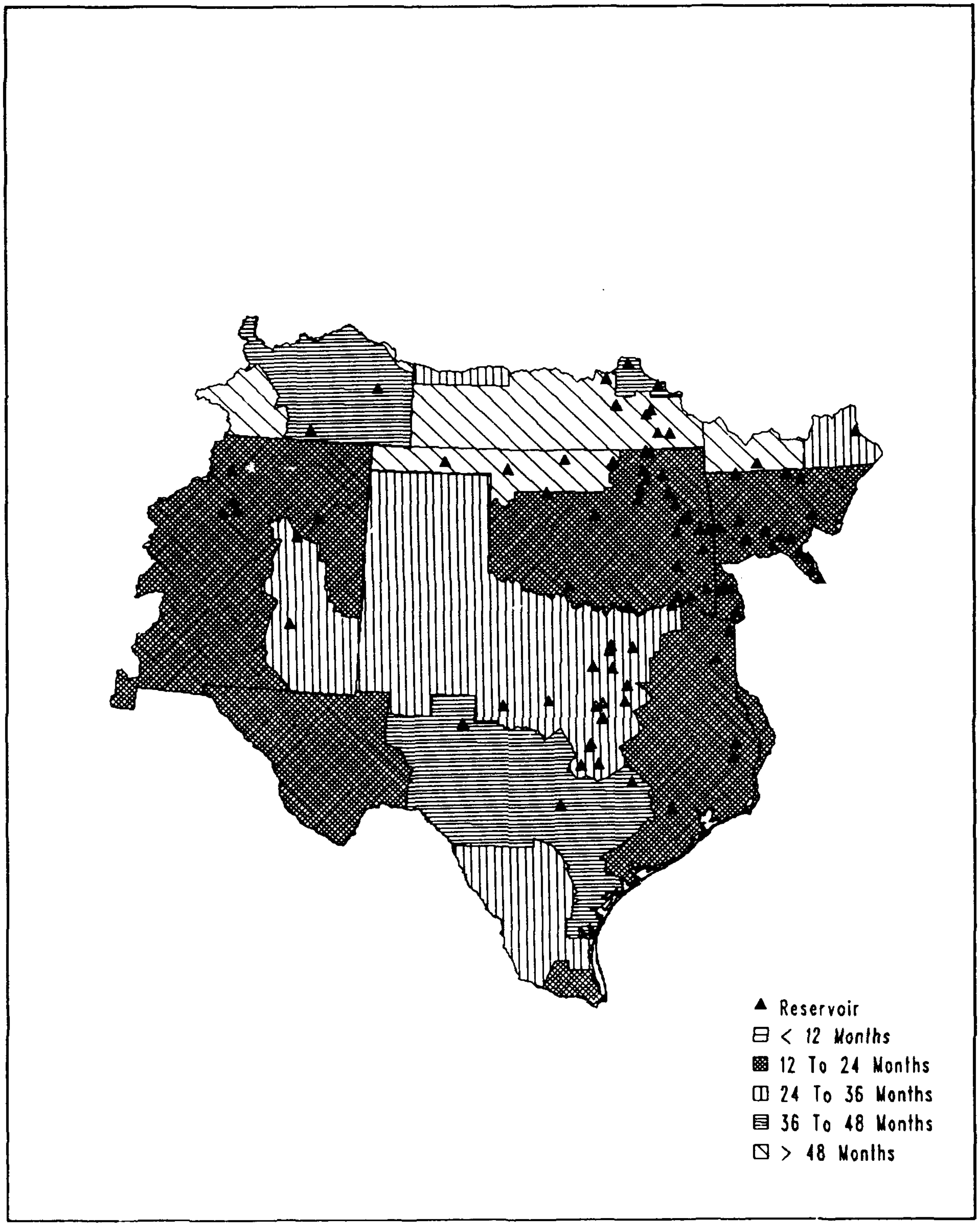

Figure 46. Southwestern Division. Climate Divisions with Severe or Extreme Drought of Different Durations (PHDI)

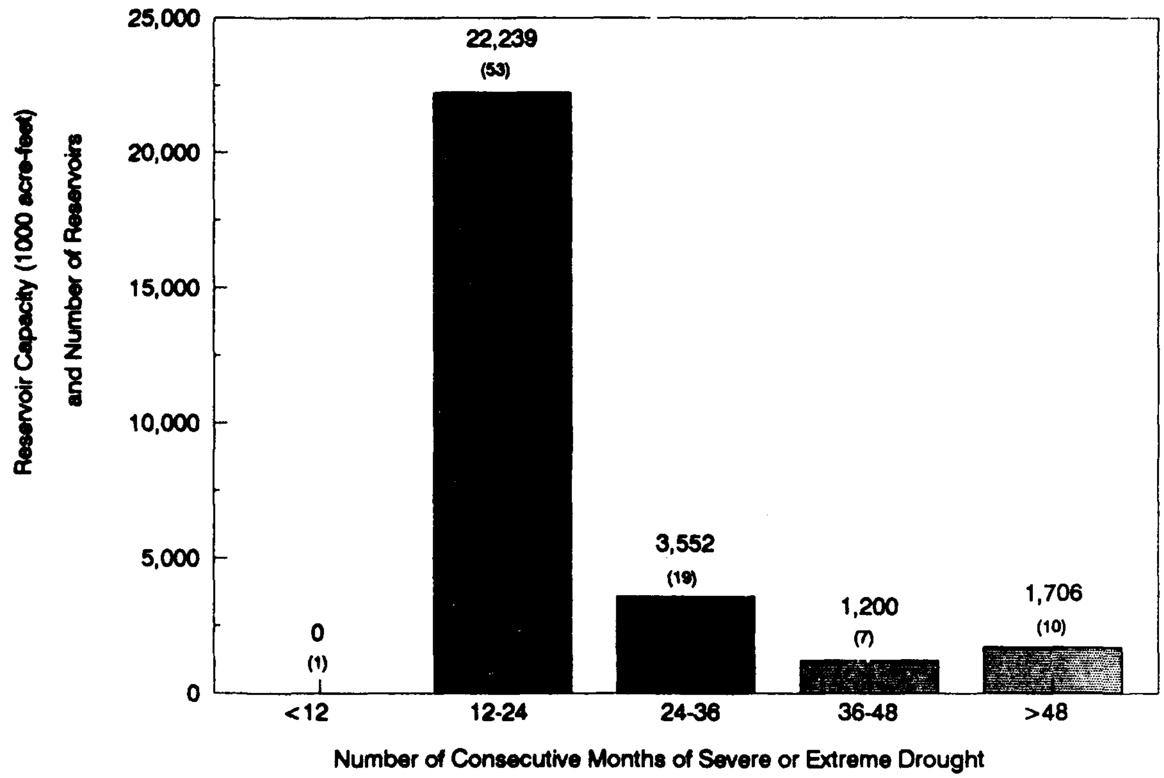

Figure 47. Southwestern Division. Multiple-Purpose Reservoirs Susceptible to Severe or Extreme Droughts of Different Durations (PHDI)

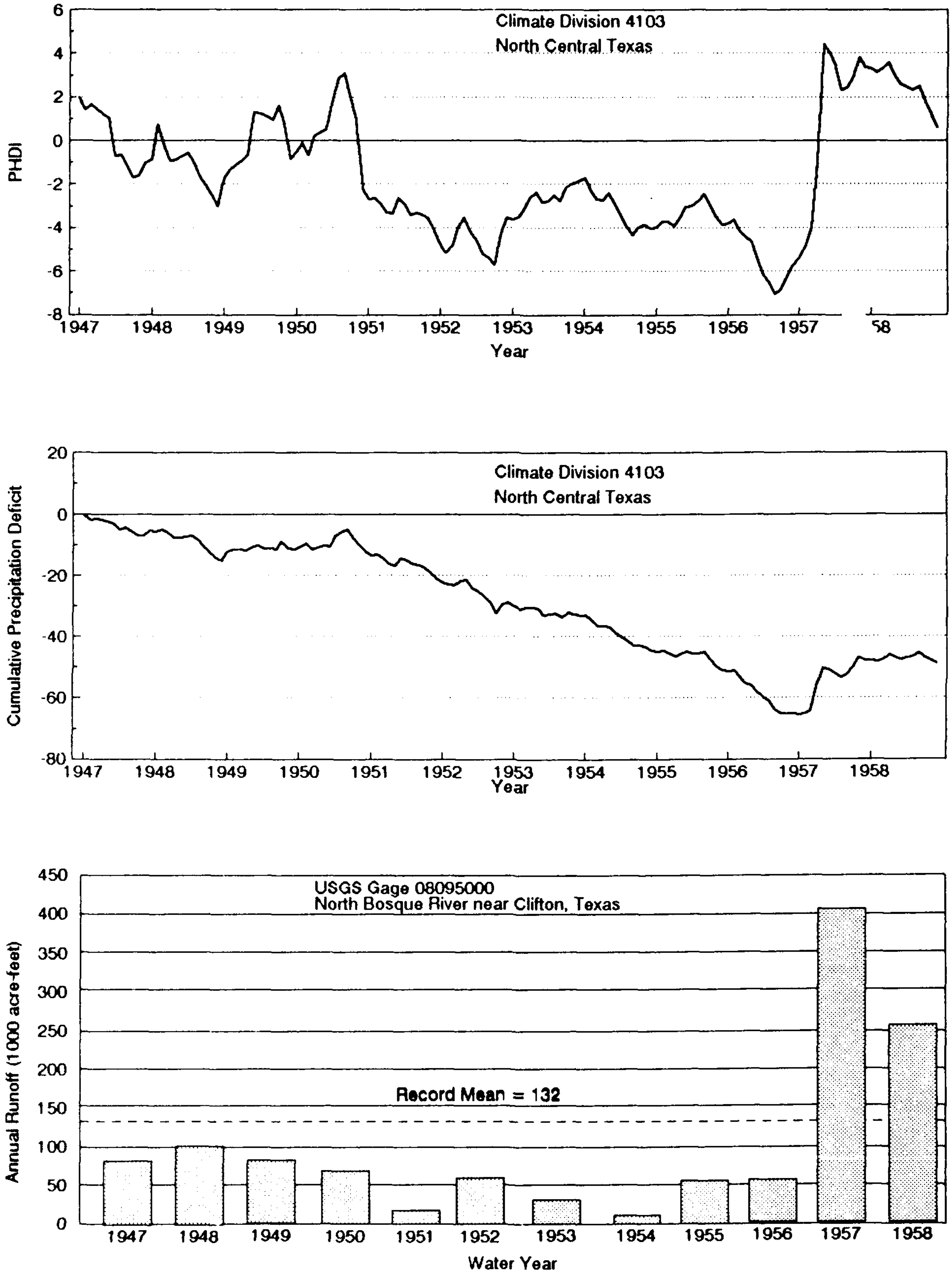

Figure 48. Comparison of PHDI, Precipitation, and Runoff for 1951-57 Drought

Missouri River (MRD)

Reservoir Capacities and Purposes. The storage capacity of reservoirs in this region is large with 16.5 million acre-feet available exclusively for flood control and 55.7 million acre-feet for multiple purposes (Table 17). Six main stem projects on the Missouri River account for 28 percent (4.7 million acre-feet) of the exclusive flood control capacity and 91 percent (51 million acre-feet) of the multiple-purpose capacity. The purposes served by the reservoirs are shown in Table 18. All multiple-purpose reservoirs have flood control capacity; recreation and fish and wildlife are provided by most.

Drought Effects. Drought affects all reservoirs in the region. However, because most multiple-purpose capacity is in the main stem reservoirs, and they serve all purposes, they are the focus of the discussion which follows. Navigation on the Missouri River occurs from its confluence with the Mississippi upstream to Sioux City, Iowa below Gavins Point Dam. Drought results in lower streamflow and a shorter navigation season. Lower streamflow may require reduced loadings and result in less tonnage moved during the navigation season. A shorter season will result in less tonnage moved. Navigation on the Mississippi River is also affected by releases on the Missouri. A major portion of the flow between the confluence of the Missouri and Ohio is provided by the Missouri River.

Hydroelectric power contributes less than 10 percent of the region's power. Nonetheless, it is an important source for peaking operations in the region's integrated system. Energy is generated at all main stem reservoirs. During drought, generation is reduced both because of lower lake levels and reduced releases. The lower generation is made up by thermal plants in the integrated system.

Water for irrigation is provided directly from the reservoirs and from river withdrawals. The reservoirs alone serve over 400 private irrigators. Low reservoir levels and low streamflow can make access to the water difficult. In addition, during low streamflow, sediment deposition increases and sandbars form, restricting flows to the water supply intakes.

Municipal water supply and powerplant cooling are served principally from withdrawals along the Missouri River. As in the case of water supply for irrigation, the effect of drought is more an increase in the difficulty of reaching the water at the intake than in having an inadequate quantity of water. Drought conditions, if they persist throughout the winter, can cause water supply problems due to ice. The ice built up at water supply intakes are a direct result of the lower flows and cold weather.

The main stem reservoirs as well as most of the other multiple-purpose reservoirs in the region serve fish and wildlife. The main stem reservoirs make a significant contribution to sport and commercial fishing. Sport fishing also occurs upstream and downstream of the reservoirs. The principal affect of drought is to reduce the flexibility of reservoir operation for fish management. Drought, especially a drought of several years, may affect spawning both in the reservoir and the river by lowering reservoir levels and reducing releases. Although lower reservoir levels may reduce fish counts of certain species during drought years, the lower levels allow for vegetation growth along the shore which become excellent spawning areas after water levels return to normal. Protection of endangered species of wildlife, by keeping releases constant, has prevented the Corps from increasing releases for navigation.

Recreation is provided at most reservoirs in the region. This includes fishing, swimming, boating, camping and other outdoor opportunities. While the reservoirs are large and provide excellent recreational opportunities, their remoteness from major population centers reduces annual visitation. Oahe Lake, with the largest visitation (3 million visitor-days in 1986), ranks 40th among all Corps' reservoirs in annual visitation. Drought creates both public and political pressure to keep reservoirs up and minimize the adverse impact on recreational opportunities. The need to conserve storage for reservoir recreation competes with the many purposes that use reservoir releases.

Drought frequently accelerates and amplifies water quality problems commonly found in rivers and reservoirs. Lower river and reservoir levels, less streamflow, and higher temperatures all contribute to poorer quality water, algal blooms, and low dissolved oxygen levels.

<u>Susceptibility of Reservoirs to Drought.</u> As part of the High Plains and Midwest, this region is characterized by long duration drought. Figure 49 shows the duration of severe or extreme drought in the climate divisions together with the exclusive and multiple-purpose reservoirs. Approximately 40 percent of the region has climate divisions with drought durations greater than 36 consecutive months in the severe or extreme range as determined by the PHDI. Figure 50 shows the distribution of multiple-purpose reservoirs by duration. Twenty-eight of the 45 reservoirs are in climate divisions with severe or extreme drought greater than 36 consecutive month duration. However, these reservoirs only represent three percent (1,579,000 acre-feet) of the total multiple-purpose capacity. The main stem Missouri River reservoirs have 91 percent of the multiple-purpose capacity and they are located in climate divisions with severe or extreme durations of up to 12 to 36 months based upon the record period, 1895 to 1989.

The 1930's were the most significant drought years, with all of the regions being severely affected. Considering mild to moderate droughts as well as severe and extreme, durations near and over 100 consecutive months are common in many climate divisions. In Montana, one climate division shows over ten years of mild to extreme drought in the 1930's.

<u>Comparison of PHDI, Precipitation, and Runoff.</u> A comparison of PHDI, cumulative precipitation, and annual runoff for north central Montana is shown in Figure 51. The drought period 1960 to 1964 is used for the comparison. As measured by the PHDI, mild to extreme drought (PHDI <-1.5) occurred from 1960 to 1964. Severe or extreme drought (PHDI <-3.0) occurred during the summer and fall of 1961, and again during the summer and fall of 1963. Monthly precipitation is below average as expected during the drought period. The cumulative precipitation deficit reached a maximum in 1964. Annual runoff from the watershed reflects this lack of precipitation.

TABLE 17

MISSOURI RIVER (MRD)
RESERVOIR STORAGE

Purpose	Number of Reservoirs	Storage Capacity (Acre-Feet)
Flood Control (Exclusive)	48	16,452,000
Navigation (Exclusive)	0	0
Hydroelectric Power (Exclusive)	0	0
Multiple-Purpose	45	55,727,000
TOTAL	48	72,179,000

TABLE 18

MISSOURI RIVER (MRD)
NUMBER OF RESERVOIRS SERVING EACH PURPOSE
WITH EXCLUSIVE OR MULTIPLE-PURPOSE STORAGE

Purpose	Number of Reservoirs
Flood Control	48
Navigation	14
Hydroelectric Power	8
Irrigation	8
Water Supply	13
Fish and Wildlife	32
Recreation	38
Low-Flow Augmentation	19

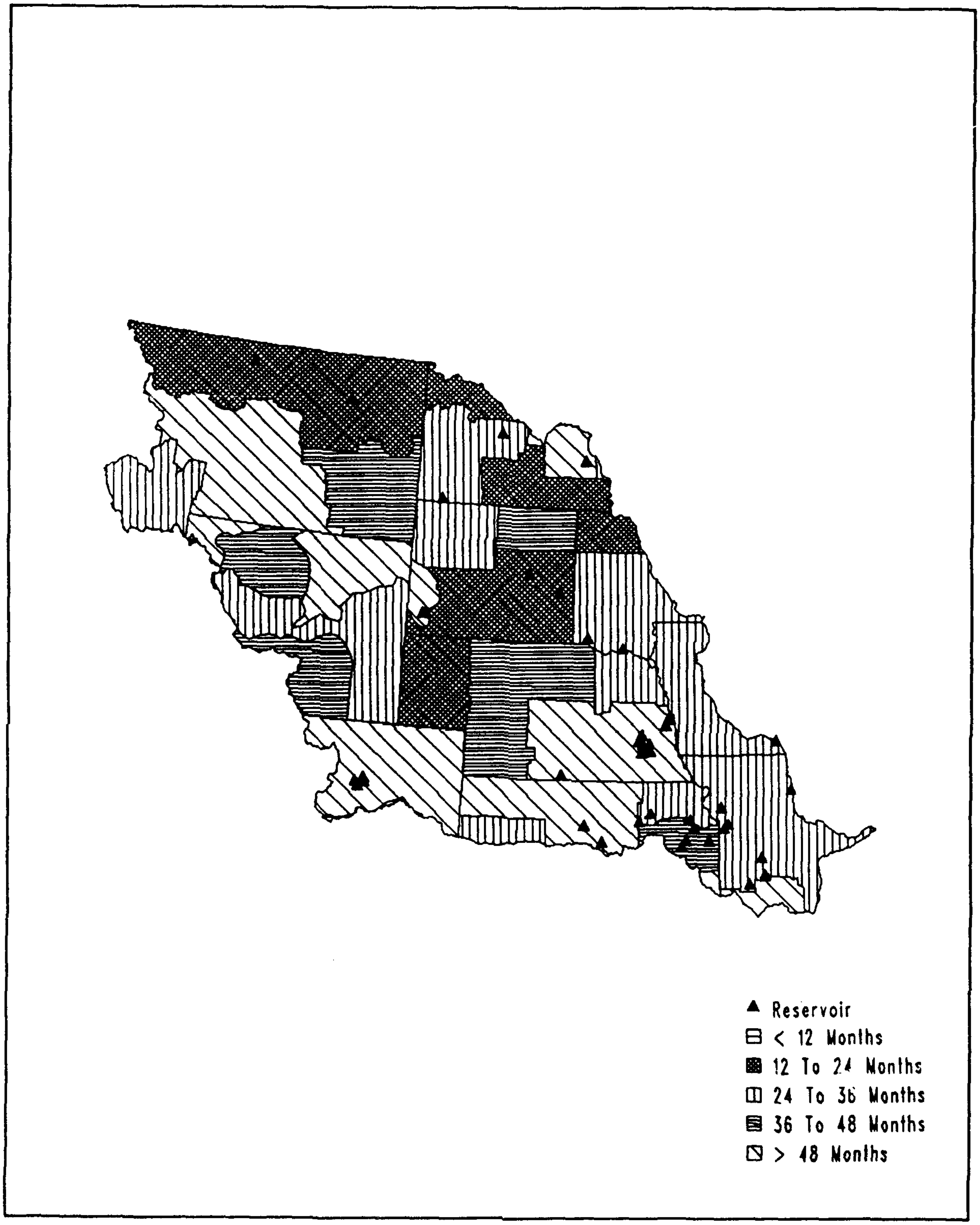

Figure 49. Missouri River Division. Climate Divisions with Severe or Extreme Drought of Different Durations (PHDI)

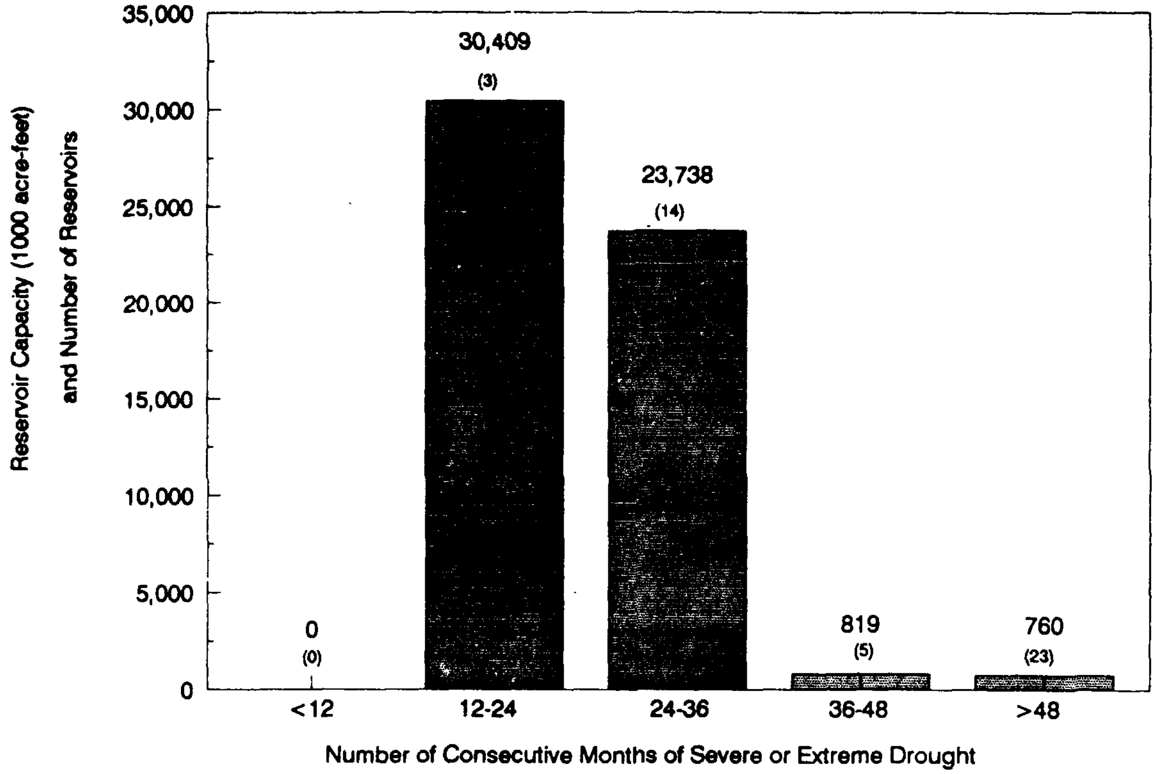

Figure 50. Missouri River Division. Multiple-Purpose Reservoirs Susceptible to Severe or Extreme Droughts of Different Durations (PHDI)

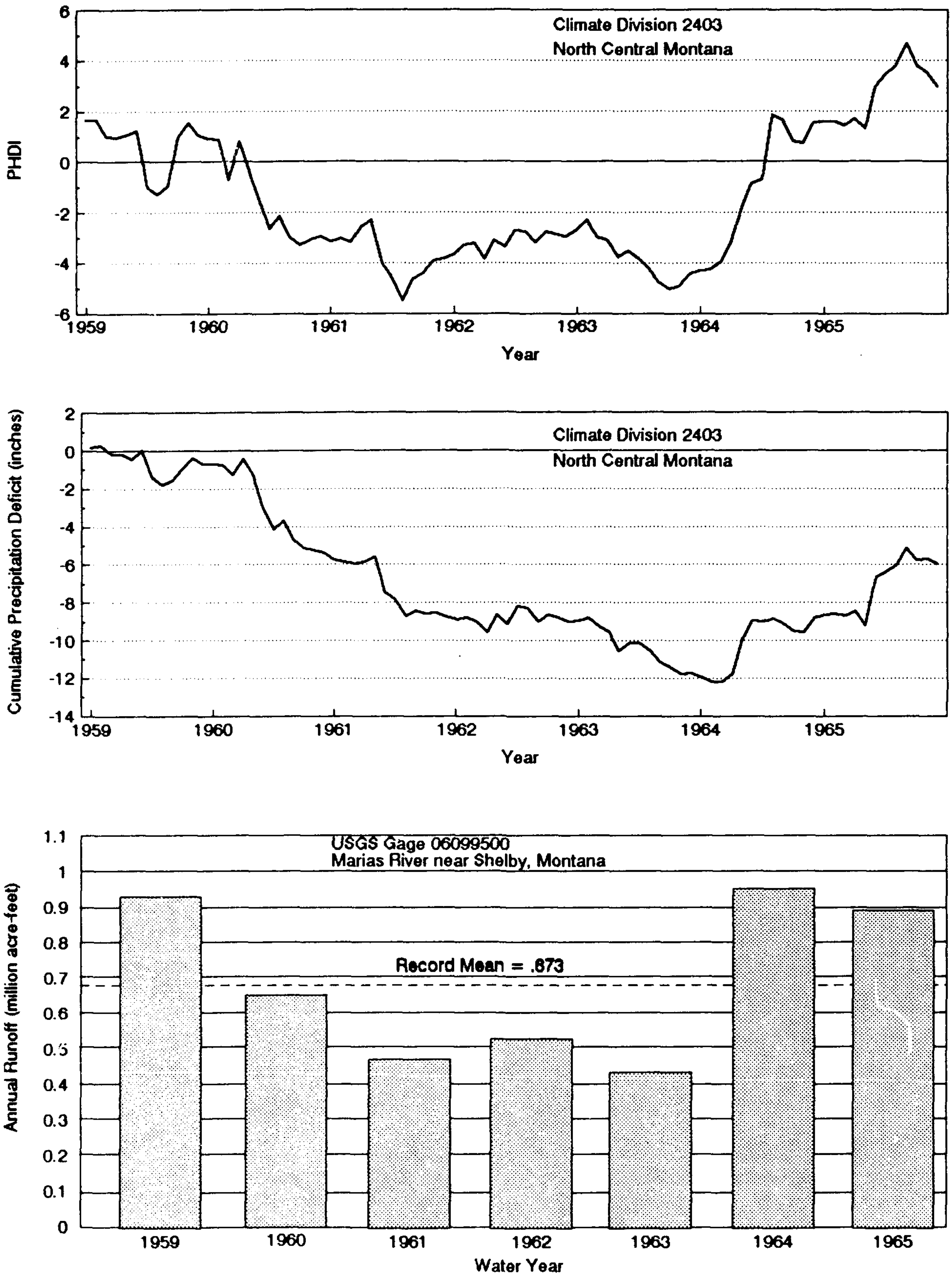

Figure 51. Comparison of PHDI, Precipitation, and Runoff for 1960-64 Drought

North Pacific (NPD)

Reservoir Capacities and Purposes. Over 90 percent of the storage capacity of the reservoirs of this region serves multiple purposes (Table 19). There is less than 1 million acre-feet of exclusive storage for flood control, navigation, and hydroelectric power combined. A multiple-purpose capacity of 11 million acre-feet serves all conservation purposes (Table 20). Hydroelectric power generation is provided at 21 of the 32 multiple-purpose projects and this generation is a major contribution to the energy produced in the Pacific Northwest. Reservoir recreation is also a significant activity and occurs at 31 of the 32 multiple-purpose projects.

An important characteristic of the water resources of the region is the major contributions made by other agencies in meeting water needs. This includes: agencies of the Pacific Northwest Coordination Agreement for coordinated operation of system storage for energy generation; 18 million acre-feet of storage capacity available from the Bureau of Reclamation for irrigation; and recreational facilities provided by the Bureau, states and local governments. Any discussion of the purposes served by Corps' reservoirs must take into account the significant role of these other agencies.

Drought Effects. Drought affects hydroelectric power through a reduced water supply that leads to an inability to meet loads to the fullest extent. In the Pacific Northwest, with a large and diverse coordinated electrical system, large storage capacity, and electrical interties to other regions, droughts of less severity can be accommodated with minimum load reductions and/or substitution of higher cost energy from outside the system. During major, long-term droughts, however, firm loads may need to be reduced. Drought also affects hydropower by reducing the efficiency of the turbines which are designed for higher heads. Operating at low reservoir levels can sometimes increase abrasion of the turbines.

Drought impacts reservoir recreation through lower reservoir levels. Boat docks, campgrounds, lake activities and aesthetics are all affected. Because of the areal extent of droughts in this region, and forest use restrictions during drought, alternate outdoor recreational facilities are often not available.

There are four navigational locks on the Snake River, and four on the lower Columbia River. In addition, Willamette Falls Locks transport vessels around Willamette Falls, and the Lake Washington Ship Canal Project provides ship access between Puget Sound and Lake Washington. During drought, the navigational requirements can often be met by streamflows released for other project purposes. Droughts cause salt water intrusion into the Lake Washington Ship Canal and into Lake Washington, a deep fresh water lake that is adversely affected by salt water. When the water supply for the ship canal is limited, the number of lockages may be curtailed, restricting lock usage.

Other drought effects include the inability to get maintenance vessels onto the reservoirs to clear debris. This debris could be sucked into the penstocks and generators, damaging the generating facilities, thus causing additional problems. Also, as at Dworshak Dam and Reservoir, it might become difficult, if not impossible, to service the sanitation facilities at the "water or trail accessible only" campsites. Fish may be a affected because salmonids and steelhead juveniles must migrate to the ocean in a set period of their lives or they will not be able to smolt and adapt to the salt water environment. Without high spring flows, there is no current to wash them downstream to the ocean, consequently, predator rates go up due to the lower water levels, and disease rates go up. For returning adults, the low flow means confusion because of the low water velocities in the reservoirs to swim into, refusal to migrate, increased susceptibility to diseases with higher water temperatures, and greater loss to predators.

Susceptibility of Reservoirs to Drought. This region has a highly diverse physical geography and a corresponding diverse susceptibility to drought. As shown in Figure 52, the coastal areas in Oregon and Washington indicate severe or extreme drought durations of less than 12 months while further inland some climate divisions indicate durations of greater than 48 months. Coastal droughts of up to 12 months are critical because: (1) municipal water supplies for all large metropolitan areas are taken from surface water, (2) forest usage restrictions (recreation and lumbering) for actual and potential forest fires (including their impact of deforested basins on reservoir operation) are applicable, and (3) adequate currents and reservoir water temperatures for upstream and downstream migration of anadromous fish and steelhead must be provided. Figure 53 indicates that 22 Corps' multiple-purpose reservoirs (10,092,000 acre-feet) are located in climate divisions with severe or extreme durations between 12 and 36 consecutive months based upon an analysis using the PHDI for the period 1895-1989.

Longer duration droughts are indicated where mild to moderate severity is considered. Durations of 60, 91 and 94 consecutive months of mild to extreme drought are indicated for parts of Washington, Oregon and Idaho respectively. The most significant historical droughts that have occurred in these states occurred in the 1920's and 1930's.

Comparison of PHDI, Precipitation, and Runoff. Figure 54 shows a comparison of PHDI, cumulative precipitation, and annual runoff for coastal Oregon. The drought period shown is 1923 to 1927. The severe or extreme period (PHDI <-3.0) occurred in 1924 and 1926. A precipitation deficit existed throughout the drought, reaching a maximum in 1926 when above normal precipitation began the recovery. Annual runoff was lowest in 1924 during the extreme period of drought.

TABLE 19

NORTH PACIFIC (NPD)
RESERVOIR STORAGE

Purpose	Number of Reservoirs	Storage Capacity (Acre-Feet)
Flood Control (Exclusive)	13	646,000
Navigation (Exclusive)	0	0
Hydroelectric Power (Exclusive)	2	128,000
Multiple-Purpose	32	11,104,000
TOTAL	33	11,878,000

TABLE 20

NORTH PACIFIC (NPD)
NUMBER OF RESERVOIRS SERVING EACH PURPOSE
WITH EXCLU SIVE OR MULTIPLE-PURPOSE STORAGE

Purpose	Number of Reservoirs
Flood Control	23
Navigation	8
Hydroelectric Power	21
Irrigation	5
Water Supply	1
Fish and Wildlife	3
Recreation	31
Low-Flow Augmentation	3

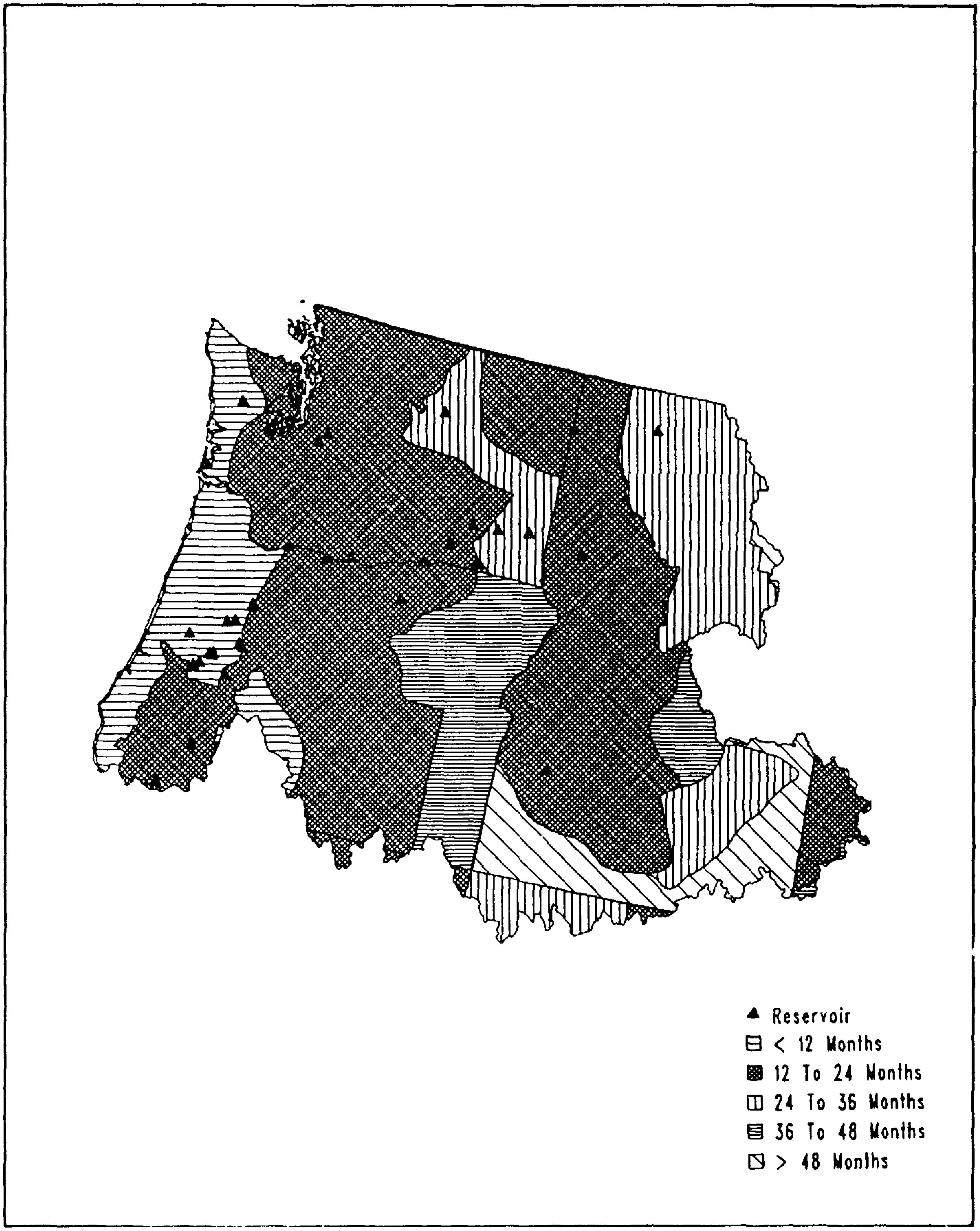

Figure 52. North Pacific Division. Climate Divisions with Severe or Extreme Drought of Different Durations (PHDI)

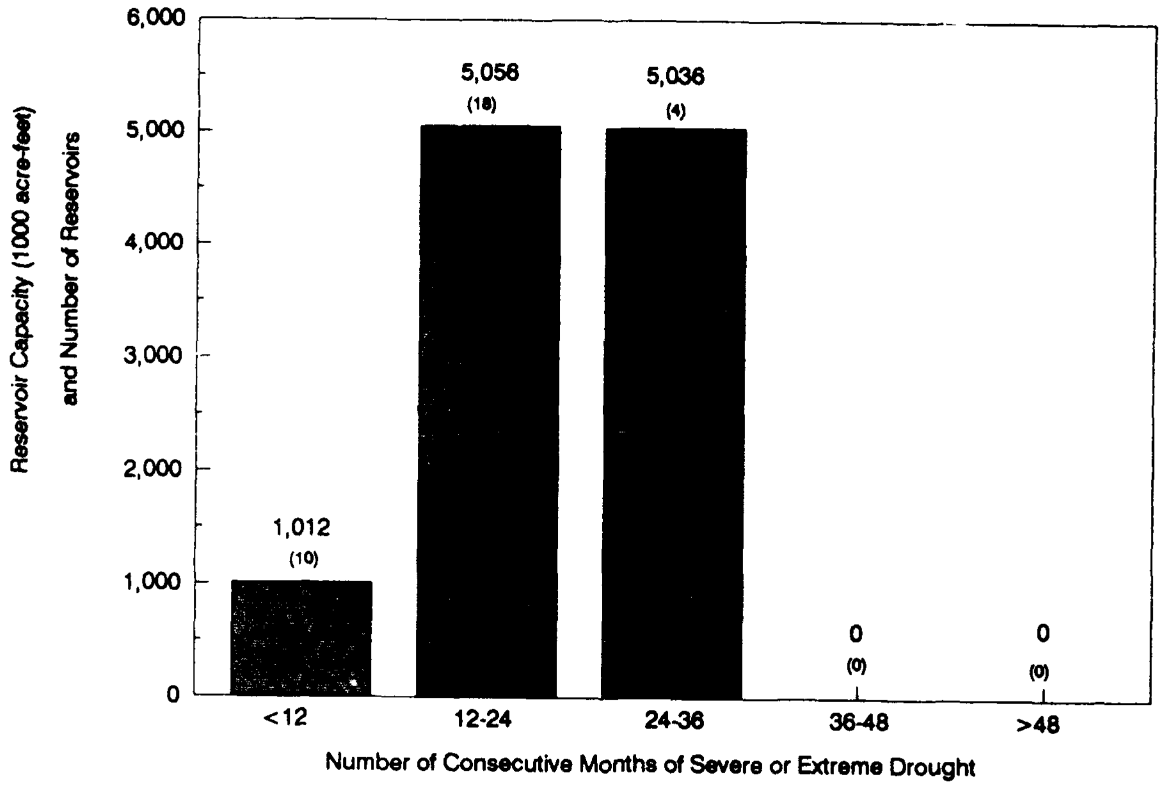

Figure 53. North Pacific Division. Multiple-Purpose Reservoirs Susceptible to Severe or Extreme Droughts of Different Durations (PHDI)

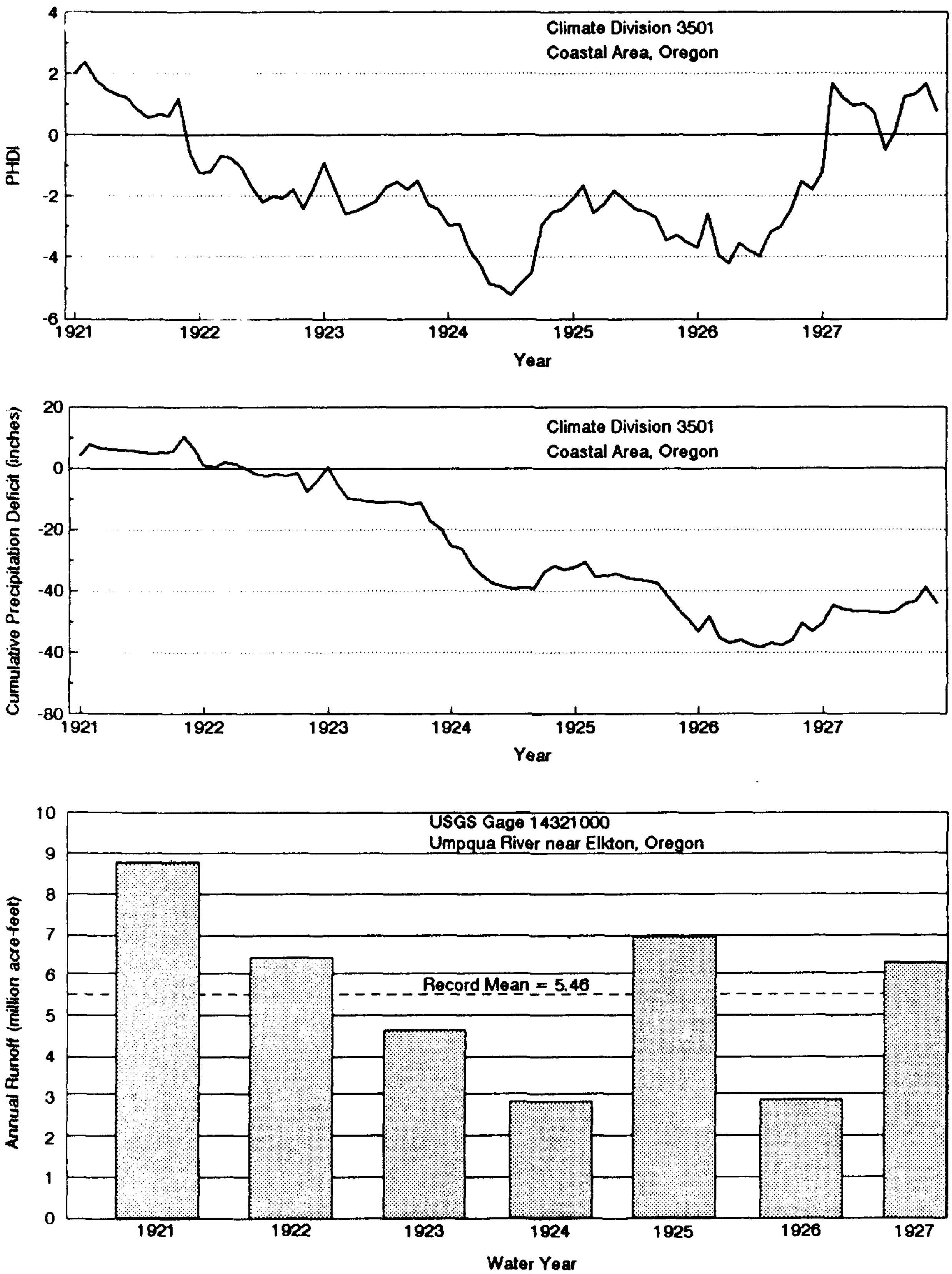

Figure 54. Comparison of PHDI, Precipitation, and Runoff for 1923-27 Drought

South Pacific (SPD)

Reservoir Capacities and Purposes. Reservoirs in this region are predominately for flood control, with 28 of the 32 projects having exclusive flood control storage space (Table 21). In the southern portion (Southern California, Arizona, Nevada), 15 of the 16 reservoirs are single-purpose flood control. Painted Rock Dam and Alamo Lake account for 3.1 million acre-feet, or 60 percent of the exclusive flood control storage. For much of this southern region, water supplies are imported from distant sources or pumped from ground water. Surface runoff is normally far short of consumptive use demand. There is only one multiple-purpose reservoir (Alamo Lake) and it serves flood control, water supply and recreation.

In the northern area (Northern California), there are 16 reservoirs and 10 serve conservation purposes. Water supply, irrigation, recreation, and hydroelectric power are the principal conservation purposes. (Table 22).

Drought Effects. Drought has an impact on all conservation purposes. Less water is available to meet requests for water supply and irrigation, lower reservoir levels reduce recreational activities, and power generation is reduced. The Corps' role in drought response is relatively minor because of the reservoir and conveyance facilities of the Bureau of Reclamation, State of California, Metropolitan Water District (MWD), city of Los Angeles, and Pacific Gas and Electric. These agencies are the dominant players during drought.

Susceptibility of Reservoirs to Drought. The diverse physiographic features of this region correspond with diverse drought potential. Drought duration for the climate divisions together with exclusive and multiple-purpose Corps' reservoirs are shown in Figure 55. The Palmer Hydrological Drought Index (PHDI) for the period 1895-1989 shows that some areas such as the Sacramento River Valley have had severe or extreme droughts of less than 12 consecutive months, while most of Utah, Arizona and portions of Colorado have severe or extreme droughts of greater than 36 consecutive months. Figure 56 shows the distribution of multiple-purpose reservoirs by duration. One reservoir, Alamo Lake, Arizona, (230,000 acre-feet) is susceptible to severe or extreme drought of greater than 48 consecutive months. The remainder of the reservoirs are in climate divisions with severe or extreme droughts of less than 24 consecutive months.

When mild to moderate droughts are considered along with those in the severe or extreme range, the drought duration as measured by the PHDI is longer. Durations of 55, 59 and 87 consecutive months are indicated for the southeast desert basins of California, Nevada and Arizona respectively. Durations in other regions of California are 30-40 months for the mild to extreme range. The years of major drought vary: the 1930's and 1950's in California, in Nevada they began in 1926 and 1933, and in Arizona, a drought of 87 months began in 1898.

Comparison of PHDI, Precipitation, and Runoff. Figure 57 shows a comparison of PHDI, precipitation and annual runoff for the San Joaquin drainage, California. The drought used for the comparison lasted from 1959 to 1963. The severe or extreme period was 1959-62. Corresponding precipitation deficits, and low annual runoff correlate with the PHDI.

TABLE 21

SOUTH PACIFIC (SPD)
RESERVOIR STORAGE

Purpose	Number of Reservoirs	Storage Capacity (Acre-Feet)
Flood Control (Exclusive)	28	5,131,000
Navigation (Exclusive)	0	0
Hydroelectric Power (Exclusive)	0	0
Multiple-Purpose	11	1,971,000
TOTAL	32	7,102,000

TABLE 22

SOUTH PACIFIC (SPD)
NUMBER OF RESERVOIRS SERVING EACH PURPOSE
WITH EXCLUSIVE OR MULTIPLE-PURPOSE STORAGE

Purpose	Number of Reservoirs
Flood Control .	32
Navigation	0
Hydroelectric Power	6
Irrigation	8
Water Supply	3
Fish and Wildlife	0
Recreation	11
Low-Flow Augmentation	0

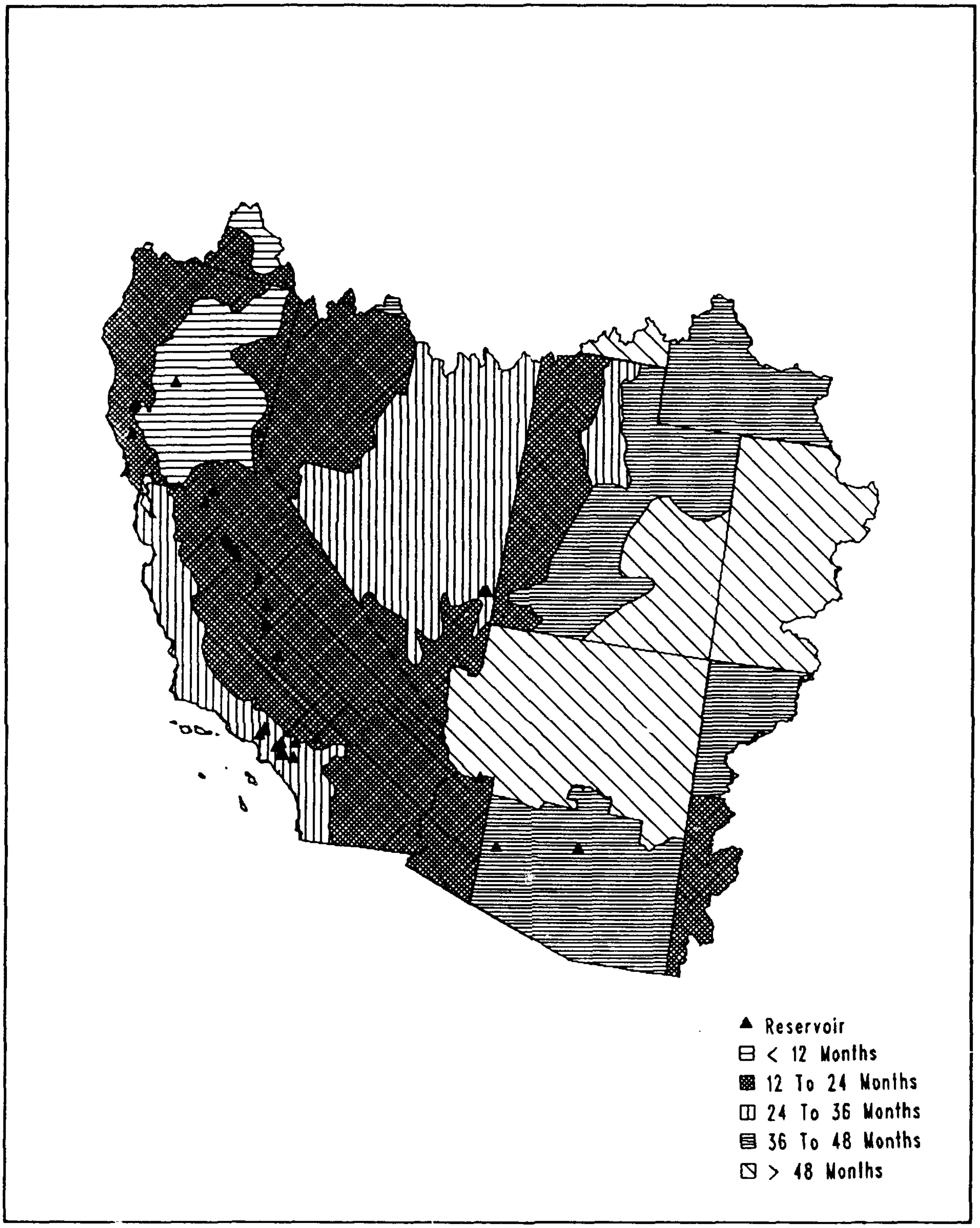

Figure 55. South Pacific Division. Climate Divisions with Severe or Extreme Drought of Different Durations (PHDI)

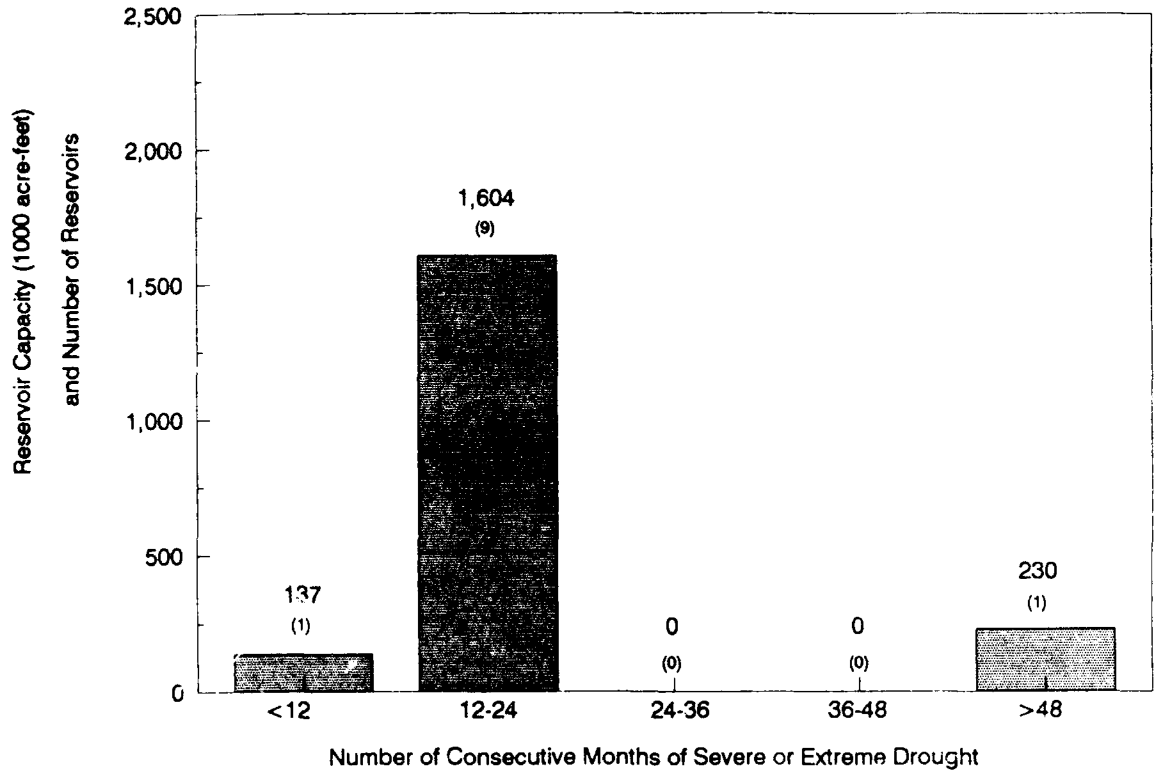

Figure 56. South Pacific Division. Multiple-Purpose Reservoirs Susceptible to Severe or Extreme Droughts of Different Durations (PHDI)

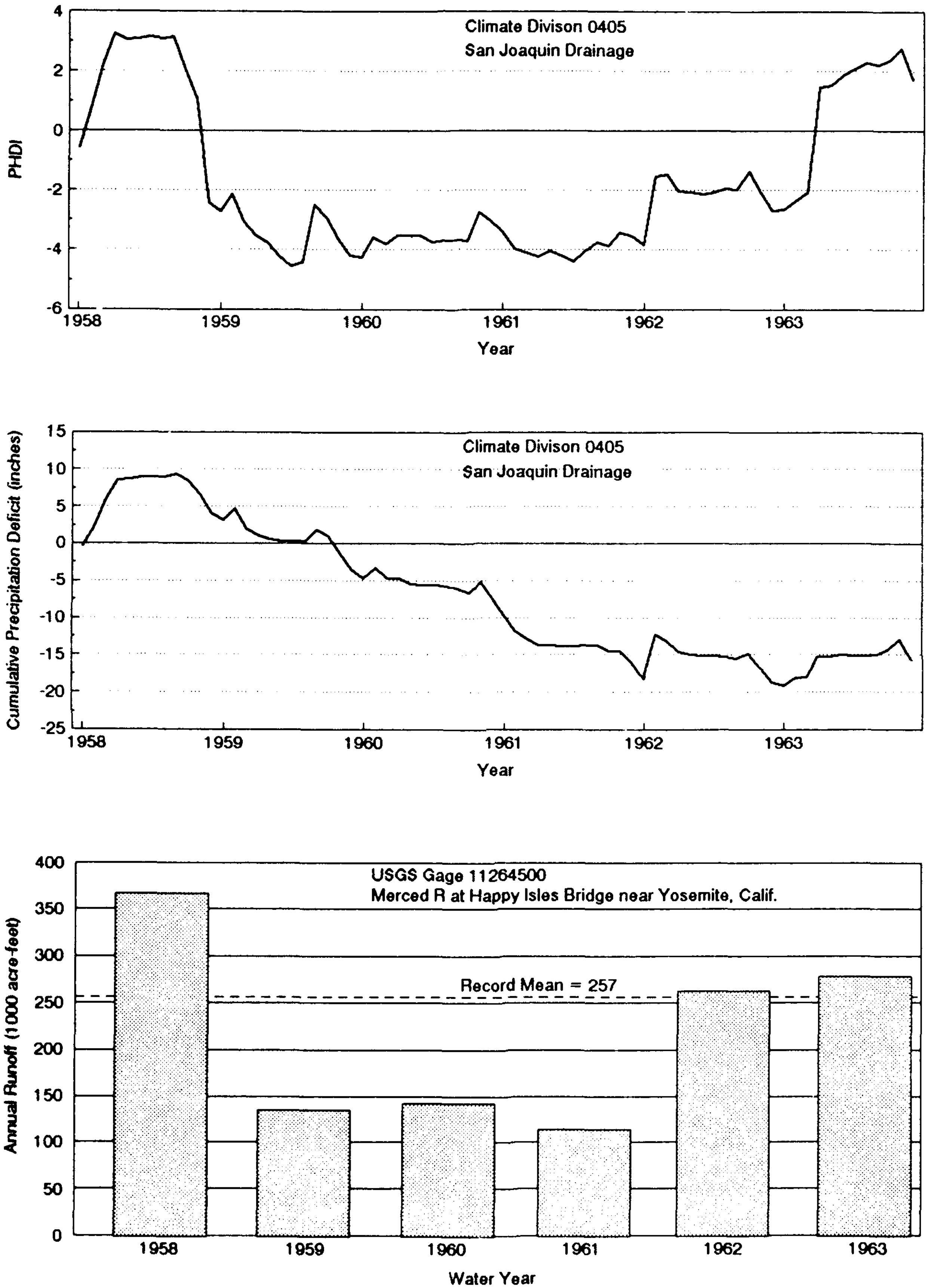

Figure 57. Comparison of PHDI, Precipitation, and Runoff for 1959-62 Drought

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

During the past 50 years the purposes for which Corps of Engineers' reservoirs operate has increased significantly through Congressional authorizations. Recreation, water supply, irrigation, fish and wildlife, water quality, endangered species, estuarine protection, and wetlands have been added to navigation, hydroelectric power, and flood control as project purposes. In addition, the water used for each purpose has grown. Nationally, waterways commerce has increased four-fold; instream water for hydroelectric power four-fold; irrigation withdrawals have doubled; and recreational use at Corps' facilities has increased nearly six times. Increasingly, fixed volumes of reservoir storage are being called upon to serve both a greater number of purposes and an increased demand for each purpose.

Most Corps of Engineers' reservoirs were designed, and construction begun, before additional purposes were added by Congress and their demand grew so significantly. Today, there is approximately 123 million acre-feet of storage capacity available in Corps reservoirs to serve multiple purposes and approximately 95 million acre-feet of reservoir capacity allocated exclusively to flood control. Nearly 70 percent of the multiple-purpose capacity is in the Missouri River and Southwestern Divisions. Both types of storage are important in meeting water needs during drought. Water stored in the multiple-purpose space serves conservation purposes directly: the task is to use the water in the wisest possible manner. Flood control space is not designed to serve conservation purposes directly, however, because it exists in most Corps of Engineers' reservoirs it provides an opportunity to investigate the possibility of storing water for conservation, temporarily or permanently, if the risk of flooding is not increased.

In planning for drought, Corps' reservoir storage capacity and purposes must be examined in a drought context. Drought creates the most intense competition for available storage and the greatest threat to meeting project purposes. Using the Palmer Hydrological Drought Index (PHDI), analyses in this study show that 87 percent of the reservoirs with multiple-purpose storage capacity are in climate divisions where historically (1895-1989) severe or extreme droughts have been of less than 36 consecutive months duration. Reservoirs susceptible to longer term severe or extreme drought are located in the mid-continent: the Missouri River, Southwestern, North Central regions. A few multiple-purpose reservoirs are located in climate divisions where the longest severe or extreme drought is less than 12 consecutive months. These are in coastal regions: principally the South Atlantic, Lower Mississippi Valley and North Pacific. When mild to moderate droughts are included in the analyses, durations of 96 consecutive months are not uncommon and durations of over 120 consecutive months have been measured in some areas of Colorado, Montana, Wyoming and North Dakota. The duration is especially important in reservoir operations because during drought the continuous, daily release of water from a fixed capacity is not balanced by a replenishing supply. The longer this imbalance continues the greater the risk of water shortage.

The principal purposes served by Corps' reservoirs vary from region to region. The dominant purpose in the New England and southern part of the South Pacific regions is flood control. A major purpose in the Ohio, North Central and Lower Mississippi

Valley regions is navigation. Drought planning and response in these regions is strongly influenced by the needs of navigation. Hydroelectric power is a dominant purpose in the North Pacific. Other regions, principally the Missouri River, Southwestern and South Atlantic, are characterized by large multiple-purpose reservoirs that serve several purposes in a major way. Some regions, most notably northern and central California and the North Pacific, are part of a reservoir and conveyance system that is dominated by facilities which are operated by other federal, state and local agencies. Where this situation exists, drought response is strongly influenced by these other agencies.

Several factors play a role in how, and to what extent, reservoir purposes are met during drought. Reservoir and streamflow requirements, for example, must be known monthly or seasonally at minimum and desired levels. Storage capacities, their service levels, and the purposes they serve are also needed. Some reservoirs, for example, have capacity that is used in time of drought, others do not. Flexibility of operation plays a role. Reservoirs with operational, seasonal, institutional, and system flexibility will be better able to respond to changing conditions. The availability of alternative ways to meet a need makes that need less vulnerable. Water supply is one example. In some regions, ground water is a readily available alternative to surface water. The consequences of water shortage is another consideration. Some purposes may face serious consequences of shortage, others less serious. These consequences should be identified and properly assessed. Lastly, good data and decision criteria are an essential part of drought planning and reservoir operations. This includes the collection of necessary data and the development of decision criteria to prepare for and respond to drought.

National and regional assessments, such as this study presents, are useful in describing reservoirs and drought for large geographic regions. They provide an overview of all Corps' reservoirs and divisions and allow comparisons for a national and regional perspective. Such assessments, however, are limited in their usefulness for planning and water control management because they do not contain many important details of individual reservoirs, systems of reservoirs, or local conditions - all of which influence reservoir operations. Each reservoir is unique and that uniqueness is defined by a wide variety of conditions, each of which may be important, and some of which are critical to effective drought response. A reservoir is unique in its geography, storage capacity, purposes, and hydrology. It is unique in its river system, legal and regulatory requirements, ownership and institutional arrangements, population served, and local, state and federal political interest. To properly plan for drought, it is necessary to examine individual reservoirs, and reservoir systems in detail.

Recommendations

It is the recommendation of this study that each Corps of Engineer reservoir be analyzed individually, or as part of a system, to develop ways to improve its operation during drought, to improve its effectiveness in meeting the purposes served, and to identify any constraints to such improvements. Such an examination should be a hydrologic assessment of the water available to the reservoir during drought and the water needed by the purposes served. It should be comprehensive enough to address reservoir storage reallocation, water transfers, and conjunctive use management which are important opportunities in some regions of the country. Sufficient funds should be provided to the division and district offices to enable them to conduct the necessary investigations. The type of studies needed in each office will vary depending upon what has already been done. Some suggestions for what should be included in these studies are offered below.

1. Computer simulation of reservoir operations during drought is the most effective way to determine how to use available storage to meet project purposes. Simulation, including a variety of optimizing system analysis techniques, can determine the magnitude and frequency of possible drought shortages, identify trade-offs between purposes, and evaluate the feasibility of storage reallocation. Most important, simulation can incorporate the needed detail to insure that the findings are realistic and credible.

2. To accurately simulate reservoir operations, data describing low-flow conditions and data describing project purposes must be collected, organized, and stored in digital form. These data include, but are not limited to, the following:

a. Historical and stochastic drought streamflow hydrology.
b. Reservoir losses such as evaporation, leakage and withdrawals.
c. Reservoir and streamflow requirements for each purpose served, including monthly variations, and maximum, minimum and desired levels.
d. Information on the hydrologic, economic, environmental and social consequences of not meeting project purposes.
e. Losses and gains downstream including river evaporation, seepage, ground water, return flow, wastewater discharge, and withdrawals.
f. Location, elevation and corresponding streamflow for water intakes along the river, and intake location and elevation at the reservoir.
g. Water rights requirements and priorities for all purposes.
h. Interconnections (physical, legal, institutional) with reservoirs, river systems, and other purposes.

3. Computer software necessary to do the analyses should be developed. Most flood control models do not have the capability to include and accurately analyze all the purposes for which Corps' reservoirs operate, nor do they include all the hydrologic and legal features necessary to represent drought, for example, return flow, ground-water contributions, and water rights requirements. Software designed for single-purpose flood control usually lacks the robustness to model multiple-purpose needs under drought conditions.

4. Development of a water supply and use balance for Corps of Engineers' reservoirs and reservoir systems provides a systematic "picture" of available water supplies and the demand placed upon them. Such a "picture" may be of Corps' reservoirs and/or related rivers, or it may be of the larger region within which the Corps operates its facilities. Because of the interconnectedness of water resources, a water balance for a larger area can place the Corps' operation in the context of the supplies and needs of others. A water balance is an important and useful analysis for all water management agencies, not only the Corps, and it is especially useful in drought planning.

5. Drought indicators can be an important aid to managing reservoirs and achieving efficient water use during drought. A good index will measure both the severity of a water shortage and the vulnerability of project purposes. Unfortunately, none of the indicators currently available are satisfactory for real-time drought operations by the Corps. Efforts to apply available drought indicators have been made by some offices, however, the results have been mixed. There is a need to continue this work by not only developing adequate indicators but by having field offices test, calibrate and verify them.

These suggestions are an important next step in the Corps of Engineers' goal to improve its national water management during drought. The same effort needs to be made to reduce the harmful impacts of drought as has been made for flooding during the last half-century. While floods and drought are significantly different, the need for effective planning and management are the same.

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APPENDICES

Corps of Engineer's Divisions and Districts

Lower Mississippi Valley Division (LMV)

Memphis	LMM
New Orleans	LMN
St. Louis	LMS
Vicksburg	LMK

Missouri River Division (MRD)

Kansas City	MRK
Omaha	MRO

New England Division (NED)

North Atlantic Division (NAD)

Baltimore	NAB
New York	NAN
Norfolk	NAO
Philadelphia	NAP

North Central Division (NCD)

Buffalo	NCB
Chicago	NCC
Detroit	NCE
Rock Island	NCR
St. Paul	NCS

North Pacific Division (NPD)

Alaska	NPA
Portland	NPP
Seattle	NPS
Walla Walla	NPW

Ohio River Division (ORD)

Huntington	ORH
Louisville	ORL
Nashville	ORN
Pittsburg	ORP

Pacific Ocean Division (POD)

South Atlantic Division (SAD)

Charleston	SAC
Jacksonville	SAJ
Mobile	SAM
Savannah	SAS
Wilmington	SAW

South Pacific Division (SPD)

Los Angeles	SPL
Sacramento	SPK
San Francisco	SPN

Southwestern Division (SWD)

Albuquerque	SWA
Ft. Worth	SWF
Galveston	SWG
Little Rock	SWL
Tulsa	SWT

APPENDIX 2

CORPS OF ENGINEERS
RESERVOIRS BY DIVISION

New England (NED)

Project	River	Type[1]	State
BALL MOUNTAIN LAKE	WEST RIVER	R	VT
BARRE FALLS DAM	WARE RIVER	R	MA
BIRCH HILL DAM	MILLERS RIVER	R	MA
BLACK ROCK LAKE	BRANCH BROOK	R	CT
BLACKWATER DAM	BLACKWATER RIVER	R	NH
BUFFUMVILLE LAKE	LITTLE RIVER	R	MA
COLEBROOK RIVER LAKE	WEST BRANCH FARMINGTON RIVER	R	CT
CONANT BROOK DAM	CONANT BROOK	R	MA
EAST BRIMFIELD LAKE	QUINEBAUG RIVER	R	MA
EDWARD MACDOWELL DAM	NUBANUSIT BROOK	R	NH
FRANKLIN FALLS DAM	PEMIGEWASSET RIVER	R	NH
HANCOCK BROOK LAKE	HANCOCK BROOK	R	CT
HODGES VILLAGE DAM	FRENCH RIVER	R	MA
HOP BROOK LAKE	HOP BROOK	R	CT
HOPKINTON-EVERETT LAKES (EVERETT DAM)	PISCATAQUOG RIVER	R	NH
HOPKINTON-EVERETT LAKES (HOPKINTON DAM)	CONTOOCOOK RIVER	R	NH
KNIGHTVILLE DAM	WESTFIELD RIVER	R	MA
LITTLEVILLE LAKE	WESTFIELD RIVER	R	MA
MANSFIELD HOLLOW LAKE	NATCHAUG RIVER	R	CT
NORTH HARTLAND LAKE	OTTAUQUECHEE RIVER	R	VT
NORTH SPRINGFIELD LAKE	BLACK RIVER	R	VT
NORTHFIELD BROOK LAKE	NORTHFIELD BROOK	R	CT
OTTER BROOK LAKE	OTTER BROOK	R	NH
SURRY MOUNTAIN LAKE	ASHUELOT RIVER	R	NH
THOMASTON DAM	NAUGATUCK RIVER	R	CT
TOWNSHEND LAKE	WEST RIVER	R	VT
TULLY LAKE	EAST BRANCH TULLY RIVER	R	MA
UNION VILLAGE DAM	OMPOMPANOOSUC RIVER	R	VT
WEST HILL DAM	WEST RIVER	R	MA
WEST THOMPSON LAKE	QUINEBAUG RIVER	R	CT
WESTVILLE LAKE	QUINEBAUG RIVER	R	MA

[1] R = Reservoir, L = Lock and Dam

North Atlantic (NAD)

Project	River	Type[1]	State
ALMOND LAKE	CANACADEA CREEK	R	NY
ALVIN R BUSH DAM	KETTLE CREEK	R	PA
ARKPORT DAM	CANISTEO RIVER	R	NY
AYLESWORTH CREEK LAKE	AYLESWORTH CREEK	R	PA
BELTZVILLE LAKE	POHOPOCO CREEK	R	PA
BLUE MARSH LAKE	TULPEHOCKEN CREEK	R	PA
COWANESQUE LAKE	COWANESQUE RIVER	R	PA
CURWENSVILLE LAKE	WEST BRANCH SUSQUEHANNA RIVER	R	PA
EAST SIDNEY LAKE	OULEOUT CREEK	R	NY
FOSTER JOSEPH SAYERS DAM	BALD EAGLE CREEK	R	PA
FRANCIS E. WALTER DAM	LEHIGH RIVER	R	PA
GATHRIGHT DAM	JACKSON RIVER	R	VA
GENERAL EDGAR JADWIN DAM AND RESERVOIR	DYBERRY CREEK	R	PA
JENNINGS RANDOLPH LAKE (BLOOMINGTON DAM)	NORTH BRANCH OF POTOMAC	R	MD
PROMPTON LAKE	LACKAWAXEN RIVER	R	PA
RAYSTOWN LAKE	RAYSTOWN BRANCH JUNIATA RIVER	R	PA
STILLWATER LAKE	LACKAWANNA RIVER	R	PA
TIOGA-HAMMOND LAKES (HAMMOND DAM)	CROOKED CREEK	R	PA
TIOGA-HAMMOND LAKES (TIOGA DAM)	TIOGA RIVER	R	PA
WHITNEY POINT LAKE	OTSELIC RIVER	R	NY
YORK INDIAN ROCK DAM	CODORUS CREEK	R	PA

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

South Atlantic (SAD)

Project	River	Type[1]	State
ABERDEEN LK/DM (TENN-TOM, AL & MS)	TOMBIGBEE RIVER	R	MS
ALICEVILLE LOCK AND DAM	TOMBIGBEE RIVER	L	AL
ALLATOONA LAKE DAM AND POWERHOUSE	ETOWAH RIVER	R	GA
ARMISTEAD I. SELDEN	BLACK WARRIOR RIVER	R	AL
B. EVERETT JORDAN DAM AND LAKE	HAW RIVER	R	NC
BAY SPRINGS LOCK AND DAM	TOMBIGBEE RIVER	L	MS
BUFORD DAM AND LAKE SIDNEY LANIER	CHATTAHOOCHEE RIVER	R	GA
CARTERS MAIN DAM AND LAKE	COOSAWATTEE RIVER	R	GA
CLAIBORNE LOCK AND DAM	ALABAMA RIVER	L	AL
COFFEEVILLE LOCK AND DAM	TOMBIGBEE RIVER	L	AL
COLUMBUS LOCK AND DAM	TOMBIGBEE RIVER	L	MS
DEMOPOLIS LOCK AND DAM	TOMBIGBEE RIVER	L	AL
FALLS LAKE	NEUSE RIVER	R	NC
GAINESVILLE LOCK AND DAM	TOMBIGBEE RIVER	L	AL
GEORGE W. ANDREWS LOCK AND DAM	CHATTAHOOCHEE RIVER	L	AL
HARTWELL LAKE	SAVANNAH RIVER	R	GA
HOLT LOCK, DAM AND POWERHOUSE	BLACK WARRIOR RIVER	L	AL
INGLIS LOCK, DAM, AND SPILLWAY	WITHLACOOCHEE RIVER	L	FL
J. STROM THURMOND DAM AND LAKE (CLARKS HILL)	SAVANNAH RIVER	R	GA
JIM WOODRUFF DAM	APALACHICOLA RIVER	R	FL
JOHN H. KERR DAM AND RESERVOIR	ROANOKE RIVER	R	VA
JOHN HOLLIS BANKHEAD LOCK DAM & PH	BLACK WARRIOR RIVER	L	AL
LAKE OKEECHOBEE	CENTRAL AND SOUTHERN FLORIDA	R	FL
LOCK A (TENN-TOM, AL AND MS)	TOMBIGBEE RIVER	L	MS
LOCK B (TENN-TOM, AL AND MS)	TOMBIGBEE RIVER	L	MS
LOCK C (TENN-TOM, AL AND MS)	TOMBIGBEE RIVER	L	MS
LOCK D (TENN-TOM, AL AND MS)	TOMBIGBEE RIVER	L	MS
LOCK E (TENN-TOM, AL AND MS)	TOMBIGBEE RIVER	L	MS
MILLERS FERRY LOCK, DAM & POWERHOUSE-WILLIAM "BILL" DANNELLY LAKE	ALABAMA RIVER	L	AL
OKATIBBEE LAKE	OKATIBBEE CREEK	R	MS
PHILPOTT LAKE	SMITH RIVER	R	VA
RICHARD B. RUSSELL DAM AND LAKE	SAVANNAH RIVER	R	GA
ROBERT F. HENRY LOCK AND DAM	ALABAMA RIVER	L	AL
RODMAN DAM AND SPILLWAY	OKLAWAHA RIVER	R	FL
S-10 & WATER CONS AREA 1	CENTRAL AND SOUTHERN FLORIDA	R	FL
S-11 & WATER CONS AREA 2A	CENTRAL AND SOUTHERN FLORIDA	R	FL
S-12 & WATER CONS AREA 3A	CENTRAL AND SOUTHERN FLORIDA	R	FL
W. KERR SCOTT DAM AND RESERVOIR	YADKIN RIVER	R	NC
WALTER F. GEORGE LOCK, DAM AND POWERHOUSE	CHATTAHOOCHEE RIVER	L	AL
WEST POINT LAKE	CHATTAHOOCHEE RIVER	R	GA
WILLIAM BACON OLIVER LOCK AND DAM	BLACK WARRIOR RIVER	L	AL

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

Ohio River (ORD)

Project	River	Type[1]	State
ALLEGHENY LOCK AND DAM 02	ALLEGHENY RIVER	L	PA
ALLEGHENY LOCK AND DAM 03	ALLEGHENY RIVER	L	PA
ALLEGHENY LOCK AND DAM 04	ALLEGHENY RIVER	L	PA
ALLEGHENY LOCK AND DAM 05	ALLEGHENY RIVER	L	PA
ALLEGHENY LOCK AND DAM 06	ALLEGHENY RIVER	L	PA
ALLEGHENY LOCK AND DAM 07	ALLEGHENY RIVER	L	PA
ALLEGHENY LOCK AND DAM 08	ALLEGHENY RIVER	L	PA
ALLEGHENY LOCK AND DAM 09	ALLEGHENY RIVER	L	PA
ALUM CREEK LAKE	ALUM CREEK OF BIG WALNUT CRK.	R	OH
ATWOOD LAKE	INDIAN FORK RIVER	R	OH
BARKLEY DAM AND LAKE BARKLEY	CUMBERLAND RIVER	R	KY
BARREN RIVER LAKE	BARREN RIVER	R	KY
BEACH CITY LAKE	SUGAR CREEK OF TUSCARAWAS R.	R	OH
BEECH FORK LAKE	BEECH FORK OF TWELVE POLE CK.	R	WV
BELLEVILLE LOCKS AND DAM	OHIO RIVER	L	WV
BERLIN LAKE	MAHONING RIVER	R	OH
BLUESTONE LAKE	NEW RIVER	R	WV
BOLIVAR DAM	SANDY CREEK	R	OH
BROOKVILLE LAKE	EAST FORK OF WHITEWATER RIVER	R	IN
BUCKHORN LAKE	MIDDLE FORK KENTUCKY RIVER	R	KY
BURNSVILLE LAKE	LITTLE KANAWHA RIVER	R	WV
CAESAR CREEK LAKE	CAESAR CREEK	R	OH
CAGLES MILL LAKE	MILL CREEK	R	IN
CANNELTON LOCKS AND DAM	OHIO RIVER	L	KY
CARR FORK LAKE	CARR FORK RIVER	R	KY
CAVE RUN LAKE	LICKING RIVER	R	KY
CECIL M. HARDEN LAKE	RACCOON CREEK	R	IN
CENTER HILL LAKE	CANEY FORK RIVER	R	TN
CHARLES MILL LAKE	BLACK FORK OF MOHICAN RIVER	R	OH
CHEATHAM LOCK AND DAM	CUMBERLAND RIVER	L	TN
CLARENCE J. BROWN DAM/RESERVOIR	BUCK CREEK	R	OH
CLENDENING LAKE	BRUSHY FK OF STILLWATER CREEK	R	OH
CONEMAUGH RIVER LAKE	CONEMAUGH RIVER	R	PA
CORDELL HULL LOCK AND DAM	CUMBERLAND RIVER	L	TN
CPT. ANTHONY MELDAHL LOCKS AND DAM	OHIO RIVER	L	OH
CROOKED CREEK LAKE	CROOKED CREEK	R	PA
DALE HOLLOW LAKE	OBEY RIVER	R	TN
DASHIELDS LOCKS AND DAM	OHIO RIVER	L	PA
DEER CREEK LAKE	DEER CREEK	R	OH
DELAWARE LAKE	OLENTANGY RIVER	R	OH
DEWEY LAKE	JOHNS CREEK OF LEVISA FORK	R	KY
DILLON LAKE	LICKING RIVER	R	OH
DOVER LAKE	TUSCARAWAS RIVER	R	OH
EAST BRANCH CLARION RIVER LAKE	CLARION RIVER	R	PA

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

Ohio River (ORD)

Project	River	Type[1]	State
EAST LYNN LAKE	EAST FK TWELVEPOLE CREEK	R	WV
EMSWORTH LOCKS AND DAMS	OHIO RIVER	L	PA
FISHTRAP LAKE	LEVISA FORK OF BIG SANDY	R	KY
GALLIPOLIS LOCKS AND DAM	OHIO RIVER	L	WV
GRAYSON LAKE	LITTLE SANDY RIVER	R	KY
GREEN RIVER LAKE	GREEN RIVER	R	KY
GREEN RIVER LOCK AND DAM #1	GREEN RIVER	L	KY
GREEN RIVER LOCK AND DAM #2	GREEN RIVER	L	KY
GREENUP LOCK AND DAM	OHIO RIVER	L	KY
HANNIBAL LOCKS AND DAM	OHIO RIVER	L	WV
HILDEBRAND LOCK AND DAM	MONONGAHELA RIVER	L	WV
HUNTINGTON LAKE	WABASH RIVER	R	IN
J. PERCY PRIEST DAM AND RESERVOIR	STONES RIVER	R	TN
JOHN W. FLANNAGAN DAM AND RESERVOIR	POUND RIVER	R	VA
KENTUCKY RIVER LOCK AND DAM 01	KENTUCKY RIVER	L	KY
KENTUCKY RIVER LOCK AND DAM 02	KENTUCKY RIVER	L	KY
KENTUCKY RIVER LOCK AND DAM 03	KENTUCKY RIVER	L	KY
KENTUCKY RIVER LOCK AND DAM 04	KENTUCKY RIVER	L	KY
KINZUA DAM AND ALLEGHENY LAKE	ALLEGHENY RIVER	R	PA
LAUREL RIVER LAKE	LAUREL RIVER	R	KY
LEESVILLE LAKE	MCGUIRE CREEK	R	OH
LONDON LOCKS AND DAM	KANAWHA RIVER	L	WV
LOYALHANNA LAKE	LOYALHANNA CREEK	R	PA
MAHONING CREEK LAKE	MAHONING CREEK	R	PA
MARKLAND LOCKS AND DAM	OHIO RIVER	L	KY
MARMET LOCKS AND DAM	KANAWHA RIVER	L	WV
MARTINS FORK LAKE	MARTINS FORK OF CUMBERLAND R.	R	KY
MAXWELL LOCKS AND DAM	MONONGAHELA RIVER	L	PA
MCALPINE LOCKS AND DAM	OHIO RIVER	L	KY
MICHAEL J. KIRWAN DAM AND RESERVOIR	WEST BRANCH OF THE MAHONING R.	R	OH
MISSISSINEWA LAKE	MISSISSINEWA RIVER	R	IN
MOHAWK DAM	WALHONDING RIVER	R	OH
MOHICANVILLE LAKE	LAKE FORK OF MOHICAN RIVER	R	OH
MONONGAHELA LOCK AND DAM 07	MONONGAHELA RIVER	L	PA
MONONGAHELA LOCK AND DAM 08	MONONGAHELA RIVER	L	PA
MONONGAHELA LOCKS AND DAM 02	MONONGAHELA RIVER	L	PA
MONONGAHELA LOCKS AND DAM 03	MONOGAHELA RIVER	L	PA
MONONGAHELA LOCKS AND DAM 04	MONOGAHELA RIVER	L	PA
MONROE LAKE	SALT CREEK	R	IN
MONTGOMERY LOCKS AND DAM	OHIO RIVER	L	PA
MORGANTOWN LOCK AND DAM	MONONGAHELA RIVER	L	WV
MOSQUITO CREEK LAKE	MOSQUITO CREEK	R	OH
NEW CUMBERLAND LOCKS AND DAM	OHIO RIVER	L	WV
NEWBURGH LOCKS AND DAM	OHIO RIVER	L	KY

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

Ohio River (ORD)

Project	River	Type[1]	State
NOLIN LAKE	NOLIN RIVER	R	KY
NORTH BRANCH OF KOKOSING RIVER LAKE	NORTH BRANCH OF KOKOSING RIVER	R	OH
NORTH FORK OF POUND RIVER LAKE	NORTH FORK OF POUND RIVER	R	VA
OHIO RIVER LOCK AND DAM 52	OHIO RIVER	L	KY
OHIO RIVER LOCK AND DAM 53	OHIO RIVER	L	KY
OLD HICKORY LOCK AND DAM	CUMBERLAND RIVER	L	TN
OPEKISKA LOCK AND DAM	MONONGAHELA RIVER	L	WV
PAINT CREEK LAKE	PAINT CREEK	R	OH
PAINTSVILLE LAKE	PAINT CREEK	R	KY
PATOKA LAKE	PATOKA RIVER	R	IN
PIEDMONT LAKE	STILLWATER CREEK	R	OH
PIKE ISLAND LOCKS AND DAM	OHIO RIVER	L	WV
PLEASANT HILL LAKE	CLEAR FORK OF MOHICAN RIVER	R	OH
R.D. BAILEY LAKE	GUYANDOT RIVER	R	WV
RACINE LOCKS AND DAM	OHIO RIVER	L	WV
ROUGH RIVER LAKE	ROUGH RIVER	R	KY
SALAMONIE LAKE	SALAMONIE RIVER	R	IN
SENECAVILLE LAKE	SENECA FORK OF WILLS CREEK	R	OH
SHENANGO RIVER LAKE	SHENANGO RIVER	R	PA
SMITHLAND LOCKS AND DAM	OHIO RIVER	L	IL
SUMMERSVILLE LAKE	GAULEY RIVER	R	WV
SUTTON LAKE	ELK RIVER	R	WV
TAPPAN LAKE	LITTLE STILLWATER CREEK	R	OH
TIONESTA LAKE	TIONESTA CREEK	R	PA
TOM JENKINS DAM	EAST BRANCH OF SUNDAY CREEK	R	OH
TYGART LAKE	TYGART RIVER	R	WV
UNION CITY LAKE	FRENCH CREEK	R	PA
UNIONTOWN LOCKS AND DAM	OHIO RIVER	L	KY
WEST FORK OF MILL CREEK LAKE	WEST FORK OF MILL CREEK	R	OH
WILLIAM H. HARSHA LAKE	EAST FORK OF LITTLE MIAMI R.	R	OH
WILLOW ISLAND LOCKS AND DAM	OHIO RIVER	L	WV
WILLS CREEK LAKE	WILLS CREEK	R	OH
WINFIELD LOCKS AND DAM	KANAWHA RIVER	L	WV
WOLF CREEK DAM-LAKE CUMBERLAND	CUMBERLAND RIVER	R	KY
WOODCOCK CREEK LAKE	WOODCOCK CREEK	R	PA
YOUGHIOGHENY RIVER LAKE	YOUGHIOGHENY RIVER	R	PA

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

North Central (NCD)

Project	River	Type[1]	State
BALDHILL DAM	SHEYENNE RIVER	R	ND
BIG STONE LAKE AND WETSTONE RIVER	MINNESOTA RIVER	R	MN
BRANDON ROAD LOCK AND DAM	ILLINOIS RIVER	L	IL
CEDARS LOCK AND DAM (KIMBERLY DAM)	FOX RIVER	L	WI
CORALVILLE LAKE AND DAM	IOWA RIVER	R	IA
DEPERE LOCK AND DAM	FOX RIVER	L	WI
DRESDEN ISLAND LOCK AND DAM	ILLINOIS RIVER	L	IL
EAU GALLE LAKE	EAU GALLE RIVER	R	WI
FARM CREEK RESERVOIR	FONDULAC CREEK	R	IL
FARMDALE	FARM CREEK	R	IL
GULL LAKE	GULL RIVER	R	MN
HOMME LAKE AND DAM	SOUTH BRANCH OF PARK RIVER	R	ND
KAUKAUNA LOCKS AND DAM	FOX RIVER	L	WI
LA GRANGE LOCK AND DAM	ILLINOIS RIVER	L	IL
LAC QUI PARLE LAKE	MINNESOTA	R	MN
LEECH LAKE DAM	LEECH LAKE RIVER	R	MN
LITTLE CHUTE LOCKS AND DAM	FOX RIVER	L	WI
LITTLE KAUKAUNA LOCK AND DAM	FOX RIVER	L	WI
LOCK & DAM NO 10	MISSISSIPPI RIVER	L	IA
LOCK & DAM NO 3	MISSISSIPPI RIVER	L	MN
LOCK & DAM NO 4	MISSISSIPPI RIVER	L	WI
LOCK & DAM NO 5	MISSISSIPPI RIVER	L	MN
LOCK & DAM NO 5A	MISSISSIPPI RIVER	L	MN
LOCK & DAM NO 6	MISSISSIPPI RIVER	L	WI
LOCK & DAM NO 7	MISSISSIPPI RIVER	L	MN
LOCK & DAM NO 8	MISSISSIPPI RIVER	L	WI
LOCK & DAM NO 9	MISSISSIPPI RIVER	L	WI
LOCK AND DAM 22	MISSISSIPPI RIVER	L	MO
LOCKPORT LOCK AND DAM	ILLINOIS RIVER	L	IL
LOCKS & DAM NO 1	MISSISSIPPI RIVER	L	MN
LOCKS & DAM NO 2	MISSISSIPPI RIVER	L	MN
LOWER APPLETON LOCKS AND DAM	FOX RIVER	L	WI
MARSEILLES DAM	ILLINOIS RIVER	R	IL
MARSH LAKE DAM	MINNESOTA	R	MN
MENASHA LOCK AND DAM (LAKE WINNEBAGO)	FOX RIVER	L	WI
MISSISSIPPI LOCK & DAM #19	MISSISSIPPI RIVER	L	IA
MISSISSIPPI RIVER LOCK #11	MISSISSIPPI RIVER	L	IA
MISSISSIPPI RIVER LOCK #12	MISSISSIPPI RIVER	L	IA
MISSISSIPPI RIVER LOCK #13	MISSISSIPPI RIVER	L	IA
MISSISSIPPI RIVER LOCK #16	MISSISSIPPI RIVER	L	IA
MISSISSIPPI RIVER LOCK #17	MISSISSIPPI RIVER	L	IA
MISSISSIPPI RIVER LOCK #18	MISSISSIPPI RIVER	L	IA
MISSISSIPPI RIVER LOCK & DAM #20	MISSISSIPPI RIVER	L	MO
MISSISSIPPI RIVER LOCK & DAM #21	MISSISSIPPI RIVER	L	MO

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

North Central (NCD)

Project	River	Type[1]	State
MISSISSIPPI RIVER LOCKS #14	MISSISSIPPI RIVER	L	IA
MISSISSIPPI RIVER LOCKS #15	MISSISSIPPI RIVER	L	IA
MT. MORRIS DAM	GENESEE RIVER	R	NY
ORWELL RESERVOIR AND DAM	OTTER TAIL RIVER	R	MN
PEORIA LOCK AND DAM	ILLINOIS RIVER	L	IL
PINE RIVER DAM	PINE RIVER	R	MN
POKEGAMA LAKE DAM	MISSISSIPPI RIVER	R	MN
RAPIDE CROCHE LOCK AND DAM	FOX RIVER	L	WI
RED LAKE RIVER	RED LAKE RIVER	R	MN
RED ROCK DAM	DES MOINES RIVER	R	IA
RESERVATION HIGHWAY	BOIS DE SIOUX	R	MN
SANDY LAKE DAM AND LOCK	SANDY RIVER	L	MN
SAYLORVILLE LAKE	DES MOINES RIVER	R	IA
ST. ANTHONY FALLS LOWER LOCK & DAM	MISSISSIPPI RIVER	L	MN
ST. ANTHONY FALLS UPPER LOCK & DAM	MISSISSIPPI RIVER	L	MN
STARVED ROCK LOCK AND DAM	ILLINOIS RIVER	L	IL
THOMAS J. O'BRIEN CONTROLLING WORKS	CALUMET RIVER	R	IL
UPPER APPLETON LOCKS AND DAM	FOX RIVER	L	WI
WHITE ROCK DAM	BOIS DE SIOUX	R	MN
WINNIBIGOSHISH DAM	MISSISSIPPI RIVER	R	MN

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

Lower Mississippi River Valley (LMV)

Project	River	Type[1]	State
ARKABUTLA DAM	COLDWATER RIVER	R	MS
BAYOU BODCAU DAM	BAYOU BODCAU	R	LA
BLAKELY MOUNTAIN DAM-LAKE OUACHITA	OUACHITA RIVER	R	AR
CADDO LAKE	CYPRESS BAYOU	R	LA
CALION (H.K. THATCHER) LOCK AND DAM	OUACHITA RIVER	L	AR
CARLYLE LAKE	KASKASKIA RIVER	R	IL
CLARENCE CANNON DAM AND MARK TWAIN LAKE	SALT RIVER	R	MO
COLUMBIA LOCK AND DAM	OUACHITA RIVER	L	LA
DEGRAY LAKE	CADDO RIVER	R	AR
DEGRAY REREGULATING DAM	CADDO RIVER	R	AR
ENID LAKE	YOCONA RIVER	R	MS
FELSENTHAL LOCK AND DAM	OUACHITA RIVER	L	AR
GRENADA LAKE	YALOBUSHA RIVER	R	MS
JOHN OVERTON LOCK AND DAM (RED RIVER W.W. 2)	RED RIVER	L	LA
JONESVILLE LOCK AND DAM	BLACK RIVER	L	LA
KASKASKIA LOCK AND DAM	KASKASKIA RIVER	L	IL
LAKE SHELBYVILLE	KASKASKIA RIVER	R	IL
MISS. R. BET. MISSOURI R. & MINEAPOLIS (POOL 26, H.T. RAINEY DAM	MISSISSIPPI RIVER	L	IL
MISS. RIV. BETWEEN MISSOURI RIVER AND MINEAPOLIS (POOL 24)	MISSISSIPPI RIVER	L	MO
MISS. RIV. BETWEEN MISSOURI RIVER AND MINEAPOLIS (POOL 25)	MISSISSIPPI RIVER	L	MO
NARROWS DAM-LAKE GREESON	LITTLE MISSOURI RIVER	R	AR
RE-REGULATION DAM (CLARENCE CANNON)	SALT RIVER	R	MO
RED RIVER W.W. LOCK AND DAM NO. 1	RED RIVER	L	LA
REND LAKE	BIG MUDDY RIVER	R	IL
SARDIS DAM	LITTLE TALLAHATCHIE RIVER	R	MS
WALLACE LAKE	CYPRESS BAYOU	R	LA
WAPPAPELLO LAKE	ST FRANCIS RIVER	R	MO

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

Southwestern (SWD)

Project	River	Type[1]	State
ABIQUIU DAM	RIO CHAMA RIVER	R	NM
ADDICKS DAM	SOUTH MAYDE CREEK	R	TX
AQUILLA LAKE	AQUILLA CREEK	R	TX
ARCADIA LAKE	DEEP FORK RIVER	R	OK
BARDWELL LAKE	WAXAHACHIE CREEK	R	TX
BARKER DAM	BUFFALO BAYOU	R	TX
BEAVER LAKE	WHITE RIVER	R	AR
BELTON LAKE	LEON RIVER	R	TX
BENBROOK LAKE	CLEAR FORK OF TRINITY RIVER	R	TX
BIRCH LAKE	BIRCH CREEK	R	OK
BLUE MOUNTAIN LAKE	PETIT JEAN RIVER	R	AR
BROKEN BOW	MOUNTAIN FORK RIVER	R	OK
BULL SHOALS LAKE	WHITE RIVER	R	AR
CANTON LAKE	NORTH CANADIAN RIVER	R	OK
CANYON LAKE	GUADALUPE RIVER	R	TX
CHOUTEAU LOCK AND DAM 17	VERDIGRIS RIVER	L	OK
CLEARWATER LAKE	BLACK RIVER	R	MO
COCHITI LAKE	RIO GRANDE + SANTA FE RIVER	R	NM
CONCHAS LAKE	CANADIAN RIVER	R	NM
COPAN LAKE	LITTLE CANEY	R	OK
COUNCIL GROVE LAKE	NEOSHO RIVER	R	KS
DAM NO 2 ARKANSAS RIVER	ARKANSAS RIVER	R	AR
DARDANELLE LOCK AND DAM	ARKANSAS RIVER	L	AR
DAVID D. TERRY LOCK AND DAM (POOL 6)	ARKANSAS RIVER	L	AR
DENISON DAM-LAKE TEXOMA	RED RIVER	R	OK
DEQUEEN LAKE	ROLLING FORK RIVER	R	AR
DIERKS LAKE	SALINE RIVER	R	AR
EL DORADO LAKE	WALNUT RIVER	R	KS
ELK CITY LAKE	ELK CITY RIVER	R	KS
EUFAULA LAKE	CANADIAN RIVER	R	OK
FALL RIVER LAKE	FALL RIVER	R	KS
FERRELLS BRIDGE DAM, LAKE O' THE PINES	CYPRESS CREEK	R	TX
FORT GIBSON LAKE	GRAND RIVER	R	OK
FORT SUPPLY LAKE	WOLF CREEK	R	OK
GALISTEO DAM	GALISTEO CREEK	R	NM
GILLHAM LAKE	COSSATOT RIVER	R	AR
GRANGER DAM AND LAKE	SAN GABRIEL RIVER	R	TX
GRAPEVINE LAKE	DENTON CREEK	R	TX
GREAT SALT PLAINS LAKE	SALT FORK OF ARKANSAS RIVER	R	OK
GREERS FERRY LAKE	LITTLE RED RIVER	R	AR
HEYBURN-POLECAT CREEK LAKE	POLECAT CREEK	R	OK
HORDS CREEK LAKE	HORDS CREEK	R	TX
HUGO LAKE	KIAMICHI RIVER	R	OK
HULAH LAKE	CANEY RIVER	R	OK

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

Southwestern (SWD)

Project	River	Type[1]	State
JEMEZ CANYON DAM	JEMEZ RIVER	R	NM
JOE POOL LAKE	MOUNTAIN CREEK	R	TX
JOHN MARTIN RESERVOIR	ARKANSAS RIVER	R	CO
JOHN REDMOND DAM AND RESERVOIR	GRAND NEOSHO RIVER	R	KS
KAW LAKE	ARKANSAS RIVER	R	OK
KEYSTONE LAKE	ARKANSAS RIVER	R	OK
LAVON LAKE	EAST FORK OF TRINITY RIVER	R	TX
LEWISVILLE DAM	ELM FORK OF TRINITY RIVER	R	TX
LOCK AND DAM NO 13	ARKANSAS RIVER	L	AR
LOCK AND DAM NO 3	ARKANSAS RIVER	L	AR
LOCK AND DAM NO 4	ARKANSAS RIVER	L	AR
LOCK AND DAM NO 5	ARKANSAS RIVER	L	AR
LOCK AND DAM NO 9	ARKANSAS RIVER	L	AR
MARION LAKE	COTTONWOOD RIVER	R	KS
MILLWOOD DAM LAKE	LITTLE RIVER	R	AR
MURRAY LOCK AND DAM (POOL 7)	ARKANSAS RIVER	L	AR
NAVARRO MILLS LAKE	RICHLAND CREEK	R	TX
NEWT GRAHAM LOCK AND DAM 18	VERDIGRIS RIVER	L	OK
NIMROD LAKE	FOURCHE LA FAVE RIVEF	R	AR
NORFORK LAKE	NORTH FORK OF THE WHITE RIVER	R	AR
NORRELL LOCK AND DAM (NO 1)	ARKANSAS RIVER	L	AR
NORTH SAN GABRIEL DAM AND LAKE GEORGETOWN	NORTH FORK SAN GABRIEL RIVER	R	TX
O.C. FISHER DAM AND LAKE	CONCHO RIVER	R	TX
OOLOGAH LAKE	VERDIGRIS RIVER	R	OK
OPTIMA LAKE	NORTH CANADIAN RIVER	R	OK
OZARK LOCK AND DAM	ARKANSAS RIVER	L	AR
PAT MAYSE LAKE	SANDERS CREEK	R	TX
PERSON SKUBITZ-BIG HILL LAKE	BIG HILL CREEK	R	KS
PINE CREEK LAKE	LITTLE RIVER	R	OK
PROCTOR LAKE	LEON RIVER	R	TX
ROBERT S. KERR LOCK AND DAM 15	ARKANSAS RIVER	L	OK
SAM RAYBURN DAM AND RESERVOIR	ANGELINA RIVER	R	TX
SANTA ROSA DAM AND LAKE	PECOS RIVER	R	NM
SARDIS LAKE	JACKFORK CREEK	R	OK
SKIATOOK LAKE	HOMINY CREEK	R	OK
SOMERVILLE LAKE	YEGUA CREEK	R	TX
STILLHOUSE HOLLOW DAM	LAMPASAS RIVER	R	TX
TABLE ROCK LAKE	WHITE RIVER	R	MO
TENKILLER FERRY LAKE	ILLINOIS RIVER	R	OK
TOAD SUCK FERRY LOCK AND DAM (POOL 8)	ARKANSAS RIVER	L	AR
TORONTO LAKE	VERDIGRIS RIVER	R	KS
TOWN BLUFF DAM-B.A. STEINHAGEN LAKE	NECHES RIVER	R	TX
TRINIDAD LAKE	PURGATOIRE RIVER	R	CO
TWO RIVERS DAM (DIAMOND A & ROCKY)	RIO HONDO	R	NM

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

Southwestern (SWD)

Project	River	Type[1]	State
W.D. MAYO LOCK AND DAM 14	ARKANSAS RIVER	L	OK
WACO LAKE	BOSQUE RIVER	R	TX
WAURIKA LAKE	BEAVER CREEK	R	OK
WEBBERS FALLS LOCK AND DAM 16	ARKANSAS RIVER	L	OK
WHITNEY LAKE	BRAZOS RIVER	R	TX
WISTER LAKE	POTEAU RIVER	R	OK
WRIGHT PATMAN DAM AND LAKE	SULPHUR RIVER	R	TX

[1]R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

Missouri River (MRD)

Project	River	Type[1]	State
BEAR CREEK LAKE	BEAR CREEK	R	CO
BIG BEND DAM-SHARPE LAKE	MISSOURI RIVER	R	SD
BLUE SPRINGS LAKE	EAST FORK LITTLE BLUE RIVER	R	MO
BLUESTEM DAM-SITE 4	OLIVE BRANCH SALT CREEK	R	NE
BOWMAN-HALEY LAKE	NORTH FORK GRAND RIVER	R	ND
BRANCHED OAK DAM-SITE 18	OAK CREEK	R	NE
BULLHOOK DAM	BULLHOOK CREEK	R	MT
CHATFIELD LAKE	SOUTH PLATTE RIVER	R	CO
CHERRY CREEK LAKE	CHERRY CREEK	R	CO
CLINTON LAKE	WAKARUSA RIVER	R	KS
COLDBROOK DAM	COLD BROOK CREEK	R	SD
CONESTOGA DAM-SITE 12	HOLMES CREEK	R	NE
COTTONWOOD SPRINGS LAKE	COTTONWOOD SPRINGS CREEK	R	SD
FORT PECK LAKE	MISSOURI RIVER	R	MT
FORT RANDALL DAM-LAKE FRANCIS CASE	MISSOURI RIVER	R	SD
GARRISON DAM-LAKE SAKAKAWEA	MISSOURI RIVER	R	ND
GAVINS POINT DAM-LOUIS AND CLARK LAKE	MISSOURI RIVER	R	SD
HARLAN COUNTY LAKE	REPUBLICAN RIVER	R	NE
HARRY S. TRUMAN DAM AND RESERVOIR	OSAGE RIVER	R	MO
HILLSDALE LAKE	BIG BULL CREEK	R	KS
HOLMES LAKE-SITE 17	ANTELOPE CREEK	R	NE
KANOPOLIS LAKE	SMOKY HILL RIVER	R	KS
LONG BRANCH LAKE	EAST FORK LITTLE CHARITON R.	R	MO
LONGVIEW LAKE	LITTLE BLUE RIVER	R	MO
MELVERN LAKE	MARAIS DES CYGNES (OSAGE) R.	R	KS
MILFORD LAKE	REPUBLICAN RIVER	R	KS
OAHE DAM-LAKE OAHE	MISSOURI RIVER	R	SD
OLIVE CREEK DAM-SITE 2	OLIVE CREEK	R	NE
PAPILLION CREEK & TRIB. SITE 16-STANDING BEAR LAKE	TRIB-PAPILLION CREEK	R	NE
PAPILLION CREEK AND TRIB. SITE 20	TRIB-PAPILLION CREEK	R	NE
PAPILLION CREEK SITE 11-GLENN CUNNINGHAM LAKE	TRIB-PAPILLION CREEK	R	NE
PAPIO DAM SITE #18 & LAKE	BOXELDER CR/PAPIO CR	R	NE
PAWNEE DAM-SITE 14	NORTH BRANCH MIDDLE CREEK	R	NE
PERRY LAKE	DELAWARE RIVER	R	KS
PIPESTEM LAKE	PIPESTEM CREEK	R	ND
POMME DE TERRE LAKE	POMME DE TERRE RIVER	R	MO
POMONA LAKE	HUNDRED TEN MILE CREEK	R	KS
RATHBUN LAKE	CHARITON RIVER	R	IA
SMITHVILLE LAKE	LITTLE PLATTE RIVER	R	MO
SPRING GULCH	SPRING GULCH	R	CO
STAGECOACH DAM-SITE 9	HICKMAN BRANCH SALT CREEK	R	NE
STOCKTON LAKE	SAC RIVER	R	MO
TUTTLE CREEK LAKE	BIG BLUE RIVER	R	KS
TWIN LAKES DAM-SITE 13	SOUTH BRANCH MIDDLE CREEK	R	NE

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

Missouri River (MRD)

Project	River	Type[1]	State
WAGON TRAIN DAM-SITE 8	HICKMAN BRANCH SALT CREEK	R	NE
WESTERLY CREEK COLORADO-AURORA	WESTERLY CREEK	R	CO
WILSON LAKE	SALINE RIVER	R	KS
YANKEE HILL DAM-SITE 10	CARDWELL BRANCH SALT CHEEK	R	NE

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

North Pacific (NPD)

Project	River	Type[1]	State
ALBENI FALLS DAM	PEND OREILLE RIVER	R	ID
APPLEGATE LAKE	APPLEGATE RIVER	R	OR
BIG CLIFF DAM	NORTH SANTIAM RIVER	R	OR
BLUE RIVER LAKE	BLUE RIVER	R	OR
BONNEVILLE LOCK AND DAM	COLUMBIA RIVER	L	OR
CHIEF JOSEPH DAM	COLUMBIA RIVER	R	WA
COTTAGE GROVE LAKE	COAST FORK WILLAMETTE RIVER	R	OR
COUGAR LAKE	SOUTH FORK MCKENZIE RIVER	R	OR
DETROIT LAKE	NORTH SANTIAM RIVER	R	OR
DEXTER REREGULATION DAM	MIDDLE FORK WILLAMETTE RIVER	R	OR
DORENA LAKE	ROW RIVER	R	OR
DWORSHAK DAM AND RESERVOIR	NORTH FORK CLEARWATER RIVER	R	ID
FALL CREEK LAKE	FALL CREEK	R	OR
FERN RIDGE LAKE	LONG TOM RIVER	R	OR
FOSTER DAM	SOUTH SANTIAM RIVER	R	OR
GREEN PETER LAKE	MIDDLE SANTIAM RIVER	R	OR
HILLS CREEK LAKE	MIDDLE FORK WILLAMETTE RIVER	R	OR
HOWARD A. HANSON DAM	GREEN RIVER	R	WA
ICE HARBOR LOCK AND DAM	SNAKE RIVER	L	WA
JOHN DAY LOCK AND DAM	COLUMBIA RIVER	L	OR
LIBBY DAM-LAKE KOOCANUSA	KOOTENAI RIVER	R	MT
LITTLE GOOSE LOCK AND DAM	SNAKE RIVER	L	WA
LOOKOUT POINT LAKE	MIDDLE FORK-WILLAMETTE RIVER	R	OR
LOST CREEK LAKE	ROGUE RIVER	R	OR
LOWER GRANITE LOCK AND DAM	SNAKE RIVER	L	WA
LOWER MONUMENTAL LOCK AND DAM	SNAKE RIVER	L	WA
LUCKY PEAK LAKE	BOISE RIVER	R	ID
MCNARY LOCK AND DAM	COLUMBIA RIVER	L	OR
MILL CREEK LAKE (OFF-STREAM STORAGE)	MILL CREEK OFFSTREAM	R	WA
MUD MOUNTAIN DAM	WHITE RIVER	R	WA
THE DALLES LOCK AND DAM	COLUMBIA RIVER	L	OR
WILLOW CREEK LAKE	WILLOW CREEK	R	OR
WYNOOCHEE LAKE	WYNOOCHEE RIVER	R	WA

[1] R = Reservoir, L = Lock and Dam

APPENDIX 2 (continued)

South Pacific (SPD)

Project	River	Type[1]	State
ALAMO LAKE	BILL WILLIAMS RIVER	R	AZ
BEAR DAM	BEAR CREEK	R	CA
BLACK BUTTE LAKE	STONEY CREEK	R	CA
BREA DAM	BREA CREEK	R	CA
BUCHANAN DAM-H.V. EASTMAN LAKE	CHOWCHILLA RIVER	R	CA
BURNS DAM	BURNS CREEK	R	CA
CARBON CANYON DAM	CARBON CANYON CREEK	R	CA
COYOTE VALLEY DAM-LAKE MENDOCINO	RUSSIAN RIVER	R	CA
DRY CREEK (WARM SPRINGS) LAKE AND CHANNEL	DRY CREEK	R	CA
FARMINGTON DAM	ROCK AND LITTLEJOHN CREEKS	R	CA
FULLERTON DAM	EAST FULLERTON CREEK	R	CA
HANSEN DAM	TUJUNGA WASH	R	CA
HIDDEN DAM-HENSLEY LAKE	FRESNO RIVER	R	CA
ISABELLA LAKE	KERN RIVER	R	CA
LOPEZ DAM	PACOIMA WASH	R	CA
MARIPOSA DAM	MARIPOSA CREEK	R	CA
MARTIS CREEK LAKE	MARTIS CREEK	R	CA
MATHEWS CANYON DAM	MATHEWS CANYON	R	NV
MOJAVE RIVER RESERVOIR	WEST FORK MOJAVE RIVER	R	CA
NEW HOGAN LAKE	CALAVERAS RIVER	R	CA
OWENS DAM	OWENS CREEK	R	CA
PAINTED ROCK DAM	GILA RIVER	R	AZ
PINE CANYON DAM	PINE CANYON	R	NV
PINE FLAT LAKE	KINGS RIVER	R	CA
PRADO DAM	SANTA ANA RIVER	R	CA
SAN ANTONIO DAM	SAN ANTONIO CREEK	R	CA
SANTA FE DAM	SAN GABRIEL RIVER	R	CA
SEPULVEDA DAM	LOS ANGELES RIVER	R	CA
SUCCESS LAKE	TULE RIVER	R	CA
TERMINUS DAM (LAKE KAWEAH)	KAWEAH RIVER	R	CA
WHITLOW RANCH DAM	QUEEN CREEK	R	AZ
WHITTIER NARROWS DAM (RIO HONDO)	SAN GABRIEL RIVER	R	CA

[1] R = Reservoir, L = Lock and Dam

APPENDIX 3

Palmer Drought Severity Index (PDSI)

The Palmer Drought Severity Index (PDSI), or an operational version of it, is a widely used indicator of drought. It is published in the "Weekly Weather and Crop Bulletin" prepared jointly by the National Oceanic and Atmospheric Administration (NOAA) and U. S. Department of Agriculture (USDA); it is used in the "Weekly Climate Bulletin" of the NOAA, Climate Analysis Center; it is included in the monthly "National Water Conditions" report of the U. S. Geological Survey; and is cited in monthly water control reports of Corps of Engineers' district offices.

The National Climatic Data Center computes the PDSI for 344 climate divisions in the contiguous United States (National Climatic Data Center, 1982). These divisions are shown in Figure 1. Each division is identified by a four digit numeric code and regional name. The first two digits are a state code (Table A3-1) and the last two are subdivisions within a state numbered from zero to a maximum to ten. Climatological divisions were used in early Climatological Service Bulletins about the turn of the century; however, they were not in general use until the beginning of the *Climatological Data* publication in January 1914. At that time, divisions were used in 29 states. By January 1930, divisions were in 31 states, and by January 1947 in 35 states. From 1948 to 1955, a number of climatological divisions were changed, primarily to bring them into agreement with crop reporting districts used by the U. S. Department of Agriculture. Beginning in 1948, the divisions were used only in presenting selected data. In 1956 and 1957, all division boundaries were reviewed and necessary changes were made to conform with climate-influencing physical features (topography, moisture sources, etc.) and, where practicable, with crop reporting district boundaries used by the Department of Agriculture.

Originally published by Palmer (1965), the index has had considerable evaluation and application in the fields of climatology and meteorology. Karl (1983) and Alley (1984) discuss the assumptions and limitations inherent in the index and its use. Karl (1986 a,b) examines the sensitivity of the index to soil moisture, temperature, potential evapotranspiration and other calibration coefficients. Numerous studies of regional climate have been conducted using the PDSI as the principal indicator of drought. Karl, Quinland and Ezell (1987) studied the climatological probability of ameliorating or terminating drought in different regions of the country. Klugman (1978) examines patterns of drought for several periods between 1931-1969 in the upper Midwest. Karl and Quayle (1981) assess the historical significance of the dry summer of 1980 which occurred in many regions of the country. Eder, Davis and Monahan (1987) examine the spatial and temporal variability of drought in the southeast. And Karl and Koscielny (1982) and Diaz (1983) use the PDSI to analyze droughts in the contiguous United States from 1895-1981.

Research and application of the PDSI in water resources planning and management is less extensive. Bowles et al (1980) examine the use of the PDSI for a water supply system and find that its best application occurs for streamflow-supplied systems. Draper et al (1981) assess the use of PDSI to define and forecast hydrological drought and conclude that it is less accurate than hydrologic forecasting methods. Dezman et al (1982) develop a surface water supply index to be used in conjunction with the Palmer Index. The surface supply index is used for areas dependent on surface water supplies originating as snowmelt in the mountains and the Palmer Index for dry land areas. The use of drought triggering mechanisms by several states and river basin commissions, including the PDSI, is examined by Hrezo et al (1986). Whittemore et al (1989) correlate recharge and groundwater quality variation for aquifers in Kansas using the PDSI.

Development of the equations and coefficients used to compute the PDSI is documented by Palmer (1965). Alley (1984) reviews this development in detail as part of his critique of the assumptions and limitations of the index. Karl and Knight (1985) also review the equations and parameters as a preface to their monthly computation of the Palmer index for the United States for the period 1895-1983. The principal equations used to compute the PDSI are briefly discussed below to provide a basic understanding of the physical basis for the index and as a preface to a discussion of its use in this study.

The monthly PDSI is a meteorological index that reflects estimates of departure of moisture from normal. Normal moisture conditions are derived from period of record data including monthly averages of evapotranspiration, soil water recharge, runoff and water loss from the soil. The index is standardized so that it has a consistent meaning in different climate areas and from month to month. A classification system translates the numerical value of the index to a descriptive measure of drought or wetness.

<u>Moisture departure from normal.</u> The difference, d, between actual precipitation for a month and the precipitation computed from a water balance of an element of soil is given by,

$$d = P - \hat{P} \qquad (1)$$

where,

d = moisture departure from normal
P = actual precipitation
$\hat{P}$ = CAFEC precipitation

Palmer (1965) defines $\hat{P}$ as the precipitation Climatically Appropriate for Existing Conditions (CAFEC), that is, the climatically normal precipitation for the month. It is computed from a water balance of the soil where $\hat{E}T$ is the evapotranspiration, $\hat{R}O$ the runoff, $\hat{R}$ the soil water recharge, and $\hat{L}$ the water loss from the soil,

$$\hat{P} = \hat{E}T + \hat{R}O + (\hat{R} - \hat{L}) \qquad (2)$$

The CAFEC precipitation, $\hat{P}$, and the water from the soil, $\hat{L}$, are the moisture supply. The moisture demand is the evapotranspiration, runoff and soil recharge. The parameter $(\hat{R} - \hat{L})$ represents the change in soil moisture storage. Each parameter is computed using data for the climate area and coefficients of monthly averages over the period of record.

Standardized index. The monthly moisture departures from normal are weighted to create a standardized index applicable to different climate areas. The moisture departure for each month is weighted by a parameter K giving what is called a moisture anomaly index, Z.

$$Z = d\,K \qquad (3)$$

The weighting factor, K, is derived empirically from the climate record for the climate area and month using the ratio of moisture demand and moisture supply and the monthly mean of the absolute values of d for all years of record. K adjusts the moisture departures from normal to create a standardized measure for different climate divisions and months.

The Palmer Drought Severity Index (PDSI) is computed using the moisture anomaly index and the previous month's PDSI.

$$PDSI_i = .897\,PDSI_{i-1} + Z_i/3 \qquad (4)$$

During the initial month the first term drops out and the index equals Z/3. When Z is zero, (normal moisture conditions, d = 0), the PDSI is .897 of the previous month.

Classification system. Palmer (1965) used drought data from central Iowa and western Kansas to plot a graph of accumulated moisture anomaly index Z versus length of dry period. The dry periods were defined as extreme drought and a numerical value of -4.0 was assigned. The region on the graph between extreme drought and near normal conditions was subdivided into three additional drought categories: severe (PDSI = -3.0), moderate (PDSI = -2.0) and mild (PDSI = -1.0). The current classification system is shown in Table A3-2.

TABLE A3-1
Climate Division State Code

01 Alabama
02 Arizona
03 Arkansas
04 California
05 Colorado
06 Connecticut
07 Delaware
08 Florida
09 Georgia
10 Idaho
11 Illinois
12 Indiana
13 Iowa
14 Kansas
15 Kentucky
16 Louisiana
17 Maine
18 Maryland
19 Massachusetts
20 Michigan
21 Minnesota
22 Mississippi
23 Missouri
24 Montana
25 Nebraska
26 Nevada
27 New Hampshire
28 New Jersey
29 New Mexico
30 New York
31 North Carolina
32 North Dakota
33 Ohio
34 Oklahoma
35 Oregon
36 Pennsylvania
37 Rhode Island
38 South Carolina
39 South Dakota
40 Tennessee
41 Texas
42 Utah
43 Vermont
44 Virginia
45 Washington
46 West Virginia
47 Wisconsin
48 Wyoming
49 Not Used
50 Alaska
51 Hawaii
66 Puerto Rico
67 Virgin Islands
91 Pacific Islands

TABLE A3-2

Classification of PDSI Wet and Dry Periods
(after Karl and Knight, 1985)

PDSI	Class
> 4.00	Extreme wetness
3.00 to 4.00	Severe wetness
1.50 to 3.00	Mild to moderate wetness
1.50 to -1.50	Near normal
-1.50 to -3.00	Mild to moderate drought
-3.00 to -4.00	Severe drought
<-4.00	Extreme drought

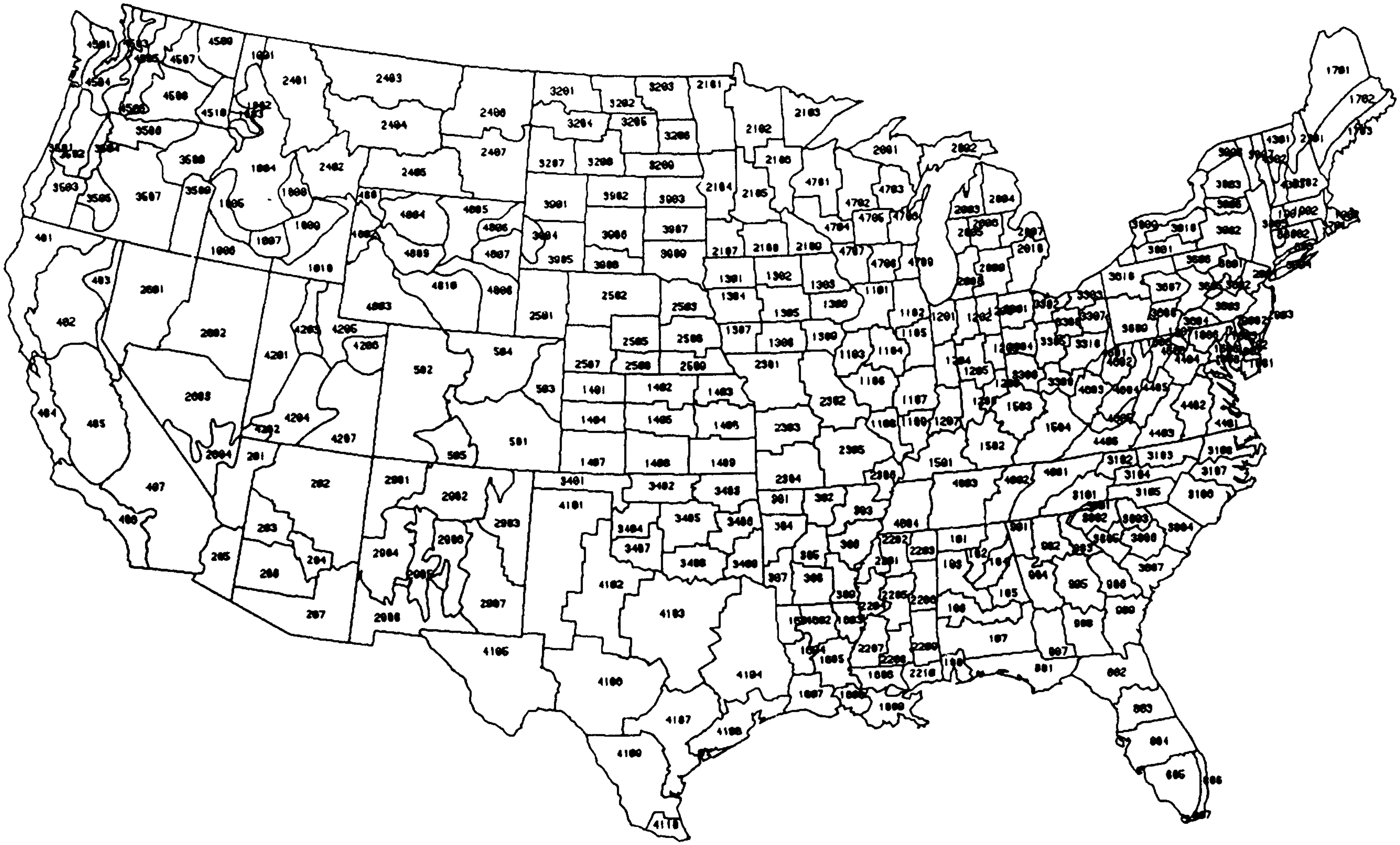

Figure A3-1. Climate Divisions. NOAA/USDA Joint Agricultural Weather Facility.

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