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STATE SUPPLY SIDE WATER MODEL

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THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

STATE SUPPLY SIDE WATER MODEL

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF PHILOSOPHY

By

HASSAN BADKOOBEHI

Norman, Oklahoma

1982

STATE SUPPLY SIDE WATER MODEL

A DISSERTATION

APPROVED FOR THE DEPARTMENT OF

CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE

By

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STATE SUPPLY SIDE WATER MODEL

BY: HASSAN BADKOOBEHI

MAJOR PROFESSOR: GEORGE W. REID, REGENT PROFESSOR

Oklahoma is presently experiencing population growth as well as industrial and agricultural expansion. This state is fortunate to have potentially sufficient water resources (not excess) within its boundaries to supply all of its anticipated needs. The problems one of management, because most of the state's water resources are located in Eastern Oklahoma, while Western Oklahoma suffers from a lack of water sources. Central Oklahoma is the median of the two areas, experiencing periods of both drought and abudance. There has been extensive water resource development in the state, but the need for blending this work into a totally coordinated statewide effort is apparent if optimum benefits are to be realized from the state's resources. Thus a generalized plan is needed to evaluate the safe yield from ground water and through storage from surface water in Oklahoma.

This study will employ the appropriate existing technologies, in a unique form to achieve a safe yield. Furthermore, it will determine and well fields should be, and approximately how much the project would

where the surface and ground water is available, how large the reservoirs and well fields should be, and approximately how much the project would cost. The investigation will consist of a case study of one of the river basins to provide detailed calculations. It is appropriate to apply the results obtained from this study to all fourteen Oklahoma River Basins to evaluate storage capacity and related costs to produce selected dependable flows.

The theoretical basis, called the supply model, assumes that the available water resource exceeds the demand, site by site. Other models would be the resources model, wherein they are equal, or demand model, wherein the demand exceeds the supply.

Utilization of this research should be a great help to administrators, public officials, engineers, and planners such as the personnel of the Oklahoma Water Resoures Board. The results obtained herein will enable them to recognize those factors that affect water uses and to plan for more feasible water resources development with a realistic basis to meet future water requirements.

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I. INTRODUCTION

The dramatic increase in Oklahoma's population and economy has placed heavy demands on Oklahoma's water resources. Future growth in this state requires that the emphasis on water resources development be enlarged from flood control and hydro-electric power development to include the beneficial use of water for municipal, industrial, energy, and agricultural supplies.

The problems that exist today threaten to worsen in decades to come as the population increases in areas already experiencing water shortage (See Appendix A). On the other hand, Oklahoma has an abundance of water within its boundaries that could meet all the state's requirements, with adequate storage facilities our future needs can be supplied, however, such water is unevenly distributed. Eastern Oklahoma boasts a wealth of stream and ground water resources, while the western area often suffers from a deficiency of water. The employment of an appropriate method could optimize the use of all potential water supplies.

A) General Approach

Water resources development has perhaps three phases: supply, resource, and demand. These phases depend to a large extent on the ratio of supply/demand. In the supply phase, this ratio is in excess of 1.00; this means that the water supply exceeds the demand. Efficiencies purely in the structural solution are sought. In the water resource phase, the water supply/demand ratio approaches 1.00; this means that supply equals the demand. Because of the decline in the resource base, the entire operational system must be considered. Measures involve both structural solutions such as a system of reservoirs, pipelines, and so on, and nonstructural solutions such as conservation technique, reuse of water, use limitation, transfer system, and so on. Finally in the water demand phase, this ratio declines below 1.00; this means that the demand exceeds the supply. Nonstructural techniques are used to solve this problem.

Because of Oklahoma's abundance of water, the potential supply/demand ratio is equal to or greater than one for the state's basins. Consequately, only the supply phase need be considered.

Data used in this study has been furnished by both federal and state agencies such as the United States Army Corps of Engineers, The Bureau of Reclamation, the United States Geological Survey, The University of Oklahoma Geological Survey, and Oklahoma Water Resources Board. These agencies are of course actively concerned with the water problem in Oklahoma.

B) Purpose

The purpose of this study is to employ the appropriate existing methods and available data to provide an evaluation of present as well as potential surface and ground water resources in Oklahoma. This research will determine where the surface and ground water is available, how large the reservoirs could be, and approximately how much the project would cost. If it is determined that surplus water currently exists or will probably exist in the foreseeable future, locations will be identified where substantial quantities of water are in excess of the state's needs, and costs will be estimated.

In short, a generalized plan is sought for evaluation of available water. This will consist of a case study of one of the river basins to provide detailed calculations.

C) Specific Goals and Objectives

The primary objective herein is to create a methodology that will provide the water resources authority a planning level estimate of available water to a specific site; briefly, one may use this methodology and resulting tables for 14 basins to determine the nearest location of potential water and related costs.

This is specifically directed at administrators, public officials, engineers, and planners in the Oklahoma Water Resources Board. It will enable them to recognize those factors that affect water uses and to plan for more feasible water resources development programs with a realistic basis to meet the future water requirements.

The technique uses available data and a supply model, independent of conflicting demands, to correlate the available water in all 14 basins by future site estimates.

II. SURFACE WATER RESOURCES AND DEVELOPMENT IN OKLAHOMA

Surface water is that which occurs in rivers, streams, lakes, swamps, and man-made reservoirs. Surface water, in the streams and lakes, is usually more accessible and plentiful than ground water. The average annual precipitation in the state is 33.39 inches and is considered adequate under normal conditions (10), but Oklahoma is plagued almost annually with a water shortage. The answer to the problem is to retain the water when it is in abundance for use during a drought or critical periods of the growing season. If only a portion of the 30,347,200 acre feet of average water passing through Oklahoma could be stored in reservoirs, appropriately located, and distributed as required, the major portion of the water problem would be solved. So enough reservoir storage must be provided for this surplus water to meet present and future needs. Farm ponds should also be basically designed as flood retention reservoirs to impound flood waters and release them gradually (10).

The federal and state governments should fully realize the water storage problem and should make giant strides in developing reservoirs in the study area and the state as well. Additional research and the expansion of ongoing investigations to develop new techniques for more efficient utilization of existing, under construction, and authorized reservoir projects, which are shown in Figure 1. The purpose of this section is to briefly describe the characteristics of major streams and major existing, under construction, and authorized reservoir projects for every River Basin in Oklahoma. For detailed and summarized information of Arkansas River and Red River and their tributaries, see Appendix B.

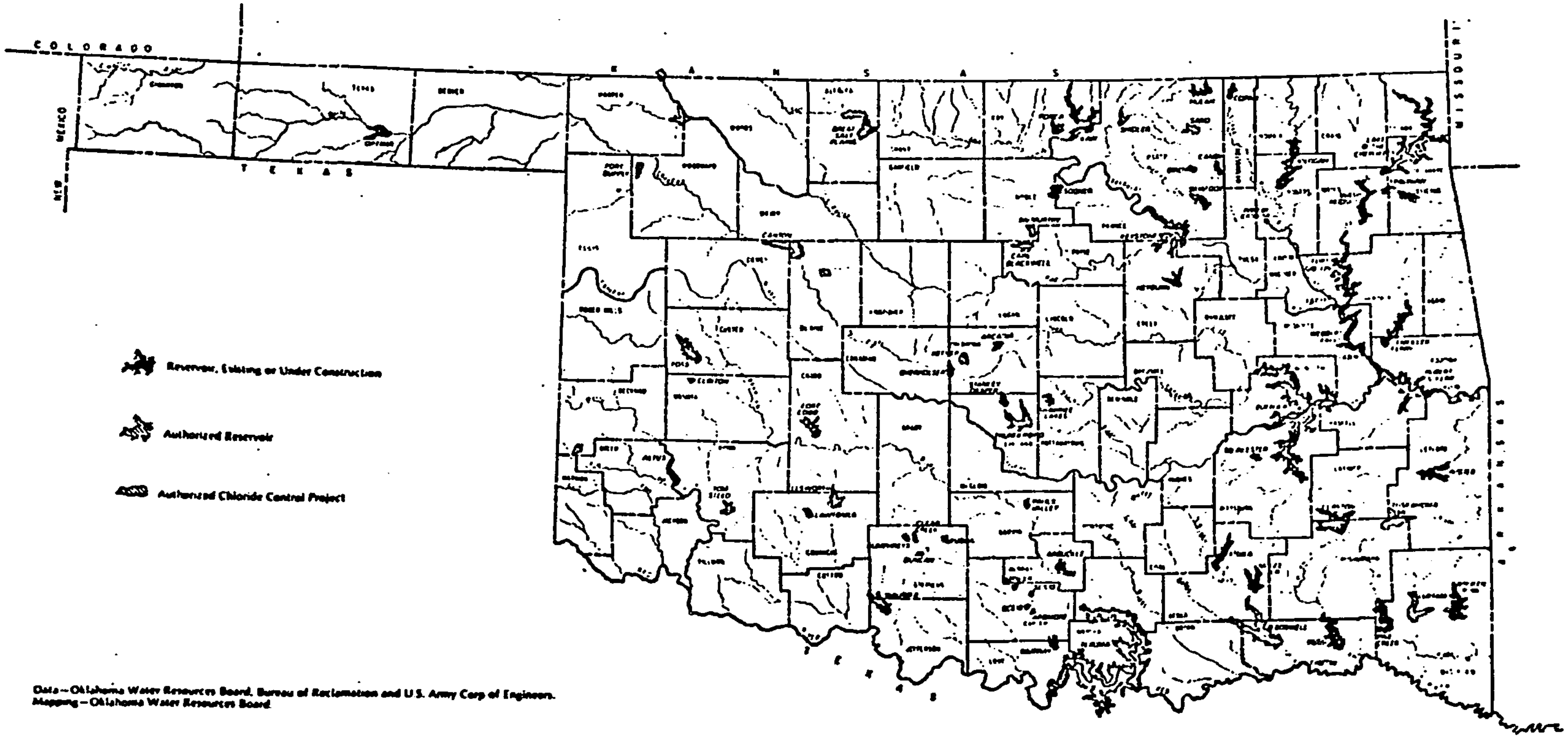

FIGURE 1   Water Resources Development

See Reference 2

A) Hydrologic Cycle in Oklahoma

The hydrologic cycle is a complex and continuous process involving the sun, oceans, river system, icecaps, winds, vegetation, soils, rocks, and man's activities. The hydrologic cycle has no beginning or end. Water is evaporated from the oceans and the land, with by far the largest amounts coming from the oceans. The evaporated water is then carried into the atmosphere, usually drifting tens of hundreds of miles before being returned to the earth as some form of precipitation. Much of this precipitated water re-evaporates or transpires and returns to the atmosphere. The remainder runs off to become streamflow or seeps into the earth to become soil moisture and ground water reservoir or aquiper. The cycle time for water movement varies from a few days to millions of years, depending upon whether the water reaches a river channel, lake, swamp, glacier, ground water, etc.

1) Geographical Characteristics

Oklahoma, with its 69,919 square miles, is a state of extremes. Geographically located between the arid West and the humid East, the long winter North and the long summer South, it is truly in the buffer zone. Topographically, parts of Oklahoma are just above the upper limit of the Mississippi river back-water area. Pine covered mountains in the southeastern section to broad plains with playa lakes in the panhandle section indicate the diversification (8).

2) Climatological Characteristics

The climate of Oklahoma is mostly continental in type; as in all of the central great plains, summers are long and hot, winters are shorter and less frigid than those of more northern plains states. Moist air currents from the Gulf of Mexico influence the weather during most of the year. Maximum precipitation occurs in the spring, decreasing through the summer months. Maximum secondary precipitation occurs in the fall. May is usually the wettest month and January the driest month (10)(11).

3) Lake Evaporation

Average annual lake evaporation varies from about 48 inches in the extreme eastern section of the state to as high as 65 inches in the southwestern corner. Evapotranspiration (loss of water into air) and percolation (seepage of water into the ground) consume an average of 80% of the annual rainfall. Figure 4 illustrates average annual lake evaporation (2)(15).

4) Temperature

Mean annual temperature over the state ranges from 64 degrees along the southern border to about 60° along the northern border. The temperature decreases westwardly across the panhandle to about 57°. A maximum of 120° F has been recorded by the weather bureau. The average annual temperature is shown in Figure 5 for period 1931-1960 (9)(15).

5) Runoff

Surface runoff represents another important part of the hydrologic cycle. As expected, runoff in Oklahoma varies considerably ranging from 2 inches in the panhandle to 20 inches in the southeast corner of the state. In the northwest region, average annual runoff is about 820,000 acre-feet per year, compared to 6,000,000 acre-feet per year in the southeast region. Average annual runoff for the entire state is about 22,000,000 acre-feet. The average annual runoff is shown in Figure 6 (9)(15).

6) Drought

Oklahoma, along with other states in the southern Great Plains, has at times been subject to droughts of varying degree and duration, although drought years have been far less frequent than dry summers and falls. Severe droughts occur in Oklahoma on a 20 to 22 year cycle. Most notable of the severe drought periods in Oklahoma were the dry years which occurred in the 1930's and were more severe for the length of time involved. The drought of the 50's ranks among the most severe of the past 400 years (12)(15).

7) Floods

Western Oklahoma is subject to long dry periods and frequent floods. The northwest and the southwest have numerous flood control structures erected by U.S. Soil Conservation Service and The Bureau of Reclamation. The U.S. Army Corps of Engineers has made a sizable contribution to main stem flood control in the north central region through reservoir storage.

In central Oklahoma most floods are caused by thunderstorms, in which waters are usually back within their banks in a few hours. Various flood and drainage problems exist along the Deep Fork Basin.

In the northeast, the Corps of Engineers has helped relieve the flood situation through reservoir storage, but this region still has some remaining flood damage. In east central Oklahoma rapid runoff from a mountainous drainage area results in floods of short duration during storms. In the southeast the Glover River leaves its usual banks frequently and causes severe flooding. The combined programs of the Soil Conservation Service and the Corps of Engineers maintain a continuous program of planning and building watershed protection and flood prevention structures throughout the entire state (12)(15).

Estimates of evaporation, precipitation, temperature, runoff, drought, flood, and other variables are of great importance to planners in accurately determining reservoir yields. Careful, in-depth analyses of such data were employed in the development of this research study.

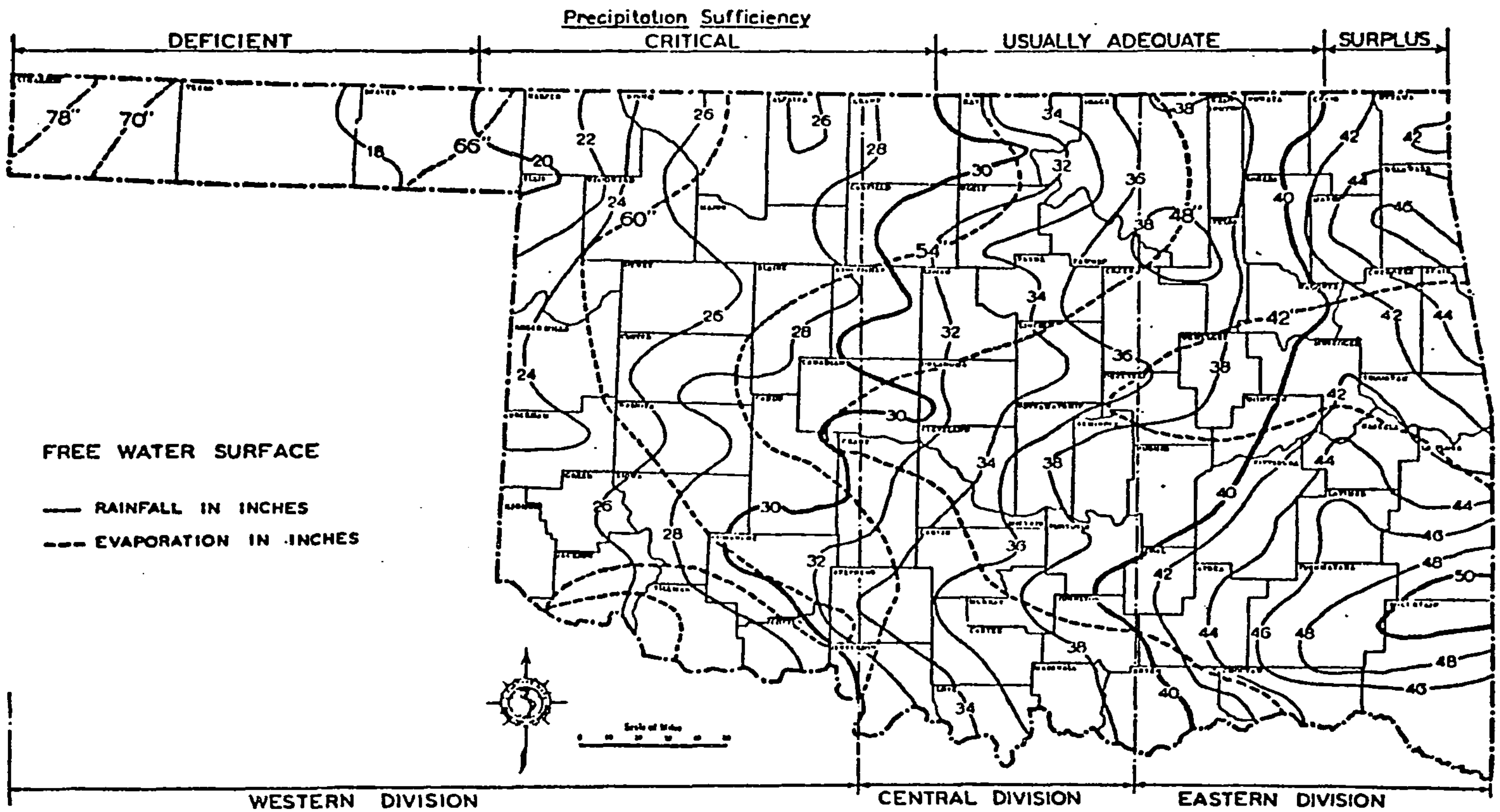

FIGURE 2 Oklahoma Mean Annual Precipitation and Evaporation Map

See Reference 11

FIGURE 3

<u>TEN YEAR MOVING AVERAGES OF ANNUAL PRECIPITATION IN STATE OF OKLAHOMA</u>

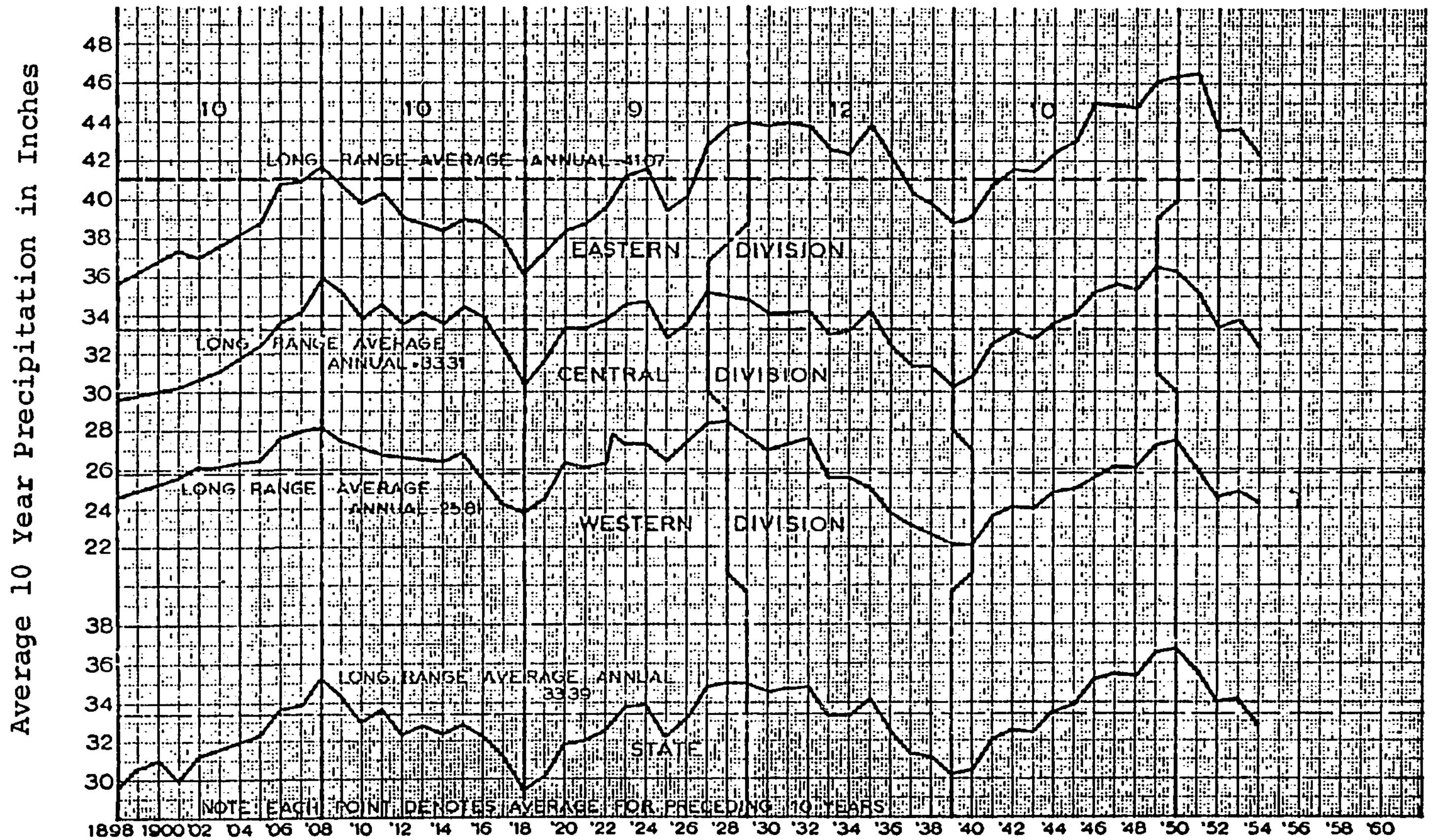

FIGURE 3 Ten Year Moving Averages of Annual Precipitation in State of Oklahoma
See Reference 11

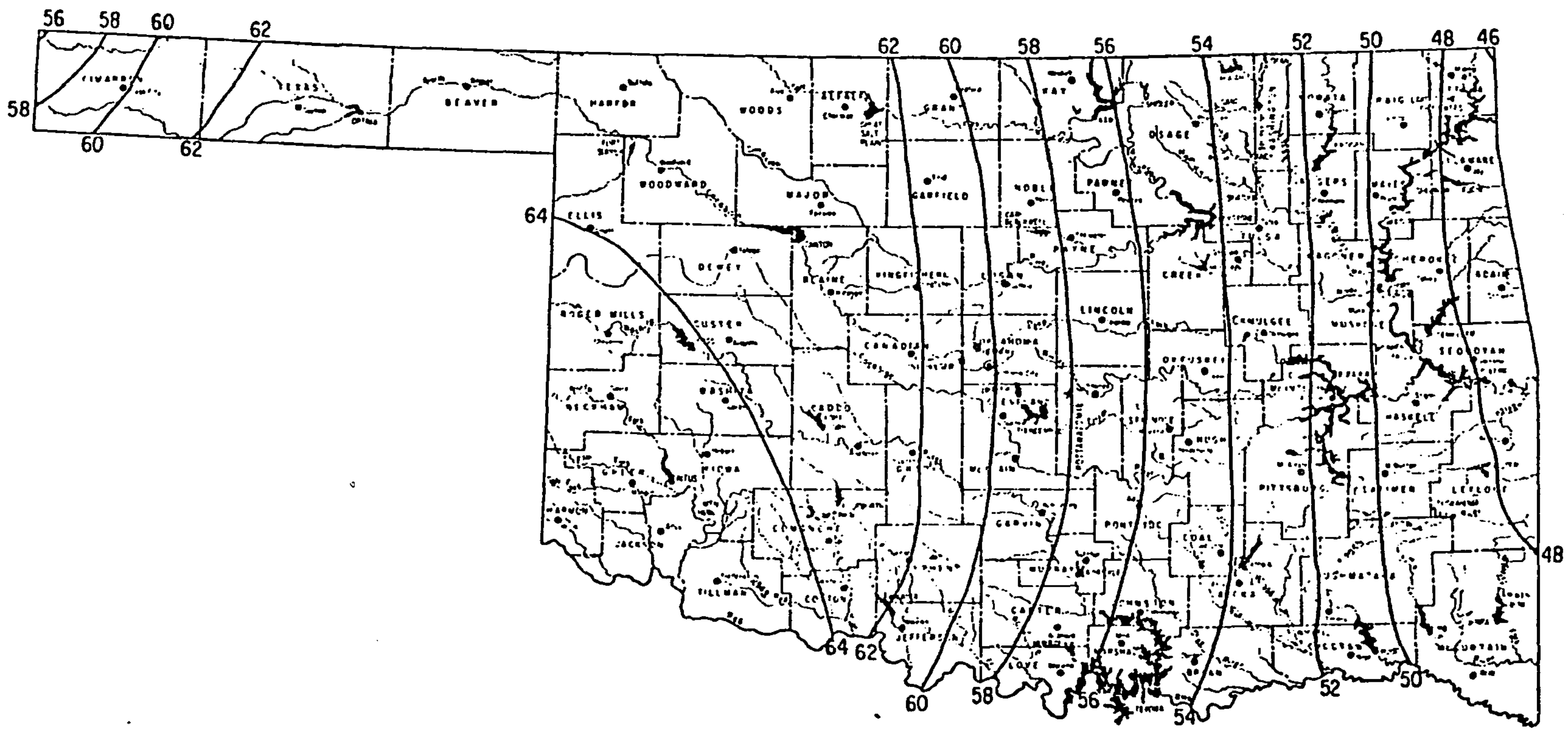

FIGURE 4 Average Annual Lake Evaporation (in inches) Period 1946-1955

See Reference 13

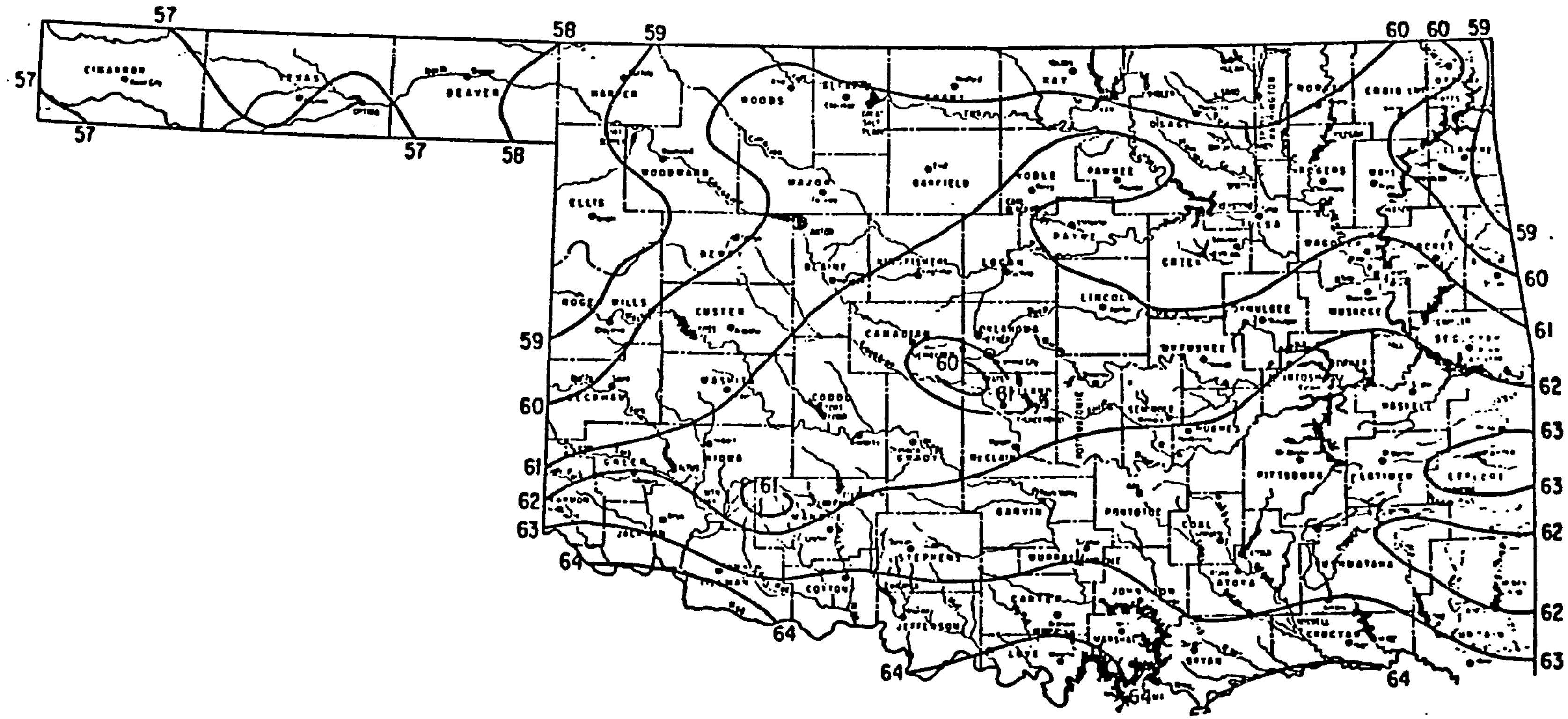

FIGURE 5 Mean Annual Temperture (in °F) Normal Period 1931-1960
See Reference 15

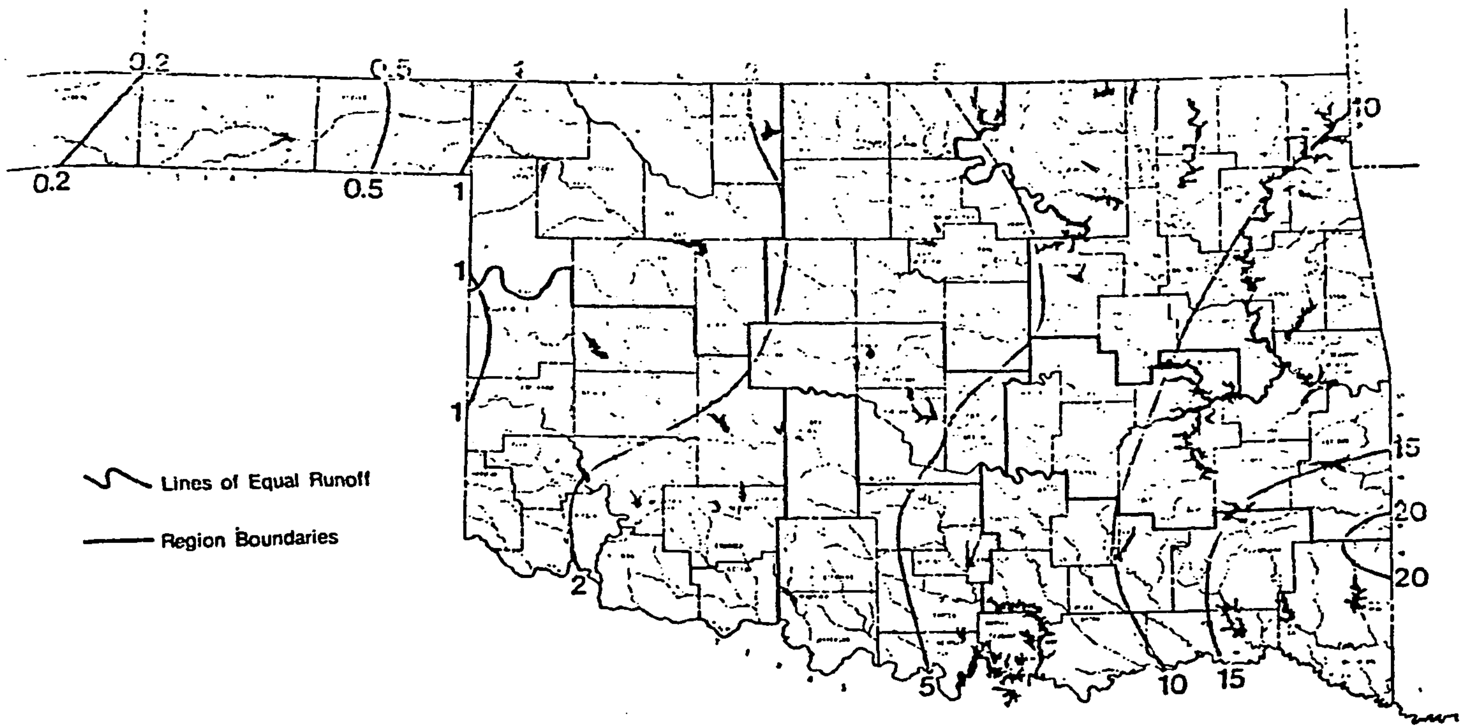

FIGURE 6 Figure Average Annual Runoff (in inches)

See Reference 15

B) Surface Water Quality

Water quality considerations were an important part of the total plan development. Water quality which restricts maximum beneficial use or reuse is affected by several factors, including population growth, industrial expansion, increased irrigation and recreation and natural pollution sources.

A discussion of "quality" is primarily about material dissolved in water. The kind and amounts of dissolved materials in water depend on such factors as runoff, climate, geology, urban and rural development, vegetation, natural pollution, flow characteristics of streams, and man's activities which result in waste water discharges to streams or alteration of the basin hydrology.

Water falling as rain contains only a small amount of dissolved materials. As water moves over and through rock and soil, more materials are dissolved into solution. The kinds and amounts of minerals dissolved depend on the availability of soluble minerals in the rock formation.

Man's activities also contribute materials to water. Oil and livestock production and municipal and industrial waste disposal plant operations produce liquid and solid wastes. Water quality may be affected by construction of storage and diversion facilities, by land treatment and by fertilization and irrigation of croplands (12).

1) Stream Water Quality

Variable streamflow is accompanied by variable stream water quality. Quality may be significantly different during periods of low streamflow than during periods of high flow, but at times other than high or low flow, dissolved mineral content will be between maximum and minimum values. However, the relationship between dissolved solids content and streamflow usually is not precise.

Variablilty is a distinguishing characteristic of stream water quality in both the Arkansas and Red River streams systems. The water quality of the Arkansas River in Oklahoma varies markedly. As the river crosses the state, the dissolved solids content of the water is high in the west and then decreases as it travels eastward. The water quality of the Red River from the Texas-Oklahoma line eastward to the Arkansas-Oklahoma line changes radically. In the western part of the state, the dissolved solids content is extremely high, primarily because of the large amount of dissolved natural salt and gypsum in its tributary streams (20).

2) Man-made Pollution

Industrial development and population growth are primarily responsible for the dramatic increase in man-made pollution in recent years. Industrial discharge in excess of permit allowances burdens surface waters with more than their assimilative capacities, and brine released from oil and gas production contributes to the pollution of both stream and ground waters. New oil fields or wells may produce little or no brine, but fields nearing depletion may yield up to 100 barrels of saltwater / barrel of oil (2).

Water-intensive coal mining operations in eastern Oklahoma produce great quantities of polluted water as a by-product. Improper disposal of this water presents serious pollution potential to the area's streams and lakes (21).

Nonpoint sources of pollution from agricultural and urban runoff are increasing rapidly and remain difficult to identify and control. Waste treatment management programs will continue to investigate means of reducing or eliminating nonpoint source pollution (22).

3) Natural Pollution

Natural mineral pollution in areas of western Oklahoma severely degrade the quality of water in Arkansas and Red River Basins. These minerals, primarily chlorides and sulfates, often render the water of the rivers unusable for municipal, industrial, or irrigation purposes.

Oklahoma's natural pollution problem is attributed to chlorides emitted from springs and salt flats. Fifteen such natural cholride emission areas have been identified in Texas, Kansas, and Oklahoma--ten of these in the Red River Basin, and five in the Arkansas River Basin.

Extensive studies of salinity problems by the U.S. Army Corps of Engineers have shown that the natural chloride pollution could be substantially reduced by implementing control measures at principal brine emission areas in Oklahoma and out of state (2). Successful implementation of the Chloride Control Projects proposed for the Arkansas and Red River Basins would supply water of better quality to eastern Oklahoma and, would greatly expand the supply of good quality water within the rest of western Oklahoma. Because such projects possess the potential for increasing supplies in water-deficient areas, their successful completion is an essential part of the Oklahoma Comprehensive Water Plan (2)(15).

4) The Problem of Industrial Wastes

The number of industries that now discharge wastes to domestic sewers has increased significantly during the past 20 to 30 years. In view of the toxic effects often caused by the presence of these wastes, the general practice of combining industrial and domestic wastes is now being reevaluated.

Therefore, industrial waste volumes are highly variable in both quantity and quality, depending principally on the product. Since very little water is consumed in industrial processing, large volumes are often returned as waste. These wastes may include toxic metals, chemicals, organic materials, biological contaminants, and radioactive materials. The design of treatment processes for these wastes is a highly specialized operation. Where industrial wastes must be processed in municipal sewage-treatment works, accurate estimates of the time distribution and total volume of the load are necessary, together with a complete analysis of the characteristics of the waste.

Pollution of lakes and streams may occur from point sources or from nonpoint sources. The former includes municipal and industrial activities in effluent discharges which are readily identifiable and normally amenable to treatment. Nonpoint sources of pollution, or dispersed pollution, results as a consequence of natural processes of secondary man-made causes. It is difficult to assess and control. An example of dispersed pollution is runoff from agricultural and forested land and/or urban areas. As the water washes over these areas, it picks up nutrients, organics, and toxicants and carries them to streams and lakes which are our water supplies.

5) Waste Recycling with Pump-back Systems

Waste water or sewage effluent discharging by municipalities and industries constitutes an appreciable portion of the state's available stream water resources. This effluent must be recognized as a valuable resource that can be reused or recycled to help meet growing water requirements.

The use of municipal and industrial effluents for irrigation is gaining greater acceptance in the state. Their high level of nutrients, chiefly nitrogen and phosphorus, increase agricultural yields to levels higher than those realized from conventional irrigation and fertilization. Many crops are presently irrigated with municipal waste water; however, its use is not recommended for the irrigation of crops intended for human consumption.

The greatest undeveloped potential for reuse is that of municipal effluents by industries. Several public utility companies have built lakes to catch these return flows, and have utilized the water successfully in their cooling towers. Cooling lakes can be used for recreation and fish farming.

The assessment of water quality management needs is necessary in effective wastewater management planning. The need may be determined by comparing the effluent requirement (implementation plan), described previously, with the current treatment facilities and their treatment levels (2).

The ongoing comprehensive water quality management planning effort is to establish a sound, long-range basis for water quality management for the protection of Oklahoma's waters.

C) Inter-state Compacts And Legal Problems

Interstate agreements are essential in the development of a long-range plan for water utilization when runoff water originates in one state and will be used in another. Intelligent planning for the future is impossible without an equitable allocation of variable water between states who rightfully have a share in this supply. Oklahoma can profitably take the lead in the development of a water compact with other states where such compacts are needed to insure that an equitable allocation of water for various uses will be made in all rivers flowing into or out of Oklahoma. Oklahoma, along with the other western states, is essentially an appropriation state. That is, the water is public water and goes to the one who first puts it to beneficial use. Kansas and Arkansas operates under the same theory (12). Therefore, it is essential that the waters of interstate streams be allocated before any complete long range plan can be developed. It is likewise necessary that agreements be reached on the control of pollution in these streams, so that water quality in future reservoirs will not be jeopardized. Oklahoma needs water from Kansas, Arkansas and Texas. They in turn need some of the water we have. It becomes a matter of trading across the table. Agreements ahead of time are more profitable than court action later (12).

1) Arkansas River Basin Compact

It has taken several years of effort but Oklahoma, Kansas and Arkansas have finally agreed on the form and content of proposed legislation, which will permit the negotiation of a compact between Oklahoma and these states that will allocate the water of the Arkansas

River and its tributaries and control the pollution in these streams. The Arkansas River Basin Compact, Arkansas-Oklahoma, 1972, as revised March 3, 1972, contains the amendment as approved by both states. These states have agreed as follows respecting the waters of the Arkansas River and its tributaries. The major purposes of this compact are (6):

a) To facilitate the cooperation of the water administration agencies of the states of Arkansas and Oklahoma in the total development and management of the water resources of the Arkansas River Basin;

b) Oklahoma is committed by the Arkansas-Oklahoma Compact generally to allow 40% of the Arkansas River water at the borders to cross into Arkansas;

c) To encourage the maintenance of an active pollution abatement program in each of the two states and to seek the further reduction of both natural and man-made pollution in the waters of the Arkansas River Basin; and

d) Utilizing the provisions of all federal and state water pollution laws and to recognize such water quality standards as may be now or hereafter established under the Federal Water Pollution Control Act in the resolution of any pollution programs affecting the waters of the Arkansas River Basin.

2) Red River Basin Compact

Similar steps have been taken with regard to Arkansas, Louisiana, Oklahoma, Texas and a compact on the Red River. These states have resolved to compact with respect to the water of the Red River and its tributaries by May 12, 1978. The principal purposes of this compact are (7):

a) To promote interstate community and remove causes of controversy between each of the affected states by governing the use, control and distribution of the interstate water of the Red River and its tributaries;

b) To provide an equitable apportionment among the signatory states of the water of the Red River and its tributaries;

c) To provide the means for an active program for the conservation of water, protection of lives and property from floods, improvement of water quality, development of navigation and regulation of flows in the Red River Basin;

d) To promote an active program for the control and alleviation of the natural deterioration and pollution of the water of the Red River Basin and to provide for enforcement of the laws related thereto;

e) Construct conservation storage capacity for the impoundment of water allocated by this compact;

f) Construct reservoir storage capacity for the purposes of flood and sediment control as well as storage of water which is either imported or is to be exported if such storage does not adversely affect the delivery of water apportioned to any other signatory state;

g) The State of Oklahoma is committed by the Arkansas-Oklahoma Compact to allow 40% of the Red River water at the borders to cross into Arkansas; and

3) Compact With Respect To Pollution Law

The term "pollution" means contamination or other alterations of the physical, chemical, biological or radiological properties of water or the discharge of any liquid, gaseous, or solid substances into any waters which creates, or is likely to result in a nuisance, or which renders or is likely to render the waters into which it is discharged harmful, detrimental or injurious to public health, safety, or welfare, or which is harmful, detrimental or injurious to beneficial uses of the water.

The signatory states recognize that the increase in population and the growth of industrial, agricultural, mining and other activities combined with natural pollution sources may lead to a diminution of the quality of water which may render the water harmful or injurious to the health and welfare of the people and impair the usefulness or public enjoyment of the water for beneficial purposes, thereby resulting in adverse social, economic, and environmental impacts.

Although affirming the primary duty and responsibility of each signatory state to take appropriate action under its own laws to prevent, diminish, and regulate all pollution sources within its boundaries which adversely affect the water of both the Arkansas River Basin and the Red River Basin, the states recognize that the control and abatement of the naturally-occurring salinity sources as well as, under certain circumstances, the maintenance and enhancement of the quality of water in both the Arkansas River Basin and the Red River Basin may require the cooperative action of all states involved.

Oklahoma now has reasonably adequate antipollution laws on the books. In many areas however, without public backing, it is difficult to enforce these laws against operators of a marginal stripper oil field or a struggling industry (7).

4) Legal Problems

Water law was developed before the advent of modern hydrology and is sometimes at odds with today's facts and conditions. Laws which are conflicting, vague and a limiting factor in water resources development must be amended and made more compatible with today's realities. The type of legal problems and questions that arise include the ownership of water, who is entitled to develop ground water and surface water supplies, how much water may be withdrawn for irrigation use and by whom, whether interbasin transfer is allowed and the use of legal constrains on water pollution. Change in water laws may be required to enhance Oklahoma's water resources development (2)(6)(7)(12)(23).

These compacts and their individual specifications must be considered in any water development planning in Oklahoma. In order to fully utilize all available stream water supplies, the state must use all water allocated under these agreements, while staying within compact requirements.

III. PROCEDURE AND METHODOLOGY FOR FORECASTING STORAGE REQUIREMENT

Among the factors to be considered in determining The Storage Requirement are the following:

A. Purposes of Reservoir Regulation

Reservoirs for water-supply systems may be divided into two main classes, namely, storage reservoirs and distributing reservoirs. A storage reservoir is required when the average flow of the stream from which a supply is to be taken is greater than the average consumption, but the minimum daily or monthly flow of the stream is less than the consumption during the same time period. Under such conditions, the excess of water discharges by the stream in times of large flow is stored in a reservoir, to make up for the deficiency in times when the flow of the stream is not sufficient to meet the demands of consumption. If the average flow of the stream is less than the average consumption, no storage reservoir, whatever the size, can meet the demands of consumption. If the minimum flow of the stream is greater than the maximum consumption, no storage reservoir is needed. It is for conditions between these two extremes that a storage reservoir is necessary. Such a reservoir is formed by constructing a dam across the stream from which the water supply is obtained (24).

The distributing reservoir makes it possible to draw water from the storage reservoir at a comparatively uniform rate, even though the rate of consumption is variable. A distributing reservoir is usually required when it is not possible or desirable for the water to flow directly from the source of supply to the distribution pipes (25).

B. Safe Yield of Reservoir

The safe yield is the maximum quantity of water which can be guaranteed during a critical period. In practice, the critical period is often taken as the period of lowest natural flow on record for the stream. In absence of storage, the safe yield of a stream system is its lowest dry-weather flow; with full development of storage, the safe yield approaches the mean annual flow. The economical yield generally lies somewhere in between. The attainable yield is modified (25)(26).

1) by evaporation;

2) by bank storage

3) by seepage out of the catchment area; and

4) by silting.

Hence, there is a finite probability that a drier period may occur, with the yield even less than the safe yield. Since firm yield can never be determined with certainty, it is better to treat yield in probabilistic terms. The maximum possible yield equals the mean inflow less evaporation and seepage losses. If the flow were absolutely constant, no reservoir would be required; but, as variability of the flow increases, the required reservoir capacity increases. Water available in excess of safe yield during periods of high flow is called Secondary yield. Hydroelectric energy developed from secondary water may be sold to large industries on a "when available" basis. Storage-yield relations are illustrated in this chapter by calculations of storage to be provided in impounding reservoirs for water supply. However, the principles demonstrated are also applicable to other purposes and uses of storage.

C. Optimal Design of a Reservoir System

The design of a reservoir requires a knowledge of the quantity of stream flow and its occurence with respect to area and time, and the operation of a reservoir requires the analysis of stream flow based on pre-reservoir flow records and on current stream flow and precipitation estimates. Reservoir-design studies, as they relate to hydrology, include the determination of the amount of storage needed for conservation or flood-control purposes; pool levels for recreation and navigation; discharge capacity to provide for release of conservation storage; and operation studies during critical high- and low-flow periods. Structural-design studies and social problems arising from population adjustments in a reservoir are not directly related to hydrology (25)(27).

1) Physical Factors

A number of physical factors must be considered in the design and operation of reservoirs. The first consideration is whether the topography of the stream valley provides a feasible dam and reservoir site with advantage capacity to satisfy the flood-control and conservation-storage requirements. Second, if feasible sites are available but the storage capacity is inadequate to satisfy all needs completely, then an allocation of the storage to the various purposes must be made as equitably as possible, the adopted allocation being a compromise between the various uses. Even if feasible sites are available, other considerations may lead to the selection of less desirable alternative sites (27).

For example, the presence of a large city along a river bank may present the adoption of the best and cheapest dam site in the vicinity and thus force the selection of a less desirable site. Urban and industrial development in a river valley can limit the upper pool level for flood-storage level. The presence of railroads, highways, bridges and dams also may cause similar limitations. In such cases, the cost of replacement of the developments probably would be more than the benefits that would be obtained. Other factors, such as historical landmarks, which cannot be replaced at any cost, can limit the selection of reservoir sites and operating levels (25)(27).

2) Economic Factors

Economic factors affecting the design and operation of reservoirs are capital costs of construction and land; annual costs of amotization, interest, operation, and maintenance; and annual benefits due to storage of flood water and release of conservation, storage, standard federal practice for justification of a project has been that annual benefits exceed annual costs; that is, the benefit-cost ratio must be greater than one. To determine the most economic project of a number of projects or the most economic degree of development of a single project, consideration should be given to the net annual benefits - annual benefits less annual costs. The most economic project or degree of development would be in the range of both the greatest benefit-costs ratio and the greatest net annual benefits. In comparing a number of alternative feasible reservoir sites, each producing the same benefits, the most economic site usually is that with the lowest capital cost (27).

3) Hydrology Factors

The two essential kinds of basic data needed for reservoir-design studies are adequate hydrologic records and adequate topographic maps. Watershed divides can be outlined on maps, and the size of the drainage area above a reservoir site can be determined with a planimeter. As we know, records of streamflow are essential for determining the amount of water available for conservation purposes (28).

Given a series of storage values for the flows observed or generated statistically, the engineer must decide which value he will use. Shall it be the highest on record, or the second, third, or so on? Obviously, the choice depends upon the degree of protection to be afforded against water shortage. This must be fitted into drought experience, which is a function of the length of record examined. To arrive at a reasonable answer, he may resort to a statistical analysis of the averaged storage values and an economically justifiable design storage. Storage values equaled or exceeded but once in 20, 50, or 100 years, i.e., 5, 2, and 1% of the time, are often considered. For water supply, Hazen[1] suggested employing the 5% value in ordinary circumstances. In other words, design storage should be adequate to compensate for a drought of a severity not expected to occur more than once in 20 years. In still drier years, it may be necessary to curtail the use of water, by limiting, or prohibiting, lawn sprinkling and car washing, for example (27).

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[1]Allen Hazen, Storage to be Provided in Impounding Reservoirs, Trans. Am. Society Civil Engineer, 77, 1539 (1914).

D. Losses from Reservoirs

The design of an impounding reservoir must include an evaluation of storage losses that may result from a natural or artificial phenomena. Natural losses occur through evaporation, seepage, and siltation, while artificial losses are usually the product of withdrawals made to satisfy prior water rights. When an impounding reservoir is filled, the hydrology of the inundated area and its immediate surrounding is changed in a number of respects (29)(30):

1) The reservoir loses water by evaporation to atmosphere and gains water by direct reception of rainfall;

2) Rising and falling water levels alter the pattern of groundwater storage and movement into and out of the surrounding reservoir banks;

3) At high stages, water may seep from the reservoir through permeable soils into neighboring catchment areas and so be lost to the area of origin; and

4) Inactivity encourages subsidence of settleable suspended solids and silting of the reservoir.

The magnitude of seepage losses depends mainly on the geology of the region. If porous strata underlies the reservoir valley, considerable losses may occur. On the other hand, where permeability is low, seepage may be negligible. Only a subsurface exploration can tell how great the expected loss will be (31).

Soil erosion on the watershed causes reservoir silting, and both erosion and silting are undesirable. Silting destroys useful storage and erosion destroys arable lands. How bad conditions are in a given catchment area depends principally upon the type of soil and rock in the watershed, the slope of the ground surface, the vegetal cover, methods of cultivation employed, and storm-rainfall intensities. Silt accumulations cannot be removed economically from reservoirs by any means as yet devised. In favorable circumstances, however, much of the heaviest load of suspended silt can be passed through the reservoir by opening large sluices that are installed for this purposes (30).

The rate and characteristic of soil-erosion can be controlled by using sedimentation basins, providing vegetative screens, employing proper farming methods, such as contour plowing and terracing, establishing forest covers, by caltivating permanent pastures, and by preventing gully formation through the construction of check dams or debris barriers. In the design of impounding reservoirs for silt-bearing streams, suitable allowance must be made for loss of capacity by silting (29)(30)(31).

E) <u>Selection of Reservoir Sites and Related Problems</u>

It is virtually impossible to locate a reservoir site having completely ideal characteristics. General considerations for choice of reservoir sites are (26)(28)(32):

1) The materials for the construction of the dam and the spillway should be easily available and in adequate supply.

2) The surface and sub-surface geology should offer resistance against seepage of the impounded water.

3) No objectionable mineral or salt which may affect the quality of water should be present.

4) No objectionable vegetation and marshy land which might affect color, odor, or taste to the water should be present.

5) The quality of the stored water must be satisfactory for its intended use. The quality of the runoff can be improved by utilizing the safe purification process to its maximum.

6) The valley on the upstream side of the dam should be broad so as to have a greater average volume per unit height and per unit length of the dam.

7) The reservoir banks and adjacent hillslopes should be stable. Unstable banks will contribute large amounts of soil material to the reservoir. Tributary areas which are unusually productive of sediment should be avoided if possible.

8) Trees and underbush may have to be removed.

9) Important roads and railway lines should be avoided as they may become submerged. Human habitation should be affected to a minimum and submergence of cultivable land should be avoided.

10) The cost of the dam is often a controlling factor in selecting a site. The cost of real estate for the reservoir, like road, railroad, cemetery, and dwelling relocation, must not be excessive.

In the development of large reservoirs, the sites of whole villages with their houses, stores, churches, and other meeting houses; their manufacturing establishments, stables, barns; their gardens, playgrounds, as well as the agricultural and woodlands of the valley are inundated (32).

Rehabilitation is an important problem. Every possible care should be taken in handling the psychological problems that arise for those who have to leave their ancestral homes. The displaced people should be taken into confidence so that they understand the importance of the work and know it is in their interest, as well as in the interest of the state and the nation. The family members should be provided with employment. Houses and other facilities should be quickly provided. Goodwill and understanding should be developed in the area (27).

Vegetation is eliminated by cutting down and removing the trees, bushes, and soon, marshy areas are either drained out or filled in. Highly organic surface soil like peat and cultivable land may have to be removed. This will reduce the undesirable effect of decaying organic matter (27)(32).

F. General Acceptable Techniques for Storage Capacity Computation

There are several methods for determining the safe yield of a watershed from the storage at a given reservoir site or, conversely, the storage which will be necessary to furnish a desired yield. Actual or synthetic records of stream flow and knowledge of the proposed operating rules of the reservoir are fundamental to all solutions. Actual records of runoff, usually monthly or yearly, are obtained from a stream gaging station on the stream relatively close to the site of the proposed dam. The longer the period of years for which records are available, the greater the likelihood of the record including a period of extreme drought which will control the yield or the required storage. If the records are given in cubic feet per second (CFS) at the gage, they are converted to acre-feet per year (Ac-Ft/Yr) and these figures are then used for the slightly different watershed area above the site of the proposed dam (33)(34).

When the proposed reservoir will have a large surface area, the actual runoff records can be modified downward to account for the expected increased evaporation losses or seepages from the reservoir. The amount of water released downstream for the use of owners below the reservoir site is also deducted from the monthly values of actual runoff. The remaining water will be available for storage, for power or water supply use, and for waste over the spillway at times when the reservoir is full (35).

1) Mass Curve Technique

One of the most satisfactory graphical procedures is to use a Mass Curve Analysis. Historically, one of the most used methods of determining storage has been the selection of some low-flow period considered to be critical (34). The most severe drought on record might be selected; for example, once the critical period is chosen, storage is usually calculated by the Mass Curve Analysis introduced in 1883 by Ripple[1]. This method evaluates the cumulative deficiency between outflow and inflow (O-I) and selects the maximum cumulative values as the required storage.

The accumulated totals of modified runoff are then added month by month or year by year and plotted as a mass curve, which is shown in Figure 7 (36).

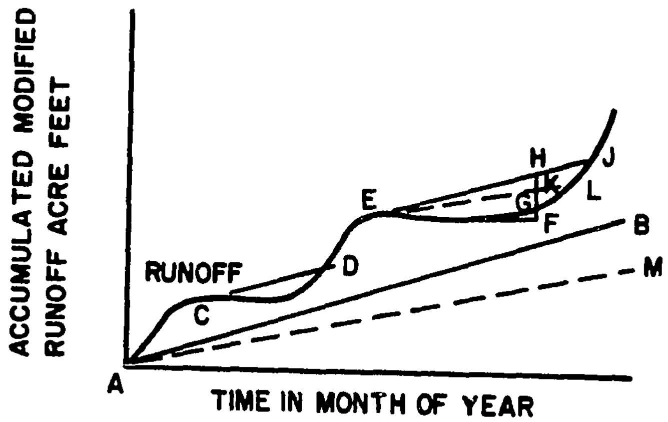

Figure 7 - Mass Diagram for Designing an Impounding Reservoir

The application of Mass Curve will be illustrated in Chapter IV of The Case Study. The variations in monthly or yearly consumption are disregarded in this method. Such variations must be considered. Therefore, the analytical method described in the following section will be used (28).

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[1]W. Ripple, "The capacity of storage reservoirs for water supply," Proc. Inst. Civil Engineering, London, 1883, 71: p. 270.

2) Analytical Procedure

Another satisfactory computation technique is the Analytical Procedure. For demands that are not constant and for the inclusion of varying allowances for evaporation from the water surface that is created by the impoundage, the analytical method possesses distinct advantages over the graphical method. The principle employed in this solution satisfies the following equation: cumulative stream inflow minus cumulative withdrawal equals the change in storage for each yearly increment. The amount of storage that must be provided is a function of the expected demands (demand may be shown as a percentage of mean annual flow) and the inflow to the impoundment. Mathematically this may be stated as follows (27)(29)(33):

OS = I-O

where OS = change in storage volume during a specified time interval.

I = total inflow volume during this period.

O = total outflow volume during this period.

Naturally, "O" will be the draft requirement imposed by the various types of use, but it may also include evaporation and transpiration, as well as flood discharges during periods of high runoff when inflow may greatly exceed draft plus available storage and outflow seepage from the bottom or sides of the reservoir. Because the natural inflow to any impoundment area is often highly variable from year to year, season to season, or even day to day, it is obvious that the reservoir function must be that of redistributing this inflow with respect to time, so that the projected demands are satisfied (37). The application of the Analytical Procedure will be presented in Chapter IV as a case study.

IV. A CASE STUDY ON THE ILLINOIS RIVER BASIN

A. Introduction

Because it is difficult to define or describe water planning with a preciseness such that all persons concerned would have the same understanding of the processes involved, this section will attempt to indicate, by example, the meaning of water supply planning. For the purpose of the example, the Illinois River Basin in the study is designed to furnish a pilot procedure on a typical basin of the Arkansas River, which can be used as a guide for further researches of this type. This basin will be used because the water use within the area has been developed, and this author has greater familiarity with this area, but similar examples could be cited elsewhere. The acceptable procedures used have been those developed and practiced primarily by the United States Army Corps of Engineers and currently accepted in the field of hydrologic study. The base period of the study was chosen from the historical computer record files of the United States Geological Survey. Useful data were also received from the United States Army Corps of Engineers, the Soil Conservation Service, and The Bureau of Reclamation.

B. Description of Basin

The Illinois River has its source in the Boston Mountains in Benton and Washington county, Arkansas, near Fayetteville and flows in a westerly direction, crossing the Oklahoma-Arkansas state line. Then it crosses the northern portion of Adair County, Oklahoma, into Cherokee County, where it turns in a southerly direction to its confluence with the Arkansas River near Webbers Falls, Oklahoma.

The highest point in the Illinois River Basin has an elevation of 2,000 feet from mean sea level (MSL) and the drop within the Illinois River channel is to an elevation of about 445 feet (MSL) at the point of junction of the Arkansas River, for a distance of over 150 miles. A study of the Illinois River Basin map is shown in Figure 8. The Basin is generally fan-shaped and averages twenty-one miles in width. The narrow section near the outlet is reduced in width to approximately seven miles (38).

The two major tributaries and the main stem of the Illinois River cross the Arkansas-Oklahoma border. While there are other minor tributaries, none of these are large enough to contribute appreciable flow during critical periods. These water courses listed in order of occurence from north to south along the common state line are:

1) Flint Creek,

2) Illinois River, and

3) Barren Fork Creek.

The largest tributary to the main stem of the Illinois River is that of the Barren Fork Creek, which has a drainage basin of 307 square miles or 18.5% of the total area of the Illinois River Basin. The next largest tributary is Flint Creek, which has a drainage area approximately 110 square miles or 6.7% of the total area of this basin. Numerous other smaller creeks contribute either to the previously mentioned tributaries or to the main stem of the Illinois River (40). Significant data of the Illinois River Basin are shown in Table 1.

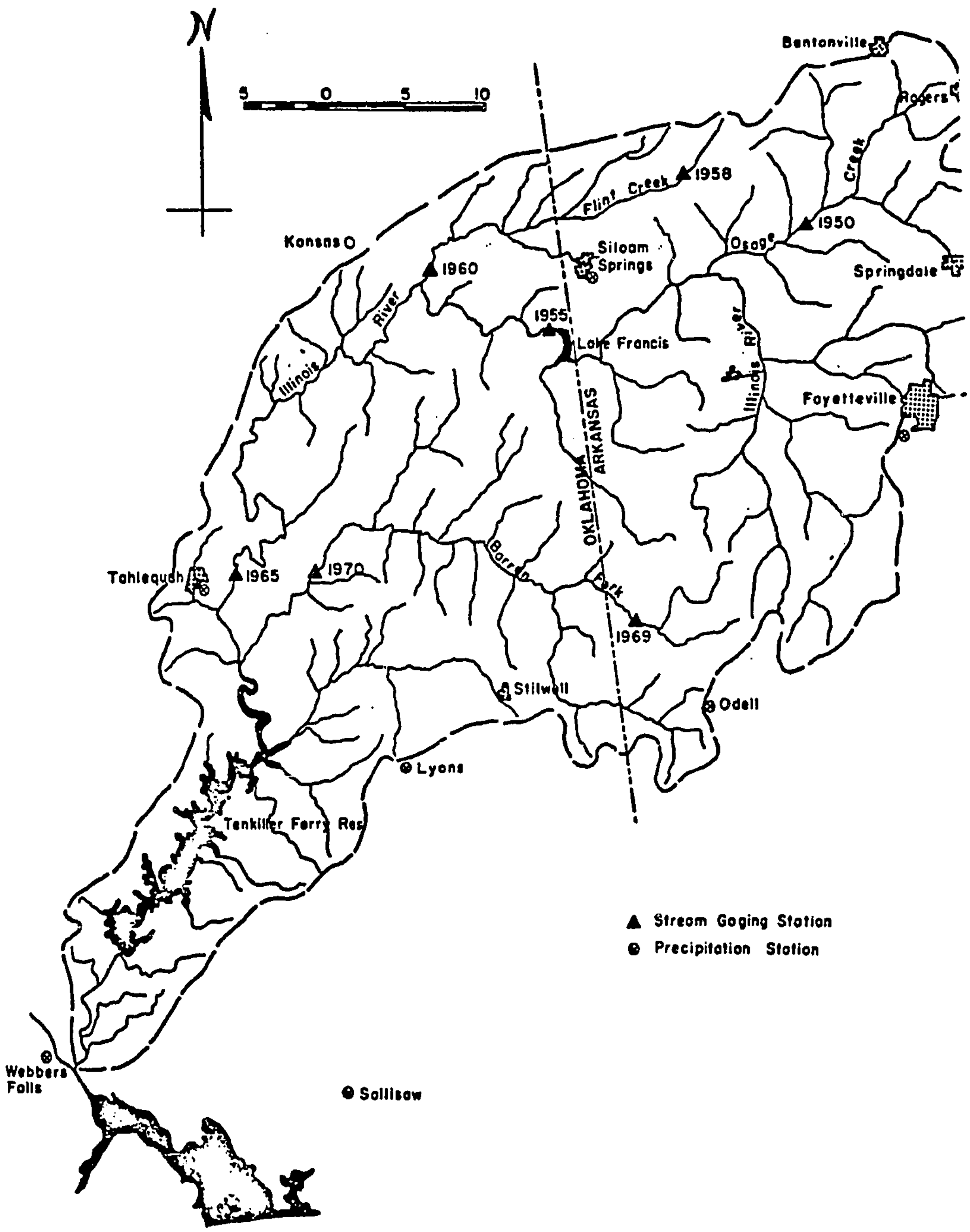

FIGURE 8 Map of the Illinois River Basin
See Reference 40

Table 1 - Significant Data of the Illinois River Basin

DRAINAGE	LOCATION
580 sq. mile	Arkansas-Oklahoma state-line
609 sq. mile	Lake Francis
635 sq. mile	USGS Gage No. 1955 (state-line)
959 sq. mile	USGS Gage No. 1965
1610 sq. mile	Tenkiller Ferry Dam Site
1626 sq. mile	USGS Gage No. 1980
1660 sq. mile	Mouth
BARREN FORK CREEK (PRINCIPAL TRIBUTARY)	
58 sq. mile	Arkansas-Oklahoma state-line
307 sq. mile	USGS Gage No. 1970
341 sq. mile	Mouth
FLINT CREEK (PRINCIPAL TRIBUTARY)	
64 sq. mile	State-line
110 sq. mile	USGS No. 1960
123 sq. mile	Mouth

Source: Adapted from Reference 39

C. Precipitation and Climate

The Illinois River Basin is characterized by long hot summers and short mild winters. Normal yearly areal temperatures range from 50° to 63° F. The extremes vary from a minimum of 29° below zero to a maximum of 120°. The annual precipitation on the Illinois River Basin averages about 45 inches; the extremes range from a minimum of 25.11 inches at Tahlequah, Oklahoma in 1954, to a maximum of 74.81 at Wilburton, Oklahoma in 1945. The average annual snowfall ranges from 9 inches to 14 inches (39). The greatest portion of this rainfall usually occurs in the spring and early summer months while the annual dry period is encountered in the late summer or in the fall season, usually in September or October. Annual average evaporation rates closely approximate the normal annual precipitation (38).

D. Evaporation Studies

Evaporation information was wholly derived from the reports of other agencies who have collected field data within the geological limits of this study. A generalized map in the United States Weather Bureau technical paper No. 37 gives a regional variation of the annual lake evaporation rate within the compact study area of 47 to 52 inches per year. This annual evaporation range is varied by the value of 50.14 inches, calculated based upon pan evaporation data collected by the United States of Army of Engineers (40)(41).

E. Stream Gaging Network

Records of daily stream flow have been collected for more than 45 years on the Illinois River near Tahlequah, Oklahoma. Shorter records of data collection have been maintained at four other gaging stations in the Illinois River Basin, see Figure 8.

Most of the above records were used in the preparation of this section. Another gaging station, which was not considered in the preparation of this research, is the Tenkiller Ferry Reservoir near Gore, Oklahoma. Monthly stream flow and mean annual stream flow records in the Illinois River Basin were obtained primarily from the records of the U.S. Geological Survey's annual series "Water Resources Data for Oklahoma" (42).

The United States Geological Survey has computed mean annual flows in cubic feet per second (CFS) at different stream gaging locations within the Illinois River Basin. A summary of these flows will be shown in Table 2.

TABLE 2 - Drainage Areas, Minimum, Average, and Annual Flow for the Different Gaging Stations in the Illinois River Basin

Station Yr. Minimum Flow Date	Base CFS	Drain. No. Rec.	Dischrg SITES	Sq. Mi.	Average No. CFS	of	Period	Area	(MAF)
1 Illinois River near Watts, OK	1955	26	1956-81	635	564	1964	151	1973	1264
2 Flint Creek near Kansas, OK	1960	13	1964-76	110	133	1964	34.4	1974	296
3 Illinois River at Tahlequah, OK	1965	45	1936-80	959	883	1954	193	1974	1,980
4 Barron Fork at Eldon, OK	1970	32	1949-80	307	288	1967	71.4	1973	637
5 Illinois River near Gore, OK	1980	40	1941-80	1626	1542	1953	62.6	1973	3114
6 Illinois River at Mouth●	--	-	-----	1669	1574	1953	64	1973	3179

● Water Year
CFS - Cubic Feet Per Second

Source: Adapted from (38)(39)(40)(41)(42)

F. Frequency of Extreme Events

The primary objective of the frequency analysis of hydrologic data is to determine the recurrence interval of the hydrologic event of a given magnitude x. The average interval of time within which the magnitude X of the event will be equaled or exceeded once is known as reccurrence interval, return period, or simple frequency, to be designated by T. If a hydrologic event equal to or greater than X occurs once in T years, the probability P(X x) is equal to 1 in T cases, or

$$P(X \geqslant x) = \frac{1}{T}$$

where T is the recurrence interval of the event. It's defined as the average interval in years between the occurence of an event of stated magnitude and an equal or more serious event. According to Clark and Chow (29, 34), the use of Binomial Distribution in recurrence interval studies has been suggested. This method gives the probability P(X;N) that a particular event will occur X times out of N trials, as

$$P(x) = C_x \, P^x q^{N-x} = C_x \, P^x (1-P)^{N-x} \qquad \text{EQUATION \#1}$$

where P is the probability that an event will occur in each individual trail (in this case) $P = \frac{1}{T}$

C_x is the number of combinations of N things taken X at a time; is the probability of failure or (1-P); N is the total number of trials; and X is the variate or the number of successful trials.

Now, if we let the number of occurences equal zero (x = 0) in a given period of years N (number of trials) and substitute this value in Equation #1, the result is

$$P(X;N) = (1-P)^N$$

This is the probability of zero events equal to or greater than the T year event. Then the probability R that at least one event equal to or greater than the T year event will occur in a sequence of N years is given by

$$R = 1-(1-\frac{1}{T})^N$$

Solution of this equation for various values of N and T provided the data for Table 3 (29)(34)(46).

This model assumes a hypothetical claimatical situation independent of preceeding and succeeding years. Dependency on preceeding and succeeding claimatical conditions would invalidate this model.

Table 3 - Probability that an Event Having a Prescribed Recurrence Interval will be Equaled or Exceeded During a Specified Design Period

T (Years)	(N) DESIGN PERIOD (YEARS)					
	1	5				
1	1.0	1.0	1.0	1.0	1.0	1.0
2	0.5	0.97	0.999	*	*	*
5	0.2	0.67	0.89	0.996	*	*
10	0.1	0.41	0.65	0.93	0.995	*
50	0.02	0.10	0.18	0.40	0.64	0.87
100	0.01	0.05	0.10	0.22	0.44	0.63

* Values are approximately = 1.0

G. Surface Water Quality Investigation in the Illinois River Basin

The Oklahoma State Department of Health has determined the Illinois River to be one of the highest water quality streams in the state of Oklahoma. The 1976 intensive study of the Illinois River was designed by this authority to be broad in scope in order to provide an over-all evaluation of general water quality and to assess the impact of numerous natural and man-made factors. The results of these assessments were to be appraised from the standpoint of what regulatory actions might best affect water quality in the Illinois River drainage basin. From these studies the following points were concluded (44):

1) In spite of the fact that the slopes are steep within the Illinois River basin, the nature of the soil is such, that washing is not prevalent. While there are clay outcroppings, the general terrain is rocky and the quality of the surface runoff water is extremely high. The turbidity in the water is high shortly after heavy rains, but the water soon clears and most of the time, the streams are clear and with a low turbidity. The mineral quality of the water is good and is suitable for municipal, agricultural and most industrial uses. Dissolved mineral matter averages 105 milligrams per liter (PPM) and the mean hardness value is 85 PPM (38)(42). The pH ranges of these waters are slightly in alkalin range, observed ranges being from 7.2 to 8.0. However, color and low pH values are occasionally encountered in runoff from the more heavily vegetated regions in the upper basin. The stream may be moderately turbid during periods of storm runoff. Because of the small amount of clay particles in the sediment load of the streams, rapid settlement of the suspended material would occur at an impoundment (39)(41).

2) The water quality of the Illinois River was determined to improve from Lake Frances to below Baron Fork with minor regressions in quality occuring below Flint Creek. Biological communities appeared stressed below these confluences and in areas of high public use.

3) Baron Fork was determined to be of highly superior water quality with no detrimental impact on the Illinois River.

4) Flint Creek was determined to be of inferior water quality with elevated nutrient levels. Point source discharges from the city of Siloam Springs sewage treatment facility were surmized to be the major factor creating this condition.

5) Non-point sources were determined to contribute approximately 95% of the nutrient loading to the Illinois River drainage basin in Oklahoma (44).

6) Urban runoff and wastewater effluent impacts were assessed at the city of Tahlequah, where the waste was shown to contribute from less than 1% to 30% of the total nutrient contribution to the Illinois River Basin in this study area. It has no significant impact on the water quality of the Illinois River (44).

7) During the several years of water quality studies in the Illinois River Basin, there were no indications of excessive mineral concentrations of water due to any activities of man (41).

H. STORAGE REQUIRED TO PRODUCE SELECTED DEPENDABLE FLOWS

The variations in discharge of the Illinois River and its tributaries throughout a year and over a period of years are such that surface impoundments are necessary for regulation of the flows for maximum utilization of the waters. Drought conditions may persist over a period of time, and reservoirs must hold considerable carryover storage to withstand sustained withdrawals. However, it is impractical to construct a reservoir large enough to control completely the stream flow at all times, but it is possible to provide enough storage for control during a large percentage of the time (49-14).

The two most satisfactory techniques which were introduced in Chapter III will be employed for each of five gaging stations on:

1) The Illinois River near Watts, Oklahoma;

2) Flint Creek near Kansas, Oklahoma;

3) The Illinois River near Tahlequah, Oklahoma;

4) Barren Fork near Eldon, Oklahoma; and

5) The Illinois River near Gore, Oklahoma.

Figures 9 through 13 and Tables 4 through 8 show the detailed procedures respectively. The application of each technique to each gaging station in the Illinois River Basin will be discussed in turn.

I. The Application of Mass Curve in the Illinois River Basin as a Case Study

The required storage in the Illinois River Basin may be determined graphically by application of a mass diagram as alluded to earlier. This technique is constructed, step by step, in the following manner: first, determine the length of the period recorded during which the yield and the demand are to be investigated; Next, determine the mean annual flow of the watershed for each year of this period from records of the stream gaging station; Then plot a line with the intervals in years from the beginning of the period as abcissas and the corresponding cumulative yields during these intervals as ordinates. Such a line will be wavy and will rise continually. The larger yield during the years are shown by the steeper portions of the wavy line. A typical yield curve is represented in Figures 9 through 13 by the heavy line ABCD.

The next step is to determine the demand per year, which is the sum of the amount of water actually consumed and the quantities lost by evaporation, percolation, and seepage. This demand per year is multiplied by the length in years of the period under investigation to obtain the total cumulative demand for the period, or demand may be calculated as a percentage of mean annual flow. A straight line representing this total cumulative demand, as line AD in Figure 9 through 13, is then plotted. The starting point for this line is the point A at which the yield curve begins. The upper extremity E is plotted by laying off the number of years in the period as an abscissa and the total cumulative demand as an ordinate.

If the upper end of the cumulative demand line lies below the yield curve, the total yield for the period will be sufficient to provide the required amount of water. However, if the yield curve is below the demand line at any point, a storage reservoir will be necessary to meet the demand during part of the period. To determine the required capacity of a storage reservoir, a line is drawn so that it is parallel to the cumulative-demand line, is tangent to a low point on the yield curve, and does not intersect the yield curve at any other point. The required storage which is equal to the greatest vertical distance between this tangent (EB) and the yield curve (AB), is (HI), which is the required storage capacity of the reservoir at any date prior to the date at the point of tangency. The wavy line (ABCD) shows the cumulative yield from a certain gaging station for consecutive years of lowest yield. (See Figures 9 - 13)

J. The Application of Analytical Procedure in the Illinois River Basin as a Case Study

The variations in yearly consumption are disregarded in the mass curve technique. Where such variations must be considered, the analytical method possesses distinct advantages over the graphical method. Because the natural inflow to any impoundment area and the rate of consumption are highly variable, it is obvious that the reservoir function must be that of redistributing this inflow with respect to time, so that the projected variable demands are satisfied. Theoretically, the analytical procedure has been discussed earlier in Chapter VI. Now, practically, its step-by-step application will be illustrated.

1) The necessary calculations for the graphicals and mathematical solution of these problems are shown in Figures 9 through 13 and Tables 4 through 8 respectively, all volumes of water being stated in cubic foot per second (cfs) and acre-foot per year (Ac-Ft/Yr).

2) The schedule gives the maximum cumulative deficiency or required storage as in Ac-Ft/Yr.

3) Column 5 furnishes the data for the mass diagram shown in Figures 9 through 13 as in Ac-Ft/Yr.

4) Columns 6, 9, and 12 give the percentage of mean annual flow (MAF) as a draft or demand, in cfs.

5) Columns 7, 10, and 13 give a negative and positive value (negative value indicates a surplus rather than a deficiency).

6) Columns 8, 11, and 14 show negative values which are not included in (O-I) until the beginning of the dry period. The surplus preceding the dry period, however, must equal or exceed the preceeding maximum deficiency; otherwise, the reservoir will not be full at the beginning of the dry period.

A summary of analytical procedure of mass curve for storage requirements to sustain 50%, 70%, and 90% of the 60% of the mean annual flow, on the Illinois River and its tributaries is shown in Table 11.

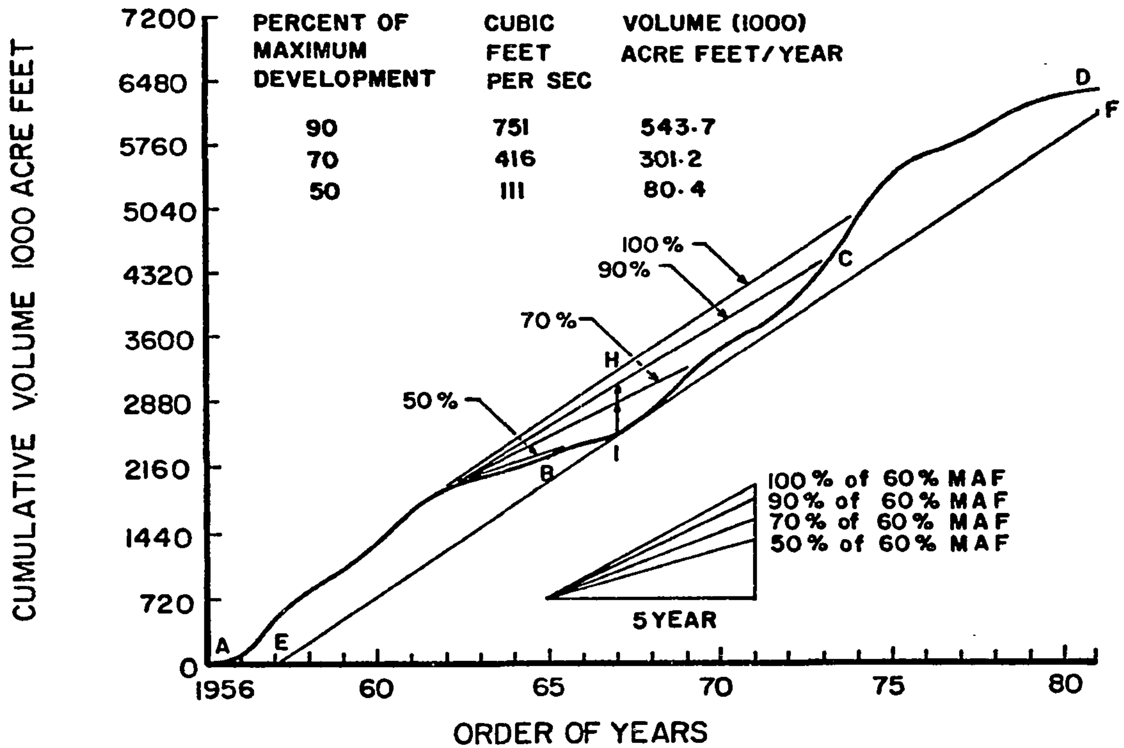

FIGURE 9 Reservoir Capacity for a Specified Yield as Determined by Mass Curve for 1956-81, the Illinois River near Watts, Oklahoma Station #1955

TABLE 4 - An Analytical Storage Procedure to Accompany Figure 10 on the Illinois River near Watts, Oklahoma, Station #1955

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
						90% of Mean Annual Flow			70% of Mean Annual Flow			50% of Mean Annual Flow		
No.	Period of Record	Mean Annual Flow CFS	60% of MAF CFS	Cumulative 60% of MAF	Cumulative Yearly Discharge (1000)	Draft O CFS	Deficiency O-I CFS	Cumulative Deficiency ε(O-I) CFS	Draft O CFS	Deficiency O-I CFS	Cumulative Deficiency ε(O-I) CFS	Draft O CFS	Deficiency O-I CFS	Cumulative Deficiency ε(O-I) CFS
1	1956	174	104	104	75.3	304	200	200	237	133	133	169	65	65
2	1957	1022	613	717	519.1	304	-309	0	237	-376	0	169	-444	0
3	1958	775	465	1182	855.8	304	-161	0	237	-228	0	169	-296	0
4	1959	383	230	1412	1022.3	304	74	74	237	7	7	169	-61	0
5	1960	742	445	1857	1344.5	304	-141	0	237	-208	0	169	-276	0
6	1961	783	470	2327	1684.7	304	-166	0	237	-233	0	169	-301	0
7	1962	602	361	2683	1942.4	304	-57	0	237	-124	0	169	-192	0
8	1963	227	136	2824	2044.6	304	168	168	237	101	101	169	33	33
9	1964	151	91	2915	2110.4	304	213	381	237	146	247	169	78	111
10	1965	362	217	3132	2267.6	304	87	468	237	20	267	169	-48	63
11	1966	376	226	3358	2431.1	304	78	546	237	11	278	169	-57	6
12	1967	165	99	3457	2502.9	304	205	751	237	138	416	169	70	76
13	1968	779	467	3924	2841.0	304	-163	588	237	-230	186	169	-298	0
14	1969	778	467	4391	3179.1	304	-163	425	237	-230	0	169	-298	0
15	1970	497	358	4749	3438.3	304	-54	371	237	-121	0	169	-189	0
16	1971	613	368	5117	3704.7	304	-64	307	237	-131	0	169	-199	0
17	1972	399	239	5356	3877.7	304	65	372	237	-2	0	169	-70	0
18	1973	1246	748	6104	4419.3	304	-444	0	237	-511	0	169	-579	0
19	1974	1233	740	7844	4955.1	304	-436	0	237	-503	0	169	-571	0
20	1975	1038	623	7467	5406.1	304	-319	0	237	-386	0	169	-454	0
21	1976	536	322	7789	5639.2	304	-18	0	237	-85	0	169	-153	0
22	1977	229	137	7926	5738.4	304	167	167	237	100	100	169	32	32
23	1978	611	367	8293	6004.1	304	-63	104	237	-130	0	169	-198	0
24	1979	440	264	8557	6195.3	304	40	144	237	-27	0	169	-95	0
25	1980	.189	113	8670	6277.1	304	191	335	237	124	124	169	56	56
26	1981	211	127	8797	6369.0	304	177	512	·237	110	334	169	42	98
	Avg.	564 CFS	338 CFS											

Drainage Area - 635 Square Mile
Mean Annual Flow During the Period of (1956-1981) - 564 CFS
MAF = Mean Annual Flow
Ac-Ft/Yr = Acre Feet per Year
CFS = Cubic Feet per second - 724 Ac-Ft/Yr

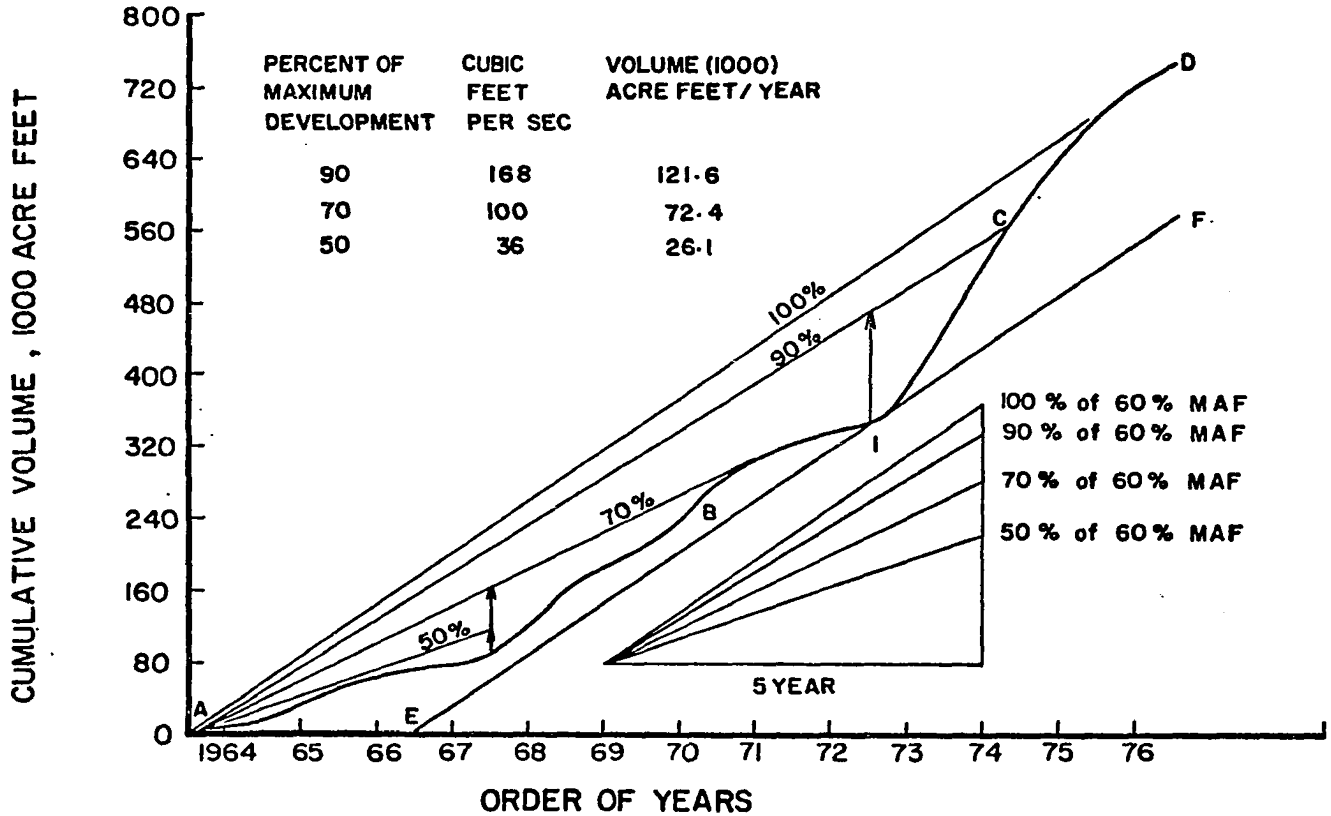

FIGURE 10 Reservoir Capacity for Specified Yield as Determined by Mass Curve for 1964-76, Flint Creek near Kansas, Oklahoma Station #1960

TABLE 5 - An Analytical Storage Procedure to Accompany Figure 11 on the Flint Creek near Kansas, Oklahoma, Station #1960

No.	1 Period of Record	2 Mean Annual Flow CFS	3 60% of MAF CFS	4 Cumulative 60% of MAF	5 Cumulative Yearly Discharge (1000)	6 90% of Mean Annual Flow Draft O CFS	7 90% of Mean Annual Flow Deficiency O-I CFS	8 90% of Mean Annual Flow Cumulative Deficiency ε(O-I) CFS	9 70% of Mean Annual Flow Draft O CFS	10 70% of Mean Annual Flow Deficiency O-I CFS	11 70% of Mean Annual Flow Cumulative Deficiency ε(O-I) CFS	12 50% of Mean Annual Flow Draft O CFS	13 50% of Mean Annual Flow Deficiency O-I CFS	14 50% of Mean Annual Flow Cumulative Deficiency ε(O-I) CFS
1	1964	34	20	20	14.5	72	52	52	56	36	36	40	20	20
2	1965	82	49	69	50.0	72	23	75	56	7	43	40	-9	11
3	1966	53	32	101	73.1	72	40	115	56	24	67	40	8	19
4	1967	39	23	124	89.8	72	49	164	56	33	100	40	17	36
5	1968	165	99	223	161.5	72	-27	137	56	-43	57	40	-59	0
6	1969	150	90	313	226.6	72	-18	119	56	-34	23	40	-50	0
7	1970	117	70	383	277.3	72	2	121	56	-14	9	40	-30	0
8	1971	101	61	444	321.5	72	11	132	56	-5	4	40	-21	0
9	1972	60	36	480	347.5	72	36	168	56	20	24	40	4	4
10	1973	264	158	638	461.9	72	-86	82	56	-102	0	40	-118	0
11	1974	296	178	816	590.8	72	-106	0	56	-122	0	40	-138	0
12	1975	145	147	963	697.2	72	-75	0	56	-91	0	40	-107	0
13	1976	119	71	1034	748.6	72	1	11	56	-15	0	40	-31	0
	Avg.	133 CFS	80 CFS											

Drainage Area - 110 Square Mile
Mean Annual Flow During the Period of (1964-1976) - 133 CFS
MAF = Mean Annual Flow
Ac-Ft/Yr = Acre Feet per Year
CFS = Cubic Feet per Second

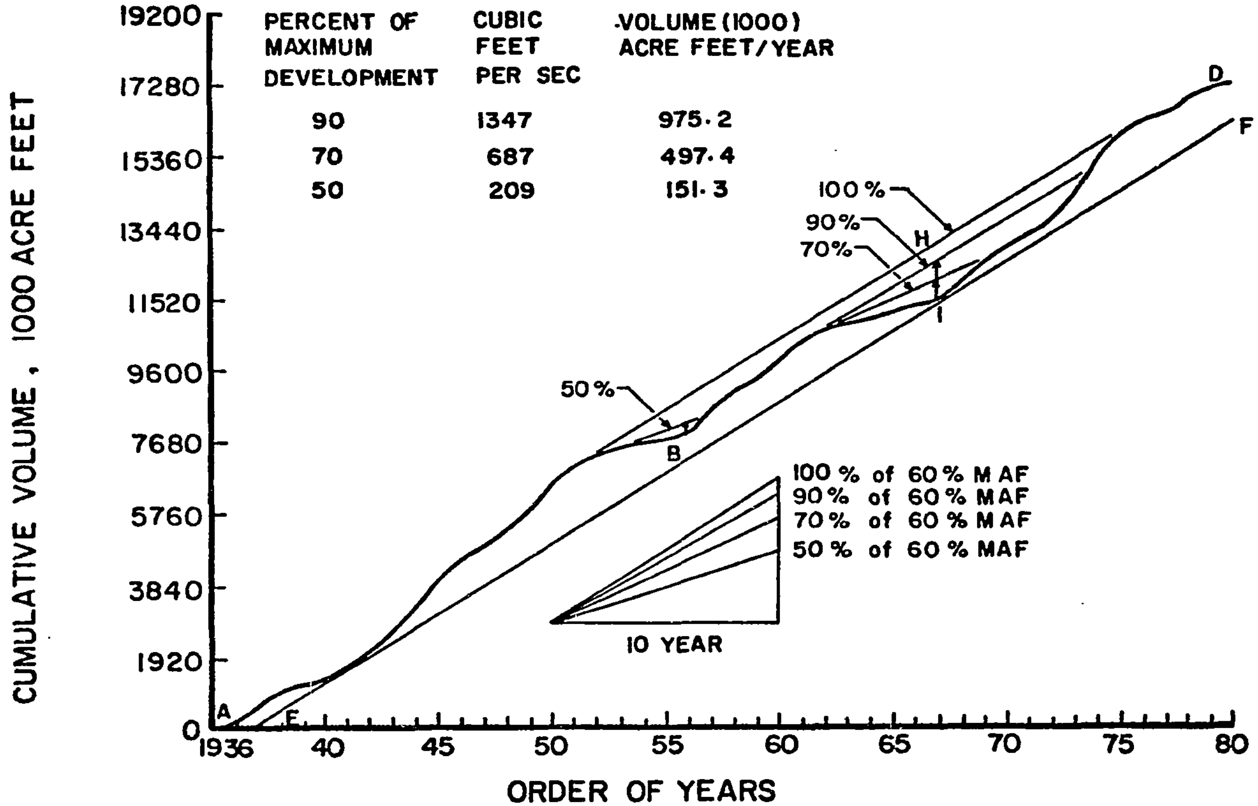

FIGURE 11 Reservoir Capacity for a Specified Yield as Determined by Mass Curve for 1936-80, the Illinois River near Tahlequah, Oklahoma Station #1965

TABLE 6 - An Analytical Storage Procedure to Accompany Figure 12 on the Illinois River nar Tahlequah, Oklahoma, Station #1965

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
						90% of Mean Annual Flow			70% of Mean Annual Flow			50% of Mean Annual Flow		
No.	Period of Record	Mean Annual Flow CFS	60% of MAF CFS	Cumulative 60% of MAF	Cumulative Yearly Discharge (1000)	Draft O CFS	Deficiency O-I CFS	Cumulative Deficiency ε(O-I) CFS	Draft O CFS	Deficiency O-I CFS	Cumulative Deficiency ε(O-I) CFS	Draft O CFS	Deficiency O-I CFS	Cumulative Deficiency ε(O-I) CFS
1	1936	354	212	212	153.5	477	265	265	371	159	159	265	53	53
2	1937	821	493	705	510.4	477	-16	249	371	-122	37	265	-228	0
3	1938	1117	670	1375	995.5	477	-193	56	371	-299	0	265	-495	0
4	1939	437	262	1637	1185.2	477	215	271	371	109	109	265	3	3
5	1940	279	167	1804	1306.1	477	310	581	371	204	313	265	98	101
6	1941	807	484	2288	1656.5	477	-7	574	371	-113	200	265	-219	0
7	1942	1270	762	3050	2208.2	477	-285	289	371	-391	0	265	-497	0
8	1943	1537	922	3972	2875.7	477	-445	0	371	-551	0	265	-657	0
9	1944	840	504	4476	3240.6	477	-27	0	371	-133	0	265	-239	0
10	1945	1855	1113	5589	4046.4	477	-636	0	371	-742	0	265	-848	0
11	1946	965	579	6168	4465.6	477	-102	0	371	-208	0	265	-314	0
12	1947	1040	624	6792	4917.4	477	-147	0	371	-253	0	265	-359	0
13	1948	985	591	7383	5345.3	477	-114	0	371	-220	0	265	-326	0
14	1949	1140	684	8067	5840.5	477	-207	0	371	-313	0	265	-419	0
15	1950	1647	988	9055	6555.8	477	-511	0	371	-617	0	265	-723	0
16	1951	936	562	9617	6962.7	477	-85	0	371	-191	0	265	-297	0
17	1952	773	464	10081	7298.6	477	13	13	371	-93	0	265	-199	0
18	1953	514	308	10389	7521.6	477	169	182	371	63	63	265	-43	0
19	1954	193	116	10505	7605.6	477	361	543	371	255	318	265	149	149
20	1955	560	336	10841	7848.9	477	141	684	371	35	353	265	-71	78
21	1956	223	134	10975	7945.9	477	343	1027	371	237	590	265	131	209
22	1957	1507	904	11879	8600.3	477	-427	600	371	-533	57	265	-639	0
23	1958	1043	626	12505	9053.6	477	-149	451	371	-255	0	265	-361	0
24	1959	547	328	12833	9291.1	477	149	600	371	43	43	265	-63	0
25	1960	1142	685	13518	9787.0	477	-208	392	371	-314	0	265	-420	0
26	1961	1161	697	14215	10291.7	477	-220	172	371	-326	0	265	-432	0
27	1962	867	520	14735	10668.1	477	-43	129	371	-149	0	265	-255	0
28	1963	346	208	14943	10818.7	477	269	398	371	162	162	265	57	57
29	1964	239	143	15086	10922.6	477	334	732	371	228	390	265	122	179
30	1965	590	354	15440	11178.6	477	123	855	371	17	407	265	-89	90
31	1966	524	314	15754	11405.9	477	163	1018	371	57	464	265	-49	41
32	1967	246	148	15902	11513.0	477	329	1347	371	223	687	265	116	157
33	1968	1117	670	16572	11998.1	477	-193	1154	371	-299	388	265	-405	0
34	1969	1143	686	17258	12494.8	477	-209	945	371	-315	73	265	-421	0
35	1970	885	531	17789	12879.2	477	-54	891	371	-160	0	265	-266	0
36	1971	893	536	18325	13267.3	477	-59	832	371	-165	0	265	-271	0
37	1972	595	357	18682	13525.8	477	120	952	371	14	14	265	-92	0
38	1973	1939	1163	19845	14367.8	477	-686	266	371	-792	0	265	-898	0
39	1974	1980	1188	21033	15227.9	477	-711	0	371	-817	0	265	-923	0
40	1975	1630	978	22011	15936.0	477	-501	0	371	-607	0	265	-713	0
41	1976	823	494	22505	16293.6	477	-17	0	371	-123	0	265	-229	0
42	1977	334	200	22705	16438.4	477	277	277	371	171	171	265	65	65
43	1978	992	595	23300	16869.2	477	-118	159	371	-224	0	265	-330	0
44	1979	627	376	23676	17141.4	477	101	260	371	-5	0	265	-111	0
45	1980	281	169	23845	17263.8	477	308	568	371	202	202	265	96	96
	Avg.	883 CFS	530 CFS											

Drainage Area - 959 Square Mile
Mean Annual Flow During the Period of (1936-1980) - 883 CFS
MAF = Mean Annual Flow
Ac-Ft/Yr = Acre Feet per Year
CFS = Cubic Feet per Second - 724 Ac-Ft/Yr

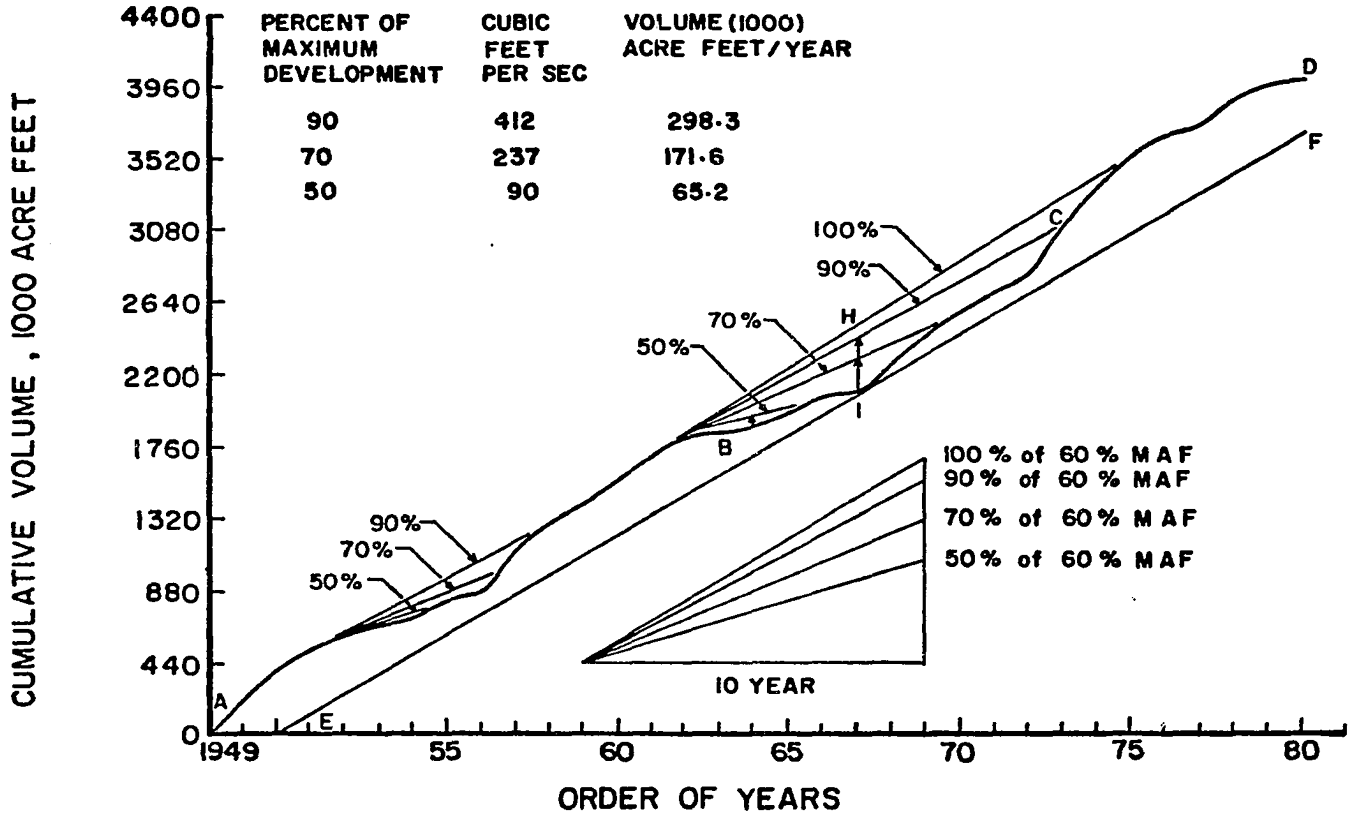

FIGURE 12 Reservoir Capacity for a Specified Yield as Determined by Mass Curve for 1949-81, Barron Fork at Eldon, Oklahoma Station #1970

TABLE 7 - An Analytical Storage Procedure to Accompany Figure 13 on the Barron Fork at Eldon, Oklahoma, Station #1970

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
						90% of Mean Annual Flow			70% of Mean Annual Flow			50% of Mean Annual Flow		
No.	Period of Record	Mean Annual Flow CFS	60% of MAF CFS	Cumulative 60% of MAF	Cumulative Yearly Discharge (1000)	Draft O CFS	Deficiency O-I CFS	Cumulative Deficiency ε(O-I) CFS	Draft O CFS	Deficiency O-I CFS	Cumulative Deficiency ε(O-I) CFS	Draft O CFS	Deficiency O-I CFS	Cumulative Deficiency ε(O-I) CFS
1	1949	469	281	281	203.4	156	-125	0	121	-160	0	87	-194	0
2	1950	453	272	553	400.4	156	-116	0	121	-151	0	87	-185	0
3	1951	249	149	702	508.3	156	7	7	121	-28	0	87	-62	0
4	1952	205	123	825	597.3	156	33	40	121	-2	0	87	-36	0
5	1953	186	112	937	678.4	156	44	84	121	9	9	87	-25	0
6	1954	90	54	991	717.5	156	102	186	121	67	76	87	33	33
7	1955	235	141	1132	819.6	156	15	201	121	-20	56	87	-54	0
8	1956	104	62	1194	864.5	156	94	295	121	59	115	87	25	25
9	1957	624	374	1568	1135.2	156	-218	77	121	-253	0	87	-287	0
10	1958	369	221	1789	1295.2	156	-65	12	121	-100	0	87	-134	0
11	1959	235	141	1930	1397.3	156	15	27	121	-20	0	87	-54	0
12	1960	363	218	2148	1555.1	156	-62	0	121	-97	0	87	-131	0
13	1961	325	195	2343	1696.3	156	-39	0	121	-74	0	87	-108	0
14	1962	283	170	2513	1819.4	156	-14	0	121	-49	0	87	-83	0
15	1963	56	34	2547	1844.0	156	122	122	121	87	87	87	53	53
16	1964	83	50	2597	1880.2	156	106	228	121	71	158	87	37	90
17	1965	197	118	2715	1965.7	156	38	266	121	3	161	87	-31	59
18	1966	205	123	2838	2054.7	156	33	299	121	-2	159	87	-36	23
19	1967	71	43	2881	2085.8	156	113	412	121	78	237	87	44	67
20	1968	373	224	3105	2248.0	156	-68	344	121	-103	134	87	-137	0
21	1969	354	212	3317	2401.5	156	-56	288	121	-91	43	87	-125	0
22	1970	355	213	3530	2555.7	156	-57	231	121	-92	0	87	-126	0
23	1971	342	205	3735	2704.1	156	-49	182	121	-84	0	87	-118	0
24	1972	230	138	3873	2804.1	156	18	200	121	-17	0	87	-51	0
25	1973	639	383	4256	3081.3	156	-227	0	121	-262	0	87	-296	0
26	1974	554	332	4588	3321.7	156	-176	0	121	-211	0	87	-245	0
27	1975	488	293	4881	3533.8	156	-137	0	121	-172	0	87	-206	0
28	1976	286	172	5053	3658.4	156	-16	0	121	-51	0	87	-85	0
29	1977	119	71	5124	3709.8	156	85	85	121	50	50	87	16	16
30	1978	358	215	5339	3865.4	156	-59	26	121	-94	0	87	-128	0
31	1979	226	136	5475	3963.9	156	20	45	121	-15	0	87	-49	0
32	1980	84	50	5525	4000.1	156	106	152	121	71	71	87	37	37
	Avg.	288 CFS	173 CFS											

Drainage Area - 307 Square Mile
Mean Annual Flow During the Period of (1949-1980) - 288 CFS
MAF = Mean Annual Flow
Ac-Ft/Yr = Acre Feet per Year
CFS = Cubic Feet per Second - 724 Ac-Ft/Yr

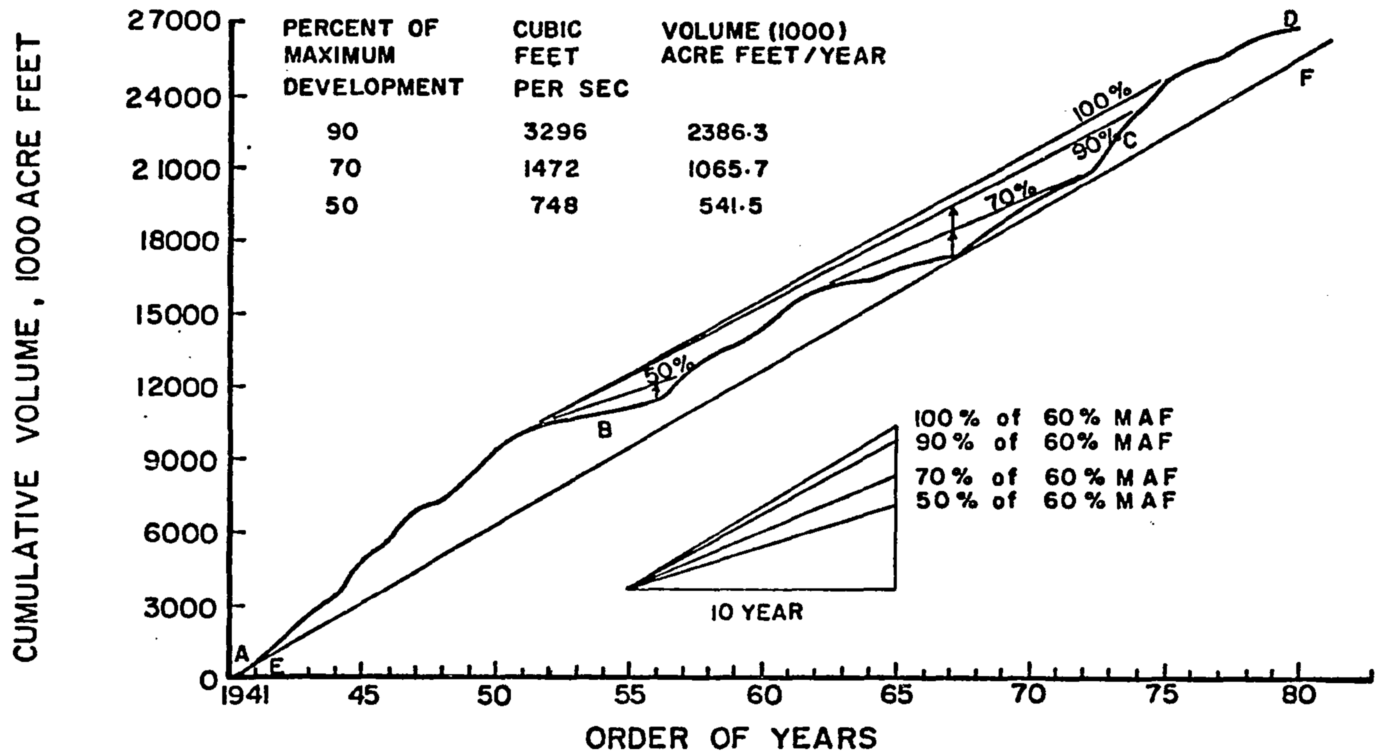

FIGURE 13 Reservoir Capacity for a Specified Yield as Determined by Mass Curve for 1941-80, on the Illinois River, near Gore, Oklahoma Station #1980

TABLE 8 - An Analytical Storage Procedure to Accompany Figure 14 on the Illinois River near Gore, Oklahoma, Station #1980

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
						90% of Mean Annual Flow			70% of Mean Annual Flow			50% of Mean Annual Flow		
No.	Period of Record	Mean Annual Flow CFS	60% of MAF CFS	Cumulative 60% of MAF	Cumulative Yearly Discharge (1000)	Draft O CFS	Deficiency O-I CFS	Cumulative Deficiency ε(O-I) CFS	Draft O CFS	Deficiency O-I CFS	Cumulative Deficiency ε(O-I) CFS	Draft O CFS	Deficiency O-I CFS	Cumulative Deficiency ε(O-I) CFS
1	1941	1352	811	811	581.2	833	22	22	648	-163	0	463	-348	0
2	1942	2144	1286	2099	1519.7	833	-453	0	648	-638	0	463	-823	0
3	1943	2723	1634	3733	2702.7	833	-801	0	648	-986	0	463	-1171	0
4	1944	1507	904	4637	3357.2	833	-71	0	648	-256	0	463	-441	0
5	1945	3654	2192	6829	4944.2	833	-1359	0	648	-1544	0	463	-1729	0
6	1946	1723	1034	7863	5692.8	833	-201	0	648	-386	0	463	-571	0
7	1947	1922	1153	9016	6927.6	833	-320	0	648	-505	0	463	-690	0
8	1948	1772	1063	10079	7297.2	833	-230	0	648	-415	0	463	-600	0
9	1949	2204	1322	11401	8254.3	833	-489	0	648	-674	0	463	-859	0
10	1950	2560	1536	12937	9366.4	833	-703	0	648	-888	0	463	-1073	0
11	1951	1446	868	13805	9994.8	833	-35	0	648	-220	0	463	-405	0
12	1952	1171	703	14508	10503.8	833	130	130	648	-55	0	463	-240	0
13	1953	63	38	14546	10531.3	833	795	925	648	610	610	463	427	427
14	1954	806	484	15030	10881.7	833	349	1274	648	164	774	463	-21	406
15	1955	597	358	15388	11140.9	833	475	1749	648	290	1064	463	105	511
16	1956	376	226	15614	11304.5	833	607	2356	648	422	1486	463	237	748
17	1957	2636	1582	17196	12449.9	833	-749	1607	648	-934	552	463	-1119	0
18	1958	1798	1079	18275	13231.1	833	-246	1361	648	-431	121	463	-616	0
19	1959	1034	620	18895	13679.9	833	213	1574	648	28	149	463	-157	0
20	1960	1926	1156	20051	14516.9	833	-323	1251	648	-508	0	463	693	693
21	1961	1916	1150	21201	15349.5	833	-317	934	648	-502	0	463	-687	6
22	1962	1446	868	22069	15978.0	833	-35	899	648	-220	0	463	-405	0
23	1963	528	317	22386	162[illegible]7.5	833	516	1415	648	331	331	463	146	146
24	1964	280	168	22554	16329.1	833	665	2080	648	480	811	463	295	441
25	1965	980	588	23142	16754.8	833	245	2325	648	60	871	463	-125	316
26	1966	871	523	23665	17133.5	833	310	2635	648	125	996	463	-60	256
27	1967	287	172	23837	17258.0	833	661	3296	648	476	1472	463	291	475
28	1968	1825	1095	24932	18050.8	833	-262	3034	648	-447	1025	463	-632	0
29	1969	1938	1163	26095	18892.8	833	-330	2704	648	-515	510	463	-700	0
30	1970	1413	848	26943	19506.7	833	-15	2689	648	-200	310	463	-385	0
31	1971	1689	1013	27956	20240.1	833	-180	2509	648	-365	0	463	-550	0
32	1972	1064	638	28594	20702.1	833	195	2704	648	10	10	463	-175	0
33	1973	3114	1868	30462	22054.5	833	-1035	1669	648	-1220	0	463	-1405	0
34	1974	2972	1783	32245	23345.4	833	-950	719	648	-1135	0	463	-1320	0
35	1975	2853	1712	33957	24584.9	833	-879	0	648	-1064	0	463	-1249	0
36	1976	1560	936	34893	25262.5	833	-103	0	648	-288	0	463	-473	0
37	1977	490	294	35187	25475.4	833	539	539	648	354	354	463	169	169
38	1978	1571	943	36130	26158.1	833	-110	429	648	-295	59	463	-480	0
39	1979	906	544	36674	26552.0	833	289	718	648	104	163	463	-81	0
40	1980	560	336	37010	26795.2	833	497	1215	648	312	475	463	127	127
	Avg.	1542 CFS	925 CFS											

Drainage Area 1626 Square Mile
Mean Annual Flow During the Period of (1941-1980) - 1542 CFS
MAF = Mean Annual Flow
Ac-Ft/Yr = Acre Feet per Year
CFS = Cubic Feet per Second - 724 Ac-Ft/Yr

K. Developed Water Projects

There are two developed reservoirs on the main stem of the Illinois River. Lake Francis is a small reservoir just inside the Oklahoma-Arkansas stateline. This provides the water supply for Siloam Springs, Arkansas. Tenkiller Ferry Reservoir near Gore, Oklahoma was completed by the Corps of Engineers in 1953. It was designed to develop a water supply of 22330 acre/feet per year, specific developments are tabulated in Table 9.

Table 9 - Developed Storage of the Illinois River Basin

Oklahoma	Total Storage Ac-Ft	Flood Control Ac-Ft	Water Supply Ac-Ft	Water Yield Ac-Ft	Surface Area Acres	Drainage Area Sq. Mile	Use*	Owner
Tenkiller Ferry Reservoir	1,230,800	576,700	22330	17900	12,900	1610	F.C. H.P. W.S.	Corp. of Engin.
Lake Francis	1,930	-----	1930	1930	630	609		

* W.S.: Water Supply
F.C.: Flood Control
H.P.: Hydro-Power

Source (2)(39)

L. Potential Reservoir Sites

The following potential reservoir sites on the Illinois River Basin could be developed (See Table 10 for storage necessary to sustain 50%, 70%, and 90% of the 60% mean annual flow for these sites).

1) Watts Dam Site is located on the Illinois River near gage station number 1955.

2) Flint Creek Dam Site is located on Flint Creek near gage station number 1960.

3) Tahlequah Dam Site is located on the Illinois River near gage station number 1965.

4) Barren Fork Dam Site is located on Barren Creek near gage station number 1970.

5) Gore Dam Site is located on the Illinois River near gage station number 1980.

M. Summary of the Case Study on the Illinois River Basin

The estimated runoff from the Illinois River Basin of 1660 square miles has an average of 1,140,000 acre-feet per year (Ac-Ft/Yr) during the water years 1941 - 1980 inclusive, equivalent to an average annual runoff of 12.8 inches. About 53% of the stream flow is contributed from drainage in Oklahoma, where an average of 604,200 (Ac-Ft/Yr) runoff from 905 square miles, is 54% of the total drainage area.

High runoff may occur during any month in the year, but in general, the streamflow is the lowest in the summer. Records show that there is flow throughout the year in the Illinois River and its principal tributaries, Flint Creek and Barren Fork.

The surface waters of the Illinois River Basin are of excellent quality, being suitable for municipal, agricultural and most industrial uses. The Oklahoma State Department of Health investigations reveal that the average concentration of the dissolved mineral content is about 105 part per million (PPM) and the hardness about 88 (PPM). The water is slightly alkaline, having an average of PH valued from 7.2 - 8.0.

The stream flow is highly variable. Forty-five years of records for the Illinois River near Gore, Oklahoma, show that the runoff varied from a high in 1945 of 3654 cubic feet per second (CFS) to a low in 1953 of 63

(CFS) for a 58 to 1 ratio. This high variability in streamflow in this region requires the development of storage by impoundment, if maximum utilization of the available water supplies is to be attained. To maintain the flow at 463, 648, and 833 CFS (the 50%, 70%, and 90% of 60% mean annual flow respectively), during 45 years base period, an impoundment at the site would have required a useable storage of 541,500, 1,065,700, and 2,386,300 acre-feet per year respectively.

This same method of evaluation of storage requirement is applicable to the remaining four gaging stations. Summary of analytical procedure of mass curve for storage requirements to sustain 50%, 70%, and 90% of 60% of the mean annual flow on the Illinois River and its tributaries is shown in Table 10.

TABLE 10- Summary of Analytical Procedure of Mass Curves for Storage Requirements to Sustain 50%, 70%, and 90% of 60% of the MAF on the Illinois River and its Tributaries

No.	SITES	Station No.	Year of Record	Base Period	Drainage Area Sq. Mile	Average Discharge (MAF) CFS	60% of Average Discharge (MAF) CFS	60% of Average Discharge (MAF) Ac-Ft/Yr	Storage Necessary to Sustain 90% of (60% of MAF) Ac-Ft/Yr	Ratio of Storage Volume 60% of MAF	Storage Necessary to Sustain 70% of (60% of MAF) Ac-Ft/Yr	Ratio of Storage Volume 60% of MAF	Storage Necessary to Sustain 50% of (60% of MAF) Ac-Ft/Yr	Ratio of Storage Volume 60% of MAF	Existing Water Supply Reservoirs Ac-Ft/Yr	% of Control of 60% MAF
1	Illinois River Watts, OK	1955	26	1956-81	635	564	338	244,712	543,700	2.22	301,200	1.23	80,400	0.33	1930	0.8%
2	Flint Creek Kansas, OK	1960	13	1964-76	110	133	80	57,920	121,600	2.09	72.400	1.25	26,100	0.45	---	---
3	Illinois River Tahlequah, OK	1965	45	1936-80	959	883	530	383,720	975,200	2.54	497,400	1,29	151,300	0.93	---	---
4	Barron Fork at Eldon, OK	1970	32	1949-80	307	288	173	125,252	298,300	2.38	171,600	1.37	65,200	9.52	---	---
5	Illinois River Gore, OK	1980	40	1941-80	1626	1542	925	669,700	2,386,300	3.56	1,065,700	1.59	541,500	0.80	22,330	0.3%
6	Illinois River at Mouth*	---	--	----	1660	1574	944	683,455	2,434,026	3.56	1,087,014	1.59	552,330	1.80	---	---

* Estimated base on runoff at station, 8½ miles upstream (Station No. 1980)
Ac-Ft/Yr = Acre Feet per Year
CFS = Cubic Feet per Second - 724 Ac-Ft/Yr
Illinois River at Mouth Ratio = 1660/1626 = 1.021
Columns 6,7,8,9,11 and 13 computed base on Tables 10,11,12,13, and 14

V. Generalized Storage Values for Oklahoma River Basins

A) Statistical Parameters

One of the main objectives of this chapter is to discuss briefly the characteristics of a statistical distribution which may be described by statistical parameters. Only these which have been applied in surface water reservoirs computation for Oklahoma River Basins, are defined below:

The Coefficient of Variation (CV):

$$CV = \frac{\delta}{\mu} \cong \frac{S}{x} \quad (1)$$

and its magnitude conveys important information. For example, it is known that the Coefficeint of Variation of annual flows for a large number of streams in Oklahoma lies in the range 0.44 for the well water regions (Little River in South East of Oklahoma) to 0.84 fo the arid regions (Salt Fork in North Central Oklahoma). They mean that a deficiency as great as 84 percent of the mean annual flow is expected to occur in the Salt Fork region as often as a deficiency of only 44 percent to mean annual flow in the south east ones. High values of CV, therefore, signify reduce maintainable draft or increased storage requirements. Thus certain general conclusions about the hydrologic regimen of a stream can be drawn simply by noting its CV value. One can describe a stream as flasy, stable, etc. by examining only two parameters; arithmetic mean and standard deviation.

B) Application of Coefficient of Variation for Oklahoma Storage Computation

For ordinary purposes, mean annual flow and Coefficient of Variation, will indicate the comparative safe yields of water supplies that are developed with and without storage. Draft is then best expressed for comparative purposes in terms of the mean annual rainfall or runoff, whatever the basis of measurement happens to be (33). Hazen[1] has shown that it is possible by an analysis of country-wide information to generalize regional storage requirements. This is accomplished by the mean annual flow of streams and their coefficients of variation. A summary of Hazen's generalized storage coefficient of variation lies in range 0.2 to 0.45 for east and 0.5 to 1.5 for west of the Mississippi River. These are illustrated in Tables 11 and 12. To develop Table 11 and 12, calculate mean annual flow in any convenient units, and coefficient of variation, then compute the storage requirement by using mass curve technique. The storage coefficient is the storage required divided by the mean annual flow.

The coefficient of variation of annual flows should be calculated for each record of ten years and over that is to be used. For streams having coefficients of variations under 0.5, use Table 11, Table 12 is for streams having coefficients of variation above 0.5

The results obtained from this study differ by 5 percent or less from the results shown on these tables (see appendix F); for this reason,

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[1]Allen, Hazen, <u>American Civil Engineers Handbook</u>, John Wiley and Sons, New York, N. Y., 1930.

it is appropriate to apply these tables to the computation involving the 14 Oklahoma River Basins to evaluate storage required to produce selected dependable flows. Figure 14 shows 14 River Basins in Oklahoma and also Table 13 reveals historical records as a stream annual flow, standard deviation, and the Coefficient of Variation for each river basin in Oklahoma. Table 14 shows the maximum, mean, minimum annual flows of drainage area of Oklahoma River Basins Existing or under construction reservoirs capacities are shown in Appendix F and storage required to produce selected dependable flow is shown in Table 15. Both draft and mean annual flow are expressed in terms of acre-feet per year (AC-Ft/Yr.).

Table 11 Generalized Storage Valves for Streams East of the Mississippi River

Storage for Stated Valves of CV

Draft	0.20	0.25	0.30	.035	0.40	0.45
.90	0.85	1.05	1.13	1.60	1.88	2.20
.80	0.54	0.64	0.78	0.97	1.19	1.39
.70	0.39	0.43	0.50	0.62	0.76	0.92
.60	0.31	0.32	0.34	0.40	0.49	0.60
.50	0.23	0.23	0.24	0.26	0.32	0.39

Source: Reference (45)(47)

Table 12 Generalized Storage Values for Stream West of the Mississippi River

Storage for Stated Values of CV

Percent mean flow	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.5
90	3.0	3.8	4.7	5.6	6.4	-	-	-	-
80	1.85	2.4	3.1	3.7	4.4	5.1	5.9	6.7	9.3
70	1.28	1.7	2.2	2.7	3.2	3.8	5.0	5.7	7.2
60	.89	1.2	1.6	2.0	2.5	3.0	4.4	4.0	6.0
50	.61	.86	1.15	1.5	1.9	2.35	2.8	3.25	5.0
40	.42	.61	.84	1.12	1.45	1.8	2.15	2.5	3.8
30	.27	.42	.61	.8	1.0	1.24	1.5	1.8	2.75

Source: See Reference (46)(47)

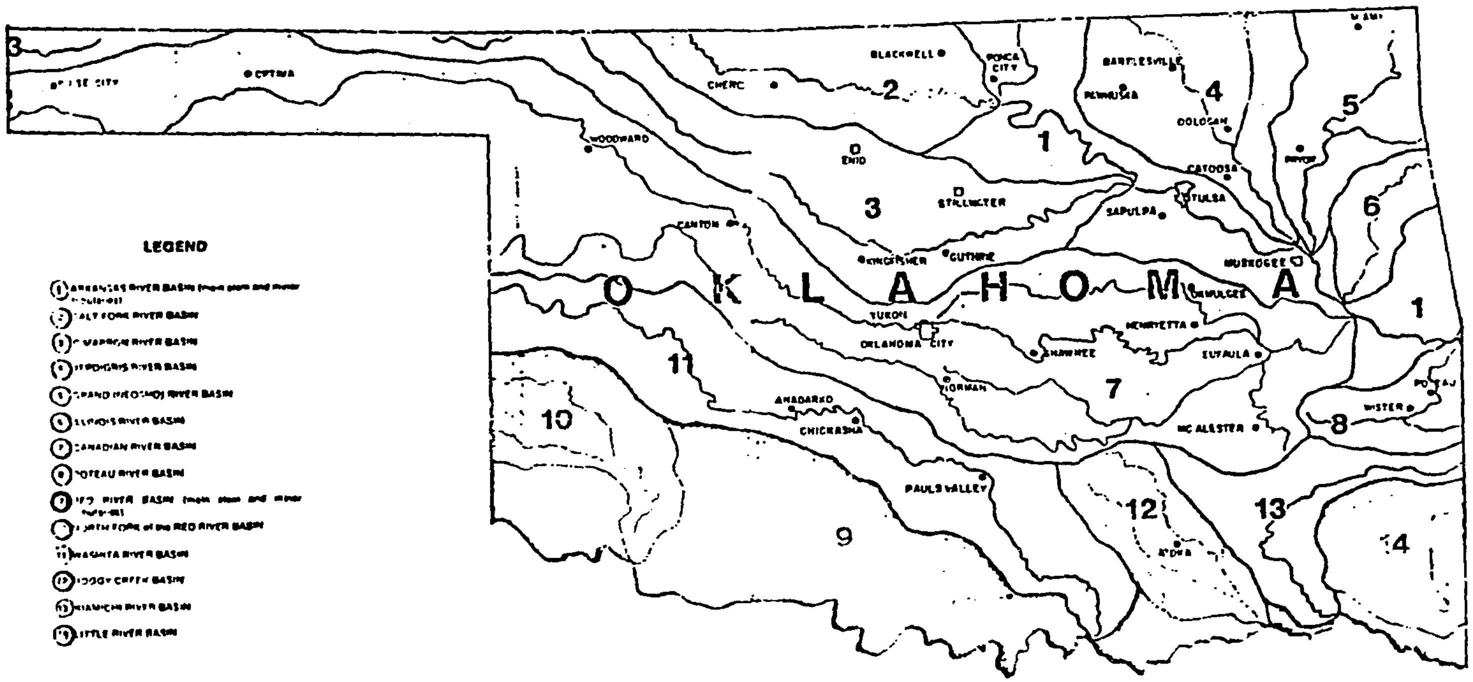

FIGURE 14 - Map of River Basins in Oklahoma

See Source 48

TABLE 13 - Historical Data and Evaluation of the Mean, Standard Deviation, and Coefficient of Variation of the 14 Oklahoma River Basins

Number	Year	07,151,000 Salt Fork M.A.F. C.F.S.	07,161,000 Cimarron River M.A.F. C.F.S.	07,178,620 Verdegris River M.A.F. C.F.S.	07,193,500 Neosho River M.A.F. C.F.S.	07,198,000 Illinois River M.A.F. C.F.S.	07,245,000 Canadian River M.A.F. C.F.S.	07,248,500 Poteau River M.A.F. C.F.S.	07,305,000 North Fork Red River M.A.F. C.F.S.	07,331,000 Washita River M.A.F. C.F.S.	07,334,000 Muddy Boggy Creek M.A.F. C.F.S.	07,335,000 Clear Boggy Creek M.A.F. C.F.S.	07,336,200 Kiamichi River M.A.F. C.F.S.	07,340,000 Little River M.A.F. C.F.S.	07,250,550 Arkansas River M.A.F. C.F.S.	07,337,000 Red River (Index) M.A.F. C.F.S.
1	1936	218	---	---	---	---	---	---	---	1163	---	---	---	1533	11770	---
2	1937	428	---	---	---	---	---	---	---	766	---	---	---	3908	24350	10020
3	1938	979	---	---	---	---	---	---	243	1714	1347	---	---	5618	32580	17630
4	1939	243	---	---	---	---	1769	895	200	391	162	---	---	2983	10600	4839
5	1940	956	307	---	---	504	1629	269	322	697	563	---	---	2696	7523	6797
6	1941	315	1255	---	---	1352	7896	813	862	1967	793	---	---	3449	31800	18910
7	1942	1087	2603	---	---	2144	14210	1322	811	3887	1840	---	---	3534	65250	23560
8	1943	396	882	---	---	2723	7439	1146	342	2282	693	403	---	1868	50480	11970
9	1944	648	1111	---	---	1507	3498	1233	241	952	694	379	---	4175	33520	7060
10	1945	1146	1509	7694	---	3654	13100	3168	278	3520	2758	1668	---	7501	62940	25310
11	1946	333	521	4039	---	1723	6884	1570	704	2368	970	614	---	5194	33790	16270
12	1947	865	1482	4498	---	1922	9007	1650	522	2539	1390	741	---	4459	38660	18120
13	1948	761	822	5102	---	1772	6402	1046	104	1065	640	485	---	3855	34910	9870
14	1949	2340	2317	5710	---	2204	7985	1460	314	1723	729	375	---	4476	45180	11100
15	1950	565	1453	4235	---	2560	9764	1618	359	1933	1397	799	---	7400	41620	19090
16	1951	1795	1986	6493	14100	1446	4595	861	681	1794	648	278	---	3656	45960	13240
17	1952	524	454	3640	7489	1171	2620	1101	683	629	405	196	---	4052	26750	7256
18	1953	103	235	804	1928	626	3264	1471	117	518	987	388	---	4932	12940	8787
19	1954	955	305	875	1158	806	2972	427	140	1258	612	302	---	1893	8474	8054
20	1955	282	1349	1208	2890	597	2601	687	165	878	522	206	---	3282	12840	7720
21	1956	156	543	297	1547	376	980	200	286	440	142	544	---	1599	5965	5708
22	1957	1857	3450	7305	11500	2636	11560	2055	580	3487	2091	1189	---	6080	55130	24800
23	1958	603	950	3898	8611	1798	6186	1438	938	934	1020	507	---	4339	35450	15150
24	1959	423	695	3175	4279	1034	4177	539	313	640	510	187	---	2507	21750	5489
25	1960	1349	2705	6764	10350	1926	10370	1611	418	1593	1097	525	---	3962	52060	11780
26	1961	929	1449	9387	13340	1916	4360	947	590	1135	493	275	---	3837	43610	10190
27	1962	716	1345	5565	8608	1445	4691	984	399	1345	688	368	---	3379	34080	10930
28	1963	277	929	1244	3755	528	1963	335	140	629	470	266	---	1747	13000	6970
29	1964	137	426	855	2257	280	976	327	688	340	319	165	---	1946	7737	4383
30	1965	847	981	4265	6192	980	1450	985	241	818	392	225	---	3024	23750	6788
31	1966	150	371	788	3471	871	1728	576	203	501	445	196	---	2080	12910	7370
32	1967	157	514	1965	3805	287	1196	589	112	436	610	376	---	2421	12510	7515
33	1968	278	550	3750	9214	1825	6458	1943	234	1161	1376	812	---	6719	33650	16530
34	1969	826	1055	7041	11290	1938	6604	1660	377	1521	1208	672	---	3623	43080	16360
35	1970	556	395	4943	7695	1413	3570	821	50	622	819	496	---	3232	27220	9147
36	1971	192	294	---	6180	1689	4330	775	111	737	772	398	---	2317	19970	5405
37	1972	234	438	---	4985	1064	3776	942	162	478	573	347	---	3080	19740	8445
38	1973	1691	2039	---	20410	3114	10170	2087	366	2308	1932	1189	2673	7523	70640	20080
39	1974	1810	2306	---	18120	2972	7468	1576	222	1976	1663	740	2545	5436	64420	15110
40	1975	1787	3605	---	15350	2853	10630	1776	422	3045	1334	784	1939	6043	64740	19640
41	1976	316	551	---	6903	1560	3089	513	203	203	597	321	748	1547	20650	6207
42	1977	323	721	---	5070	490	1666	671	646	646	623	392	965	3065	17330	9602
43	1978	354	525	---	9822	1571	2522	454	322	915	525	298	606	1671	27020	5320
44	1979	569	886	---	6790	906	3499	1907	130	1031	728	382	1977	5161	24340	10300
45	1980	861	1658	---	4450	560	2641	---	214	887	175	106	611	2576	19570	5089
46	1981	286	---	---	1948	---	1012	---	---	---	---	---	---	3181	7737	6651
Ave. at Gage		672	1170	4059	7533	1517	5163	1133	289	1352	878	476	1508	3751	30652	11479
Ave. at Mouth		973	1240	4262	7548	1548	5179	2154	329	1491	1180	640	2425	3196	30529*	11364**
δ		568	714	2520	4948	868	3589	623	205	898	557	331	873	1643	17976	5793
CV=δ/M.A.F.		0.58	0.60	0.60	0.66	0.56	0.70	0.3	0.62	0.60	0.50		0.36	0.52	0.59	0.50

M.A.F. = Mean Annual Flow CPS = Cubic Feet/Second

*Arkansas River 30,529 * 724 = 22,102,996 Acre--Feet/Year

**Red River 11,364 * 724 = 8,227,536 Acre--Feet/Year

Total Surface Water Leaving the State = 22,102,996 + 8,228,536 = 30,330,352 Acre-Feet/Year

Source: Adapted from 46 years The United States Geological Survey Computer Print Out Record

TABLE 14 - Maximum, Mean, and Minimum Annual Flows of Drainage Area of Oklahoma River Basins

O Z	River Basin	Drainage Area at mouth (sq. miles)	Gage Nearest Mouth (Name No.)	Drainage Area at Gage (sq. miles)	Year of Record (year)	Mean Annual Flow At Gage C.F.S.	Drainage Area Ratio	Mean Annual Flow at Mouth C.F.S.	Year of Maximum Discharge	Maximum Discharge C.F.S.	Minimum Discharge C.F.S.	Year of Mimimum Discharge
1	Salt Fork Arkansas Rv. No. 2	6,558	Tonkawa 07151000	4,528	46	672	1.448	973	1974	57800	0	1956
2	Cimarron River	18,927	Perkins 07161000	17,852	41	1,170	1.060	1,240	1975	93200	0.9	1955
3	Verdigris Rv. No. 4	8,303	Inola 07178620	7,911	26	4,059	1.050	4,262	1961	114000	6.2	1957
4	Grand Rv. No. 5	12,520	Ft. Gibson 07193500	12,495	31	7,533	1.002	7,548	1951	132000	0	1972
5	Illinois Rv. No. 6	1,660	Gore 07198000	1,626	41	1,517	1.021	1,574	1950	147000	2.1	1959
6	Canadian Rv. No. 7	47,705	Whitefield 07245000	47,576	43	5,163	1.003	5,179	1943	239000	0.4	1957
7	Poteau Rv. No. 8	1,888	Wister 07248500	993	41	1,133	1.901	2,154	1939	70000	0	1939,40 43,54,55,64
8	North Fork Red River	4,828	Headrick 07305000	4,828	43	289	1.138	329	1956	25700	0	21 Years out of 43 year record
9	Washita Rv. No. 11	7,945	Durwood 07331000	7,202	45	1,352	1.103	1,491	1957	87800	0	56,57
10	Boggy Creek No. 12	2,429	Caney 07335000 Farris 07334000	720 1,089 1,807	38 43	476 878 1,354	1.344	640 1180	1943 1938	35700 46900	0 0	5 yrs. of 38 yrs, 16 yrs of 43 yrs
11	Kiamichi Rv. No. 13	1,830	Antlers 07336200	1,138	8	1,508	1.608	2,425	1977	49200	0	73,78,80
12	Little Rv. No. 14	2,267	Horatio 07340000	2,662	46	3,751	0.852	3,196	1945	112000	2	1936
13	Arkansas Rv.	149,977	Van Burn 07250550	150,547	46	8,644	0.996	7,623*	1943	784000	0	1976
14	Red Rv.	47,555	Index, Ak. 07337000	48,030	45	2,356	0.990	2,102*	1938	28600	0	1956

Source: Adapted from Raw Data Compiled by the United States Army Corps of Engineers and the United States Geological Survey

M.A.F. = Mean Annual Flow
CPS = Cubic Feet Per Second

*
**See Appendix C

TABLE 15 - Storage Required to Produce Selected Dependable Flows in the Oklahoma River Basins

No.	River Basin	Drainage Area at mouth (sq. miles)	Gage Nearest Mouth (Name No.)	Drainage Area at Gage (sq. miles)	Year of Record (Year)	Mean Annual Flow at Gage C.F.S.	Drainage Area Ratio	60% Mean Annual Flow at Mouth C.F.S.	60% Mean Annual Flow at Mouth C.F.S.	60% of Mean Annual Flow at Mouth Acre-Feet/Yr.	Standard Diviation σ C.F.S.	Coeff. of vari. $CV = \frac{\sigma}{M.A.F.}$	90% of (60% of M.A.F.) Coeff. of M.A.F.	90% of (60% of M.A.F.) Storage Required Acre ft/yr	70% of (60% of M.A.F.) Coeff. of M.A.F.	70% of (60% of M.A.F.) Storage Required Acre ft/yr	50% of (60% of M.A.F.) Coeff. of M.A.F.	50% of (60% of M.A.F.) Storage Required Acre Ft/yr	Existing Water Supply Reservoirs Acre-ft/yr	% of Control of M.A.F. by Exist. Reservoir
1	Salt Fork Arkansas River No. 2	6,558	Tonkawa 07151000	4,528	46	672	1.448	973	584	422,816	568	0.58	3.64	1,539,050	1.31	553,890	0.61	342,481	0	0
2	Cimarron River No. 3	18,927	Perkins 07161000	17,852	41	1,170	1.060	1,240	744	538,656	716	0.60	3.8	2,046,813	1.9	1,023,446	.56	301,647	190,000	35%
3	Verdigris River No. 4	8,303	Inola 07178620	7,911	26	4,059	1.050	4,262	2558	1,851,992	2520	0.60	3.8	7,037,570	1.7	3,148,390	0.86	1,592,713	766,300	41%
4	Grand River No. 5	12,520	Ft. Gibson 07193500	12,495	31	7,535	1.002	7,548	4529	3,278,996	4948	0.66	4.3	14,099,694	2.0	6,557,990	1.03	3,377,366	110,200	3%
5	Illinois River No. 6	1,640	Gore 07198000	1,626	41	1,517	1.021	1,574	944	683,455	868	0.56	3.55	2,426,264	1.58	1,078,859	0.79	539,929	25,400	37%
6	Canadian River No. 7	47,705	Whitefield 07245000	47,576	43	5,163	1.005	5,179	3108	2,250,192	3589	0.70	4.7	10,575,909	2.2	4,950,420	1.15	2,587,721	598,880	27%
7	Poteau River No. 8	1,888	Wister 07248500	993	41	1,133	1.901	2,154	1293	936,132	623	0.30	1.13	1,057,830	0.5	468,066	0.24	264,672	9,600	1%
8	North Fork Red River No. 10	4,828	Hendrick 07305000	4,244	43	289	1.138	329	198	143,352	205	0.62	3.98	570,540	1.8	258,033	0.92	131,884	234,160	163%
9	Washita River No. 11	7,965	Durwood 07331000	7,202	45	1,352	1.103	1,491	895	647,980	898	0.60	3.8	2,462,320	1.7	1,101,570	0.86	557,263	344,650	53%
10	Boggy Creek No. 12	2,429	Canyey 07335000 Farris 07334000	720 1,087 1,807	38 43	476 878 1,354	1.344	640 1,180	1092	790,608	331 557	0.50	3.0	2,371,820	1.28	1,011,980	0.61	482,271	233,300	30%
11	Kiamichi River No. 13	1,830	Antlers 07336200	2,138	8	1,308	1.608	2,625	1455	1,053,420	873	0.36	1.66	1,748,680	0.65	684,720	0.27	284,423	418,700	40%
12	Little River No. 14	2,269	Horatio 07340000	2,662	46	3,751	0.852	3,196	1918	1,388,632	1643	0.52	3.16	4,388,080	1.36	1,888,540	0.66	916,497	223,000	16%
13	Arkansas River	149,977	Van Buren 07250550	150,547	46	8,644	0.996	7,623	4574	3,311,576	17976	0.59	3.72	12,319,110	1.66	5,497,240	0.64	2,119,409	389,300	11%
14	Red River	47,555	Index Arkansas 07337000	48,030	45	2,356	0.990	2,102	1262	913,688	5793	0.50	3.0	2,741,060	1.28	1,169,520	0.61	557,350	325,000	34%

M.A.F. = Mean Annual Flow
CV = Coefficient of Variation
σ = Standard Deviation
C.F.S. = 724 Acre-Feet/Year
AC-Ft./Yr. = Acre-Feet Per Year

Adapted from tables 17,18

C) Total Costs of the Surface Reservoirs

The costs of storage vary in accordance with such non-engineering factors as the price of land; the costs of relocating people, capital facilities; and with such engineering factors' as the character of the site, capacity of the area behind the dam, and technology of dam construction. Preliminary investigation of histroical data revealed no clearly established trend over time in costs per unit of capacity. As Chow points out "Forces contributing to a secular increase in unit cost growing out of exhaustion of superior sites or necessity for utilizing more expensive land were either concealed by inadequacies of accounting techniques or were offset by decline in cost resulting from technological advances in dam construction." (34) Variability in unit costs among reservoirs could be clearly determined as a result of differences in capacity of the reservoir and differences in the physiography of sites.

Costs of storage were estimated by the United States Army Corps of Engineers based on 1959 prices. These costs have been adjusted from 1959 to 1980 prices, by the use of the Engineering News-Record Construction Cost Index and Bridge Engineering Section of Oklahoma Highway Transportation Department file record. By using the data from Table 15, cost curve was constructed showing the costs per acre-foot of storage capacity to the different size of reservoirs. This curve is shown in Figure 15.

The effects of combining the median of existing reservoir capacity for each river basin (See Appendix E), the date of Table 15 and Figure 15 are given in Table 17. This table shows the estimated number of reservoirs necessary to sustain a selected percentage of mean annual flow, and their relative estimated costs per acre feet by reservoir size for each river basin in this state.

For some of the river basins like Canadian River, Grand River, and Washita River, we may reduce the estimated number of reservoirs by constructing larger ones. This would reduce the reservoir construction costs.

Table 16

Costs of Storage Per Acre-foot by Size Class of Reservoir Based on 1959 Price and Adjusted to 1980 Price (65)(70)(71).

0 Z	Class Size Acre-Feet	Price per Acre-Feet Based on 1959 Price Dollars	Price per Acre-Feet Adjusted to 1980 Price Dollars
1	10,000	120	487
2	30,000	86	349
3	50,000	73	296
4	80,000	62	252
5	150,000	50	203
6	300,000	40	162
7	700,000	30	122
8	1,500,000	24	97
9	3,000,000	18	73
10	7,000,000	14	57
11	30,000,000	10	41

See Appendix B for more detail)
(Trend - price 1980/price 1959 = 302/74.45 - 4.06

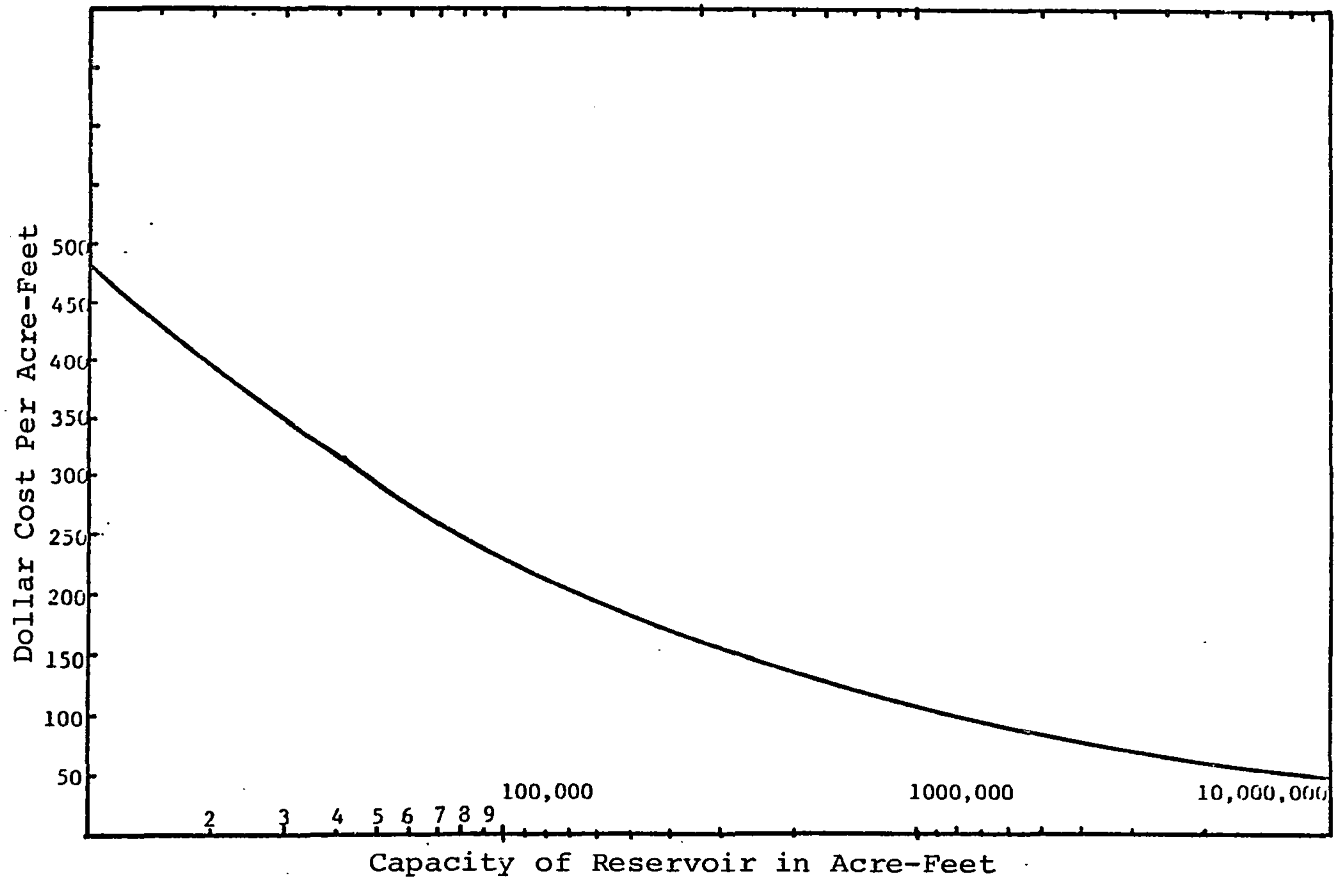

FIGURE 15 Curve Showing Average Cost of Reservoirs for Water Storage Constructed by the Corps of Engineers Based on 1980 Prices

TABLE 17 - Reservoir Storage and Related Cost Estimate Per Acre-Foot (AC-Ft) for Oklahoma River Basins

No:	Oklahoma River Basin	90% of (60% of M.A.F.) Storage Required AC-Ft/Yr	Net Storage Required AC-Ft/Yr	Median of Existing Reservoir Capacity AGFT/Yr	No. of time Reservoir may be builded	Estimated dollar cost per AC-Ft	70% of (60% of M.A.F.) Storage Required AC-Ft/Yr	Net Storage Required AC-Ft/Yr	Median of Existing Reservoir Capacity AC-Ft/Yr	No. of times Reservoir may be builded	Estimated Dollars cost AC-FT	50% of (60% of M.A.F.) Storage Required AC-Ft/Yr	Net Storage Required AC-Ft/Yr	Median of Existing Reservoir Capacity AC-Ft/Yr	No. of times Reservoir may be builded	Estimated dollar cost per AC-Ft
1	Salt Fork (Arkansas Rv.)	1,539,050	1,539,050	240,000	6	170	553,890	553,890	250,000	2	170	342,481	342,481	240,000	1	170
2	Cimarron Rv.	2,046,893	1,856,893	95,000	19	230	1,023,446	833,446	95,000	9	230	301,647	111,647	95,000	1	230
3	Verdegris Rv.	7,037,570	6,271,270	221,100	28	175	3,148,390	2,382,090	221,100	14	175	1,592,713	826,413	221,100	4	175
4	Grand Rv.	14,099,690	13,989,490	244,200	(57)*	170	6,557,990	6,447,790	244,200	(26)*	170	3,377,366	3,267,166	244,200	(13)*	170
5	Illinois Rv.	2,426,265	2,400,865	576,700	4	125	1,079,859	1,054,459	576,700	2	125	539,929	514,529	576,700	1	130
6	Canadian Rv.	10,575,900	9,977,020	81,700	(122)*	240	4,950,420	4,351,540	81,700	(53)*	240	2,587,721	1,988,841	81,700	(24)*	240
7	Poteau Rv.	1,057,830	1,048,230	400,000	3	140	468,066	458,466	400,000	1	140	224,672	215,072	400,000	1	170
8	North Fork (Red Rv.)	570,540	336,380	117,080	3	215	258,033	23,873	117,080	1	370	131,884	0	117,080	0	---
9	Washita Rv.	2,462,320	2,117,670	62,600	(34)*	270	1,101,570	756,920	62,600	(12)*	270	557,263	212,613	62,600	3	270
10	Boggy Creek	2,371,820	2,138,520	116,650	18	220	1,011,980	778,680	116,650	7	220	482,271	248,971	116,650	2	220
11	Kiamichi Rv.	1,748,680	1,329,980	468,650	3	135	684,720	266,020	468,650	1	170	284,423	0	45,850	0	---
12	Little Rv.	4,388,080	4,165,080	419,050	10	140	1,888,540	1,665,540	419,050	4	140	916,497	693,497	419,050	2	140
13	Arkansas Rv. (Main Steam)	12,319,110	11,929,810	457,200	26	135	5,497,240	5,107,940	457,200	11	135	2,119,409	1,730,109	457,200	4	135
14	Red River	2,741,060	2,416,060	1,400,540	2	110	1,169,520	844,520	1,400,540	1	110	557,350	232,350	1,400,540	1	175

*For some of the river basins like Canadian River, Grand River, and Washita River, we may reduce the estimated number of reservoirs by constructing larger ones. This would reduce the reservoir construction costs.

VI Ground Water Resources and Development in Oklahoma

Oklahoma has tremendous resources of fresh underground water. The exact amount in storage is unknown but it is estimated by the United States Geological Survey to be more than 300 million acre-feet above a depth of 2,000 feet, or more than 77.5 times the amount of water stored as water suppply in all surface reservoirs and lakes of the state and more then 9.9 times the average annual flow of all the streams draining in the state. If spread evenly on the surface, it would cover the entire state to a depth of more than 7 feet. The rate of replenshment is very rapid in some places, such as in the limestones of the Ozark and Arbuckle Mountains in the eastern portion of the state; but in others such as in the High Plains, it is very slow. In the past municipalities, industries, and irrigators, as well as rural inhabitants, have generally turned to this resource to satisfy their demands because of (50)(51)(57):

1) The widespread geographical occurence of aquifers.
2) The absence of sufficient surface water supplies or lack of facilities for storing and distributing available supplies.
3) The economic incentive i.e. the relative low costs of developing and pumping this resource in some areas as compared to the costs of construction of storage and treatment facilities for surface water supplies.

In projecting future water requirements in Oklahoma and evaluating sources of supply for future demands, there are, however, several major constraints on ground water as a firm, long range supply (52)(53).

a) Lack of adequate quantitative information on the maximum safe yield and recharge potentials of aquifers has handicapped the development of effective management programs for many important aquifers.

b) Ground water quality is threatened by the discharge of wastes, by increasing in mineralization as a result of recycling of irrigation return flows and seepage losses, and saline water intrusion caused by modification through pumping of the natural hydro dynamics of aquifiers.

Without properly planned and positive management programs, aquifers maybe over-developed or improperly developed, resulting in possible general economic decline and losses of business, premature depletion of supplies locally, and loss of capital investments, in wells, pumps and distribution facilities.

Ground water will, however, continue to constitute an important part of the total future water supply of Oklahoma. Proper management of aquifers and optimum conjunctive use of ground and surface water resources is essential. Figure 16 shows the major ground water aquifers throughout Oklahoma.

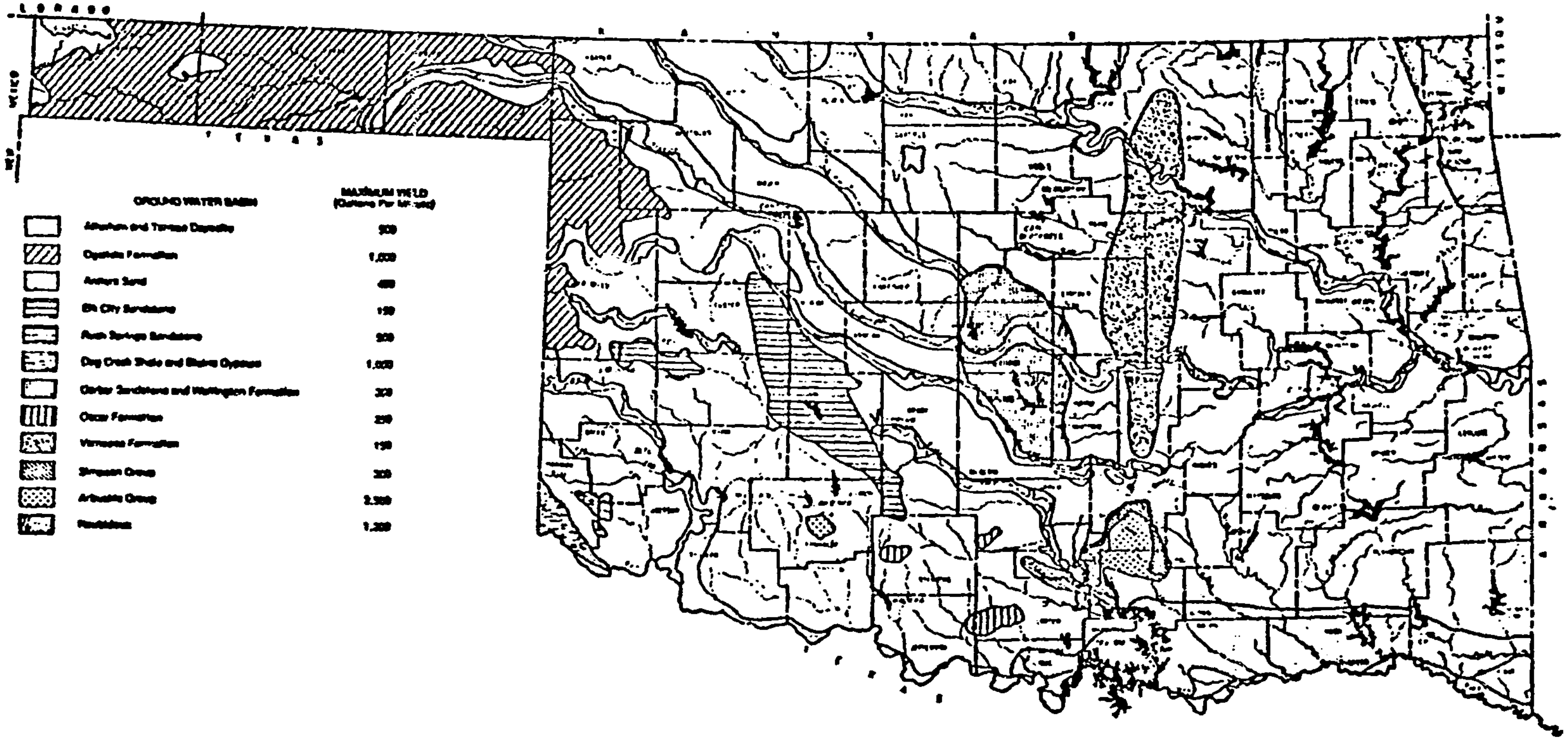

FIGURE 16 Map of Ground Water Basin in Oklahoma

Source: See Reference 9

A. SAFE YIELD OF THE GROUND WATER

Estimating ground water resources is accompanied with even greater uncertainty than estimating surface water safe yields, because the ground water portion of the hydrologic cycle is more complex, less well understood, and not visible to the observer. The term "safe yield" of an underground reservoir was first introduced in 1932 by O.E. Meinzer who defined it as "...The practicable rate of withdrawing water from it (the aquifer) perenially for human use." 63 Todd defined safe yield as "...The amount of water which can be withdrawn from (the ground water basin) annually without producing an undesired result." 55 For a particular basin, the amount of discharge must be balanced by a comparable amount of recharge over a period of time, less any change in storage. This balance can be expressed quantitatively by an equation of hydrological equilibrium. Thus the calculation of safe yield involved the collection of data on: (52)

1) Surface inflow and outflow
2) Water imports and exports
3) Precipitation
4) Consumptive use (processes of evapotranspiration)
5) Changes in ground and surface water storage and
6) Subsurface inflow and outflow

Many of these items are difficult to measure. Subsurface inflow and outflow discharges cannot be directly gaged, and ground water storage changes require detailed information about the existence of ground water in the basin. Adequately measuring groundwater storage would thus require the delineation of an aquifer and an analysis of all well logs.

The concept of safe yield has come under criticism, partly because it is often misinterpreted, implying a fixed underground water supply. Indeed, the United States Geological survey does not even include the term "safe yield" in its 1972 list of revised definations of ground-water terms (64).

Subject to the foregoing criticisms, it would still be helpful to have some estimate of the magnitude of a ground water resource. In the absence of a detailed and specific well log and aquifer data, one approximation of the long term yield of an area can be obtained by a consideration of the underlying geology. Thus, different physiographic regions would have varying amounts of ground water as a consequence of their differing geohydrologic properties. A more conservative estimate of .2-.3 mgd per square mile was made by the United States Geological survey. This estimate presumes maximum development of the aquifer formation. For the purpose of this study, yield estimates of the ground water resources were obtained from either the Oklahoma Water Resources Board, The University of Oklahoma Geological Survey, the United States Geological Survey or from published records. Consequently, the estimates vary in realiability and age. Quite often the estimate represents installed well pump capacity rather than aquifer yield.

B. Advantages and Disadvantages of Groundwater Storage and Use

The analysis of groundwater resources plays an important role in the total development of a water resource system. The term groundwater is used to represent the water which has saturated the pores or interstices of a confined or unconfined aquifer system. Groundwater storage and use has several advantages over surface storage and use: (31)(34)

1) Requires little land area

2) Mountains uniform water temperature

3) Has high biological purity

4) Evaporation from groundwater basins is insignificant when compared with that from surface reservoirs.

5) Groundwater basins provide natural treatment and purification for both naturally percolating and artificially recharged water systems.

6) Groundwater often provides emerging drought relief

On the negative side, ground water is subject to some quality problems and development costs. Chemicals and salts can dissolve in underground water and make it unsuitable for residential, industrial, or agricultural use, because Geologic formations influence the chemical character of the water below the surface. Inflows of sewage, industrial wastes or water from nearby saline basins can also degrade a groundwater basin's quality, as can the quality of recharged water and physical factors characteristics of the basin. Under influence from man, groundwater quality and quantity can change either postively or negatively as percolated waters change in quality, quantity, or source. In addition, a groundwater user must supply extraction facilities and pay the cost of energy for pumping water from underground (55).

C. Evaluation of Groundwater Storage

In the zone of saturation, groundwater fills all of the interstices; hence, the effective porosity provides a direct measure of the water contained per unit volume. A portion of the water can be removed from substance strata by drainage or by pumping of a well; however, molecular and surface tension forces hold the remainer of the water in place (55)

1) Void. Groundwater occurs in the voids, or pores, or geologic formations. Porosity measures this void space and is defined by (34).

$$\alpha = \frac{W}{V}$$

where W is the volume of water required to saturate all voids and V is the total volume of the rock. It is usually expressed as a percentage.

2) Specific Retention. The specific retention Sr of a soil or rock is the ratio of the volume of water it will retain after saturation against the force of gravity to its own volume thus (34)(55).

$$Sr = \frac{Wr}{V}$$

where Wr is the volume occupied by retained water, and V is the bulk volume of the soil or rock.

Not all the water stored in a geological formation can be withdrawn by normal engineering operations. There is, therefore, a difference between total storage and useful storage. The quantity that will drain off by gravity is called the specific yield; its counterpart is the specific retention. Specific retention varies from zero for plastic clays to values close to the magnitude of the porosity for coarse sands and gravels(27).

3) Specific Yield. The specific yield Sy of a soil or rock is the ratio of the volume of water that, after saturation, can be drained by gravity to its own volume.

Therefore (55).

$$Sy = \frac{Wy}{V}$$

Where Wy is the volume of water drained volumes of Sr and Sy can also be expressed as percentages. Becasuse Wr and Wy constitute the total water volume in a saturated material, it is apparent that

$$\alpha = Wr + Wy$$

where all pores are interconnecting.

Values of specific yield depend on grain size, shape and distribution of pores. Compaction of the stratum, and time of drainage.

Specific yield may be determined in a number of different ways, including the following: (1) saturation of samples of rock or soil with water followed by their drainage by gravity or centrifugal force; (2) drainage of samples taken from just above the capillary fringe after the water table has fallen (specific retention); (3) determination of the volume of ground drained by removing a measured volume of water through pumping operations; and (4) measurement of the particle size and porosity of a sample and estimation of its specific yield from known values of similar materials. Representative specific yield for various geologic material are listed in Table 18.

TABLE 18 Representative Values of Specific Yield

Material	Specific Yield percent
Grave, coarse	23
Gravel, medium	24
Gravel, fine	25
Sand, coarse	27
Sand, medium	28
Sand, fine	23
Silt	8
Silt Stone	12
Clay	3
Sandstone, fine-grained	21
Sandstone, medium-grained	27
Limestone	14

Adapted from Source in Reference 55

4) Estimation of Groundwater Storage

The amount of groundwater theoretically recoverable from any area can be estimated as follows:

$$V = H.\ A.\ Sy$$

where

V = The volume of Groundwater in any aquifer in Acre feet

H = Thickness of saturation in any aquifer in feet

A = area of aquifer in acre

Sy = specific yield

The volume of water thus determined does ont represent the amount that can be pumped; to drill enough wells to drain all the water from the aquifer is not economically feasible. In addition, as the water levels are lowered by pumping, the saturated thickness decreases the well yields and the pumping lifts increase. Thus, pumping for general use becomes impractical or uneconomical as the water in the aquifer nears exhaustion.

The aquifer is a complex hydrologic system with widely differing heads in Oklahoma. Although the aquifer is believed to have an overall specific yield of about 15 percent in the state, its storage coefficient has been found to be as low as 0.0001 where it is under artesin head. To illustrate this computation we may look at the following example:

If it is assumed that all but 50 feet of the saturated material could be drained by pumping, then the amount of groundwater that theoretically could be pumped from storage (in acre feet) can be estimated by multiplying the area (ACRE) in which the thickness of saturation exceeds 50 feet by the average thickness (in feet) of saturation in excess of 50 feet by Specific Yield. By Planimetering the intervals of saturation in the high plains deposits of the Cimarron Basin, it was determined that in an area of about 5000 square miles, the amount of water that theoretically could be pumped from storage if the water table were lowered to within 50 feet of the base of the aquifer is 108 million acre-feet. Table 19 shows in detail the application of groundwater storage estimation model on Cimarron aquifer in Oklahoma (56).

Table 19. Estimated recoverable groundwater in storage in the High Plains deposits of the Cimarron Basin 1/

Interval of saturated thickness (ft.)	Average saturated thickness (ft. -50 ft.)	Area (sq. mi.)	Storage (acre-feet)
50 - 100	25	836	2,006,400
100 - 150	75	555	3,996,000
150 - 200	125	255	3,060,000
200 - 250	175	333	5,594,400
250 - 300	225	552	11,923,200
300 - 350	275	631	16,658,400
350 - 400	325	862	26,894,400
400 - 450	375	586	21,096,000
450 - 500	425	168	6,854,400
500 - 550	475	79	3,602,400
550 - 600	525	54	2,721,600
More than 600	575	55	3,036,000
Total			107,543,200

1/ Based on estimated specific yield on 15 percent.

* sq. mile = 640 acre

Source: Adapted from Reference 56

D. Present and Potential

Ground Water Development in Oklahoma

Oklahoma has large quantities of groundwater, but the water is not equally distributed throughout the state. It originated from moisture that falls on the surface of the land and percolates into the water-bearing strata. Under favorable conditions about 15% of the water that falls on the surface percolates into the ground. This water cannot be classified as true groundwater until it enters the zone of complete saturation. Some water in the soil remains, but is quickly depeleted by plants, drying sun and winds (57).

This source supplies 61 percent of the water needed in Oklahoma. More than 80 percent of present irrigation water comes from groundwater reservoirs. Approximately 300 towns and cities obtain their water supplies from wells and springs (2)(3)(4)(15).

The principal groundwater reservoirs, or aquifers of Oklahoma may be classed in four general groups (57). (1) Semi Consolidated sand and gravel underlying the high plains, (2) Alluvial deposits along the streams and adjacent to the valleys, (3) Sandstones, and (4) limestone aquifers, including dolomite and gypsum.

Due to lack of available stream water, present groundwater development is mainly in Western Oklahoma. Eighty percent of all ground water used in the state is used in this region for agricultural purposes. The result in many areas is overdevelopment of groundwater basins, as pumpage exceeds recharge from precipitation. Wells closely spaced and pumped at high rates for significant periods of time create cones of depression around wells, causing interference. Water level declines and yield and storage reduce. Although local potential exists in the Elk City sandstone and some of the alluvium and terrace deposits, major groundwater basins like the ogallala formation, Rush Springs sandstone and Tillman Terrace are being dewatered. Within the next 20 years, pumping may become financially infeasible and therefore alternative water sources will be needed (15).

The Central region has potential for increased development. The Garber-Wellington Formation contains water in storage which could supplement future water needs of Oklahoma City and surrounding towns. The Vamoosa formation and alluvium and Terrace deposits are not fully utilized (15).

Eastern Oklahoma, in contrast, has experienced little ground water development because of readily available stream water. Groundwater is predominantly used for domestic wells or to supplment stream water. Development potential is good as there is ground water in storage and recharge exceeds present pumpage. The Roubidoux formation contains a large amount of water in storage, and is currently under study by the United States Geological Survey. The Antlers Sandstone contains water in storage which could supplement future water needs of southeast Oklahoma (2,15).

These principal aquifers form twleve major ground water basins in Oklahoma. They occur in the state with an estimated 320 million acre feet of fresh water in storage. It is estimated that about 50 percent or about 160 million acre feet, is recoverable. Less significant amounts are available in at least 150 minor basins (15). To know precisely how much groundwater is available will require more hydrologic data than is currently available. Water levels must be taken over the whole state. Presently, measuring is done only on western groundwater basins. Efficient development can only occur with proper management of the state's groundwater resources. Table 19 shows the total groundwater estimated recoverable from Oklahoma groundwater storage (2)(15).

Table 20 Total Groundwater Estimated Recoverable From Storage

Ground Water Basin	Water Storage (1000 AF)	Estimated Recoverable (Percent)	Estimated Total Available Water (1000 AF)
Alluvium and terrace deposits	18,400	60	11,000
Ogallala Formation	76,000	60	46,000
Antlers Sand	70,000	40	28,000
Elk City Sandstone	1,400	40	1,000
Rush Springs Sandstone	31,200	50	16,000
Dog Creek Shale and Blaine Gypsum	600	50	300
Garber-Wellington Formation	52,000	50	26,000
Oscar Formation	8,900	40	4,000
Vamoosa Formation	36,000	40	14,000
Simpson Group	3,300	40	1,000
Arbuckle Group	15,000	50	8,000
Roubidoux	7,200	40	3,000
Statewide Total	320,000		159,000

[1]Based on quality, economic, legal and technological constraints.

[2]Will not equate because of rounding off.

Source See (2)(15)

E) Groundwater Quality Problems in Oklahoma

Groundwater is available over most of Oklahoma in sufficient quantity for domestic supply; however, in some parts of the state the water is too high in chlorides or sulfates for most uses. In some areas, groundwater may be of better quality than surface water. The groundwater quality is good in the outcrop areas, and suitable for industrial, municipal, and irrigation use. In the downdip from the outcrop, the quality of the water deteriorates because of hardness and very high calcium sulfate concentrations. Locally in the southeastern and northwestern parts of the state, the water has a high sodium chloride content, but it is suitable for irrigation. Also, ground water quality in Oklahoma varies greatly both with respect to the properties of the water-bearing rocks and the geographic location within the state. Quality in the west is generally inferior to that of the east due largely to the effects of rainfall and evaporation and to the type of geologic formation.

Groundwater quality problems fall into four broad categories: (1) Waste management, (2) non-point sources of pollutions (3) general water quality, and (4) use of aquifers as storage reservoirs (58).

Wastes (residuals) can be disposed in the atmosphere, streams, and other surface-water bodies or into or on the solid earth. Each of these options have associated trade-offs. We are becoming increasingly aware that disposal, either as solids or liquids into the solid earth has associated hazards of contamination and transport by groundwater. It is a challenge to the groundwater hydrologist to design those systems for minimum contamination potential.

The problem is perhaps best exemplified by the present search for a geologic disposal site for high-level radioactive wastes. The problems of radioactive waste disposal are problems of predicting the solution and potential transport of the contaminations by groundwater.

Low-level radioactive wastes, ordinary municipal wastes, and toxic industrial wastes are being disposed of in areas where aquifers can potentially be contaminated.

Increased use of chemicals both agriculturally and municipally may be causing wide-spread aquifer contamination. In fact, in many places it may be some time before the effects of contamination are recognized. Because of the slow movement of groundwater, it may take decades before contaminants can be suitably diluted, diminished, or flushed from the system (57).

Aquifers have been used for the storage of a variety of fluids for some time. Water storage through artificial recharge is obvious to all of us. Natural gas has been stored for some time in aquifers. The United States Geological Survey is now beginning to look at storing freshwater and heat (hot water) in aquifers. There are problems associated with the necessary technologies to accomplish such storage. Again, it becomes a question of understanding the transport of fluids other than ordinary water in groundwater systems. Further fundamental research will be necessary before we fully understand the physics and chemistry of these problems. Both laboratory and field experiments will be necessary to improve our understanding (2)(15)(57)(58).

1) Groundwater Pollution

There are many actual and potential sources of groundwater pollution, and the effects on groundwater must be examined in terms of inorganic and bacteriological quality characteristics.

Poor quality groundwater may result from a combination of several contributing factors or sources. These sources are: (22) Natural pollution, oil field brines, over-pumping, irrigation return flows, land application of wastes, solid wastes, evapotranspiration by native vegetation, animal wastes, waste lagoons, accidental spills of hazardous materials, injection wells, septic tanks and municipal sanitary landfills, the last three sources being very important in Oklahoma.

2) Groundwater Pollution Indicators

To evaluate a groundwater pollution problem, it is necessary to have an understanding of the indicators pollution and the concentrations at which these indicators affect beneficial uses of the water. Water pollution is generally indicated by excessive concentrations of the following (21):

a) chemical indicators--total dissolved solids, chlorides, sulfate, calcium, magnesium, sodium, iron, boron, and others;

b) biological indicators--caliform organisms, biochemical oxygen demand, viruses, bacteria, etc.;

c) industrial indicators--pesticides, herbicides, acids, arsenic, heavy metals, detergents, gasoline, and others.

Many pollution indicators reach groundwater because of man's activities, but many others contaminate groundwater through natural processes not related to man.

3) The Chemical Quality of Groundwater

The chemical quality of groundwater reflects the chemical composition of the materials with which the water comes in contact. Water percolating down through soil and rocks dissolves mineral in its movement through a groundwater basin. The amounts and kinds of minerals depend on the types available and duration of contact. The water quality of groundwater rosources is generally good. The most developed groundwater basins, such as the Ogallala, Rush Springs sandstone, and

Antlers, have excellent water quality, suitable for municipal, industrial and irrigation use. The Garber-Wellington groundwater basin has a low total dissolved solids concentration.

4) Future Emphasis

More study is needed on the quality of Oklahoma groundwater resources. Currently, water quality samples are only taken for complaint investigations or the United States Geological Survey reports on groundwater resources of an area. A periodic monitoring program, as exists for streamwater, is needed for groundwater. This will help supply information to citizens wishing to use groundwater to meet their needs. A monitoring program will also alert regulatory agencies to developing pollution problems (2)(15).

Without stretching our imaginations, the groundwater profession is currently confronted with several problems and issues that place new demands on it. Foremost, in my judgment, are problems of (1) groundwater quality, (2) policy issues, (3) the need for more and better quantitative field data on real systems, and (4) improved planning and management.

F) Total Costs Estimation of Groundwater Production

No system for estimating costs ever provide 100 percent accuracy. However, historical data and analysis of the construction cost of many wells provide an excellent means of estimating future costs in any given geographical area. Although any cost analysis has the problem of discriminating proper and realistic data input, general guidelines can be estimated. Studies completed by Engineering Enterprise, Inc., Water Well Journal and Water Well Technology are excellent examples of the analysis of well construction costs in different formations, both domestic and industrial-municipal (59)(60)(61).

Groundwater production costs depend to a large extent on (1) geological location, (2) labor supply, and (3) geological environment and other factors. A particular well cost will fluctuate since general cost factors can combine to either simplify or complicate well construction. The use of the following information need not necessarily be limited to Antlers aquifer in Southeastern Oklahoma, although the information is based on wells drilled in some other aquifers of the state. In those parts of Oklahoma where geologic conditions are similar and where labor costs are comparable, the results are applicable to other parts of the state.

The United States Army Corps of Engineers, Tulsa District authorized Engineering Enterprises, Inc., of Norman, Oklahoma, to prepare a report on "procedures and costs for developing groundwater in the Antlers aquifer southeastern Oklahoma (11). This report presented a probable range of costs that was dependent on the depth drilled for well yield of 100, 500, and 1000 gallon per minute (gpm). According to this report, the total cost of developing a groundwater supply system includes engineering, exploration, pump facilities, wells, land, pipelines, storage, and operation and maintenance costs. The determination of costs for land, pipelines, and storage are too site-specific to be included in this general analysis of water costs (61).

Costs of engineering have been estimated on the basis of 20 percent of construction costs to reflect the geological supervision of test drilling and construction supervision which are normally an add-on to a standard engineering percentage fee. The costs of exploration are based on an assumption of drilling and electric logging of three tests holes for each production well. The unit price used for test drilling is $6.00 per foot and the unit price for electric logging is $15.0 per foot.

The approximate well costs are summarized for the various diameters in Figure 17. The range of well depth, as shown, reflects the probable range for each diameter. For example, a well deeper than 300 feet will probably encounter sufficient aggregate permeable sands to justify a 12 inch well (61).

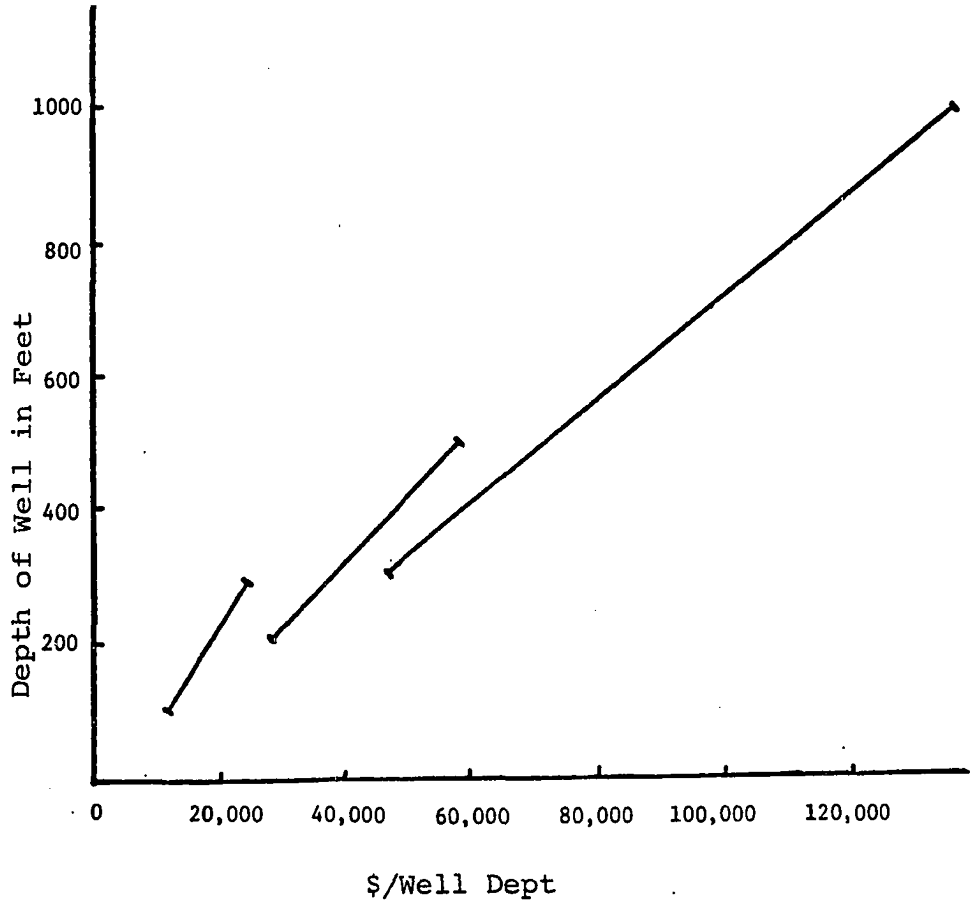

FIGURE 17 Cost Verses Depth for Well Size
See Reference 61, p. 14

Table 21 summarizes the estimated costs. This table presents the cost range for wells, pumping facilities, exploration and engineering. Also presented are the sums of the minimum costs and sums of maximum costs per the 100,500, and 1000 gpm capacity wells. These numbers show the total cost range for developing a given quantity of water. The numerical average cost is an approximation for each well size. The average cost per gpm may be used for planning peak capacities. However, actual costs for a specific municipality may vary substantially from the aveage cost shown (61)

Table 21 Summary of Estimated Costs
for Groundwater Production

	Cost Ranges		
Well Capacity	100 gpm	500 gpm	1000 gpm
Well Costs			
Minimum	$12,000	$ 28,000	$ 47,000
Maximum	$25,000	$ 61,000	$140,000
Pump cost			
Minimum	$ 7,000	$ 16,000	$ 22,000
Maximum	$11,000	$ 26,000	$ 55,000
Exploration			
Minimum	$ 3,000	$ 5,000	$ 8,000
Maximum	$ 7,000	$ 12,000	$ 22,000
Engineering Costs			
Minimum	$ 4,000	$ 9,000	$ 14,000
Maximum	$ 8,000	$ 18,000	$ 39,000
Total Costs			
Minimum	$26,000	$ 58,000	$ 91,000
Maximum	$51,000	$117,000	$256,000
(Should yield 200 gpm)			
Numerical Ave. Cost	$38,500	$ 87,500	$173,000
Ave. Cost/gpm (for peaking capacity)	$ 260	$ 175	$ 173
Final weight installed average cost per gpm	$ 205/gpm installed capacity		

Source see Reference 61, page 17

CONCLUSIONS

The author has developed a general planning level model to provide information by basin and aquifer on potentially available water from the ground and from the surface with storage, including the cost of storage and the cost of wells. For the planner to establish approximate costs for either ground or surface water at any geographical point, it will be necessary to add the cost of treatment and transportation of water from a reservoir site to a point of use, or the cost of well field water treatment. Conceptually, the process developed herein is limited in technology and in application.

Water must come from the surface and ground - the surface supply is extremely variable, and regulated demands are obtained by providing surface storage. The groundwater depends on estimates of sustained yield and sizing of wells. Oklahoma, with an average annual flow of about 30,330,500 acre-feet per year presently leaving the state, has enough water to meet every future need, even in periods of drought. Unfortunately, this supply is not uniform, but varies widely from season to season and from year to year; nor is the supply equitably distributed according to location of mineral and agricultural resources and population. At the present time, only a small portion of these resources are being regulated for use (an estimated 16 percent). So, regulated use of reservoir will provide additional water.

Several appropriate methods have been presented for determining the safe yield of a watershed from the storage which can be developed economically at a given reservoir site. The most satisfactory graphical procedure is to use a mass curve. The most satisfactory computation technique is to use Hazen's procedure primarily because of available data and ease of use. These two methods have been applied to the five gauging stations in the Illinois River Basin as a case study. These evaluations have been presented in a graphical and tabular form for each gauging station. The graphical results obtained from this study differ by 5 percent or less from the results obtained by Allen Hazen's methods. For this reason and for expediency, it is appropriate to apply Hazen's results to all fourteen Oklahoma River Basins to evaluate number and size of reservoirs required to produce selected dependable [50, 70, and 90 percent] mean annual flows, and their related costs. Table 22 shows the summary of these results. Storage is presented as a total basin value which can be further analyzed in terms of numbers and combination of reservoirs to make up the total. For some of the river basins, like the Canadian River, the Grand River, and the Washita River, one could reduce the estimated number of reservoirs by constructing larger ones, thus reducing construction costs, while other basins can only be developed fully through the use of many small reservoirs. This problem is beyond the scope of this study.

All raw data and information were collected by public agencies such as the United States Geological Survey, the United States Army Corps of Engineers, and the Geological Survey.

In a given river basin, there is a limited number of available sites for impoundment. No attempt was made to investigate these. As an estimation, the average size and location of previously constructed reservoirs were used to suggest costs, and where locations were to be distributed. The first sites were limited by use of benefit/cost ratio for 50 year forecast periods; usually the easier and cheaper sites were

TABLE 22 - Summary of the Storage Required and Related Cost Estimated Per Acre Feet for 14 Oklahoma River Basins

No.	River Basin	Year of Record	Mean Annual Flow at Mouth C.F.S	60% of M.A.F. Mouth C.F.S	60% of M.A.F. at Mouth AC-Ft/Yr	90% of 60% of M.A.F. Storage Required AC-Ft/Yr	No. of times Reservoir may be built	Estimated dollar cost per AC-Ft	70% of 60% of M.A.F. Storage Required AC-Ft/Yr	No. of times Reservoir may be built	Estimated dollar cost per AC-Ft	50% of 60% of M.A.F. Storage Required AC-FT/Yr	No. of time Reservoir may be built	Estimated dollar cost Per AC-Ft	Median of Existing Reservoir Capacity AC-Ft/Yr
1	Salt Fork Arkansas River	46	973	584	422,816	1,539,050	6	170	553,890	2	170	342,481	1	170	240,000
2	No. 2 Cimarron Rv.	41	1,240	744	538,656	2,046,903	19	230	1,023,446	9	230	301,647	1	230	95,000
3	No. 3 Verdigris Rv.	26	4,262	2558	1,851,992	7,037,570	14	175	3,148,390	14	175	1,592,713	4	175	221,110
4	No. 4 Grand Rv.	31	7,548	4529	3,278,996	14,099,690	26	170	6,557,990	26	170	3,377,366	13	170	244,200
5	No. 5 Illinois Rv.	41	1,574	944	683,455	2,426,265	2	125	1,079,859	2	125	539,929	1	130	576,700
6	No. 6 Canadian Rv.	43	5,179	3108	2,250,192	10,575,900	122	240	4,950,420	53	240	2,587,721	24	240	81,700
7	No. 7 Poteau Rv.	41	2,154	1293	936,132	1,057,830	3	140	468,066	1	140	224,672	11	170	400,000
8	No. 8 North Fork Red River	43	329	198	143,352	570,540	3	215	258,033	1	370	131,884	0	--	117,080
9	No. 10 Washita Rv.	45	1,491	895	647,980	2,462,320	34	270	1,101,570	12	270	557,263	3	270	62,600
10	No. 11 Boggy Creek	38 43	640 1,180	1092	790,608	2,371,820	18	220	1,011,980	7	220	482,271	2	220	116,650
11	No. 12 Kiamichi Rv.	8	2,425	1455	1,053,420	1,748,680	3	135	684,720	1	170	284,423	0	--	468,650
12	No. 13 Little Rv.	46	3,196	1918	1,388,632	4,388,080	10	140	1,888,540	4	140	916,497	2	140	419,050
13	No. 14 Arkansas Rv.	46	7,623	4574	3,311,576	12,319,110	26	135	5,497,240	11	135	2,119,409	4	135	457,200
14	No. 1 Red River	45	2,102	1262	913,688	2,741,060	2	110	1,169,520	1	110	557,350	1	175	1,400,540

M.A.F. Mean Annual Flow
C.F.S. Cubic Feet Per Second
AC-Ft/Yr Acre-Feet Per Year

used first. So, generally, but not necessarily, subsequent sites should cost more, and be fewer and larger. Therefore, location is an extremely important cost consideration, with transportation being a major overriding cost, particularly for irrigation water.

Water for irrigation, power, industry, and municipalities is identified in the application of the technique by state and federal agencies; the model will provide only a source, volume, and cost (at site or well-head). Treatment, site and pumping cost will also need to be available to connect the alternative water sites against the project uses. Generalized treatment and transportation costs are available but a follow up of this research could provide these data in a convenient form for use with the source data. A surface water source sub-model could also be developed to provide data on size and number of alternative storage facilities in a basin. Remembering that the storage figure is a generalized aggregate, the specific pattern of aggregates is yet to be determined.

Utilization of the information contained herein will be a great help to administrators, public officials, engineers, and planners such as the Oklahoma Water Resources Board. It will provide them with a planning level estimate of available water to specific sites. Briefly, information for determing the nearest location of potential water and the related costs for 14 Oklahoma river basins is presented in Table 22.

From one point of view, Oklahoma has tremendous proven resources of fresh underground water; the exact amount of water in storage is not known. The United States Geological Survey has estimated approximately 320 million acre-feet groundwater storage above a depth of 2,000 feet in Oklahoma. This is more than 82.7 times the amount of water stored as water supply in all surface reservoirs and lakes of the state and more 10.6 times the average annual flow of all the streams draining the state.

Though this estimate of groundwater is a little more than 80 times the amount presently stored, and ten times the potentially regulated storage, it should be looked at essentially as a non-replenishable supply, and only 50 percent recoverable. As a general rule, the recovery time on a surface supply in Oklahoma is 2.5 years; on a ground water supply, it may be 10 to 100 years. So, though there exists an enormous amount of water underground, even if it could be taken out, it is not a sustained yield. The ground aquifer storage can be taken out, it is not a sustained yield. The ground aquifer storage can be thought of as a reservoir, but unlike surface storage, it is spread over the state and not pinpointed and it is constrained in its delivery by ground water hydraulics.

Determination of potential point site yields was used and the calculations were made on generalized field representations of specific yields and aquifer characteristics. These certainly could be refined. It is also important to stress that discharge from wells, etc., really should not be used to "iron out" demand variations, only supply variations. Surface reservoirs can provide both functions.

It is estimated that about 50 percent or about 160 million acre-feet per year is recoverable. Oklahoma's major groundwater aquifers are stream deposits (alluvium, terrace deposits, and the Ogallala formation), limestone, sandstone, and gypsum. This source supplies 61 percent of the water needed at present in Oklahoma. More than 80 percent of the present irrigation water comes from groundwater reservoirs. Approximately 300 towns and cities obtain their water supplies from wells and springs.

These principal aquifers form twelve major groundwater sources. Table 19 shows in detail the application of groundwater storage estimation model on the Cimarron aquifer in the state, and Table 20 shows the total groundwater estimated recoverable from the storage of all twelve principal aquifers in Oklahoma.

Water-well production costs: according to reserach conducted by Engineering Enterprise on "Procedures and Costs for Developing Groundwater in the Antlers Aquifer in Southeastern Oklahoma," well costs prediction may be summarized as follows (61):

A) Capital Cost = 254.2/acre-foot.

Amortizing this cost over 20 years using uniforms series worth of a present sum (or capital recovery factor) at an interest rate of 8 percent.

(254.2/acre-ft) (0.10185) = \$25.89 acre-foot/year

(\$0.0795/1000 gallon/year)

B) Pump Replacement Cost = \$25.4/acre-foot

Accumulate this amount over a 10 year period using the uniform series worth of a future sum (or sinking fund factor) at an interest rate of 8 percent.

(25.4 acre-ft) (0.06903) = \$1.75 acre-foot/year

(\$0.054/1000 gallon/year

C) Power Cost = \$29/acre-foot/year

(\$0.089/1000 gallon/year

D) Operation and Maintenance Cost = $57.88/acre-foot/year or ($0.0038/1000 gallon/year)

Total water well production Costs = $57.88/acre-foot/year or ($0.178/1000 gallon/year

These costs appear reasonable for the development of a groundwater supply system including land, pipelines, and storage costs. The pumping capability is twice the average demand to permit peaking in the summer. These cost ranges may be applied to specified areas when aquifer conditions are very similar to those in Antlers. All costs are presented as 1980's costs. Due to changes in the inflation rate in exploration, wells, pumps, engineering, power, and operation and maintenance costs, it would be difficult to predict with any accuracy what costs would be in the future.

VIII. Recommendations

A. Specific Recommendations

A methodology for long-term water supply planning, along with its application to the case study of Oklahoma, was presented. The following specific recommendations can be drawn from this dissertation.

1. The future of Oklahoma will require water in excess of the present supply because of the necessity of regulations in surface water, ground water, and so on. Consequently, attention must be given to practices designed to hold water in flush years, equalize supply on a real basis, and conserve what water is available by programmed use and reduced losses so as to obtain maximum use for both surface and groundwater.

2. For each water planning region, complete information about all of the sources in the region, both surface and groundwater, should be collected. This will require basic studies of all of the natural factors influencing the availability of water, such as climatology, hydrology, and geology of the region. Changes generally occur gradually. Years of monitoring are necessary before definite trends can be shown. Therefore, information collected over long periods of time is more representative than short term data. A continuing data collection and research program is needed to insure full utilization of available resources. More detailed data will be necessary for specific plan formulation, project designing, and operation and

regulation development. Considerable data have been collected for several of the major aquifers, for certain areas, but for other areas the mechanics of replenishment and movement of water, and the quantities available for development are virtually unknown. Therefore, for any future planning, additional close study is required. There is a scarcity of basic social, economic, physical, technological, and groundwater data in the study area. The high priority objective of the state agencies should be emphasized to overcome these problems.

3. The state needs to assess its agricultural, industrial, and municipal water requirements. This would enable building future water projects on a realistic basis.

4. Continuous compact agreements with our neighboring states should allocate waters and control pollution

5. A mathematical model of supply and demand needs to be developed, considering structural and non-structural changes. The model should be a tool which could provide answers to questions of water quality and quantity as well as to questions on interstate compacts.

6. A multiple water supply system should be an essential consideration in developing a long-term water management plant for a region. A region considering conservation and optimum

uses of water unfortunately has no methodology for the analysis of multiple water supply systems.

7. It should be recognized that the cost estimating procedures provided in this study are valid only for making preliminary comparisons and serve only to measure costs to a degree which will assist in evaluating planning alternatives. Cost estimates derived by these procedures should not take the place of detailed engineering estimates for specific projects.

8. Close supervision should be maintained over all structures which store water. This would assure that stored water is put to the highest possible beneficial use and is not wasted. Recommendations may be made to the Federal Government from time to time concerning the allocation of storage for beneficial use.

9. Research is also necessary to increase the general knowledge of existing resources and to overcome the problem of resource development. Additional research is needed to develop new techniques and programs for more effective utilization of existing data. The water quality research program also needs to be modified and expanded.

B. General Recommendations

In addition to the previous specific recommendations which were from this study, the following general recommendations are presented:

1. Waste discharged into Oklahoma streams by municipalities and industries can deprive down-stream users of many of the beneficial uses of those waters. Groundwater deposits are extremely susceptible to infiltration by brine and other oil field wastes. Effective controls are recommended to prevent the resulting losses of available water.

2. All streams and bodies of water designated should be protected. Any new point source discharge of wastes or increased load from an existing point source should be prohibited.

3. Full cooperation under existing Oklahoma laws should be mandatory between state agencies in the control of pollution of streams, groundwater, and lake water supplies.

4. Water laws should be modified in order to provide a strong support for water resources development in the state. There is a great need for flexibility in water laws in the state concerning many issues, such as water withdrawn for irrigation, ownership of water, responsibilities of developing ground and surface water supplies, etc.

5. In order to ensure adequate water supplies to eastern Oklahoma residents, industries, and irrigation, the eastern Oklahoma water supply studies should remain a significant consideration.

6. A region-wide public education program is necessary to assure the opponents that diversion of excess and surplus waters from the basins or origin will not interfere with any other projected use of water in the basins.

7. Examples of conservation methods that may be used are evaporation reduction from lakes and reservoirs, run-off water control using rock tunnels and galleries, groundwater storage and management, and many other methods.

8. Technical developments should increase usable supplies of fresh water and should conserve existing sources.

9. It is essential that sufficient funds be available to carry through the planning and development stages.

C. Additional Work

1. Surface water model should be extended to include easily accessible cost for treatment and transport.

2. Development is overdue to locate alternative ground and surface potential supplies to provide water, etc.

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APPENDICES

Appendix

A) Total Population, Percent Change in the Population from 1970 to 1980 for State Planning Region and All Oklahoma.

B) Major Stream Systems in Oklahoma.

C) Calculation Procedure of the Net Arkansas River and Red River Basin Average Discharge.

D) Construction Cost Indices and Construction Review Inflation in Construction Material.

E) Existing or Under Construction Reservoirs with Their Median Capacities in Oklahoma.

F) An Analytical Storage Procedure to Accompany and Explain Tables 12, 13, 14, and 15 on the Cimarron River in the Basin 2 with Compare to Table 29.

Appendix A

Total Population, Percent Change in the Population from 1970 to 1980 for State Planning Region and all Oklahoma.

Appendix A

According to the 1980 United States Census, the population of Oklahoma was 3,025,266, an 18.2 percent increase from 1970. Population change 1970-1980 for state planning regions and all Oklahoma are shown in Table 24 and Figure 18.

Table 23 Total Population, Percent Change in the Population from 1970 to 1980 for State Planning Districts and All Oklahoma

PLANNING DISTRICT	1970 POPULATION	1980 POPULATION	NET CHANGE	% CHANGE
ACOG	661446	785439	123993	18.75
ASCOG	243346	274480	31134	12.80
COEDD	173663	212521	38858	22.37
EODD	191220	243412	52192	27.29
INCOG	475264	569130	93866	19.75
KEDDO	141005	167199	26194	18.57
NECO	166091	210126	44035	26.51
NODA	161698	174242	12544	7.75
OEDA	70172	76509	6337	9.03
SODA	163997	193910	29913	18.24
SWODA	111561	118298	6737	6.04
State Total	2,559,463	3,025,255	465803	18.2

Source:
Adapted from Oklahoma State Data Center, "Final Population and Race Total for Oklahoma, Census 80", April 1981. P. 2

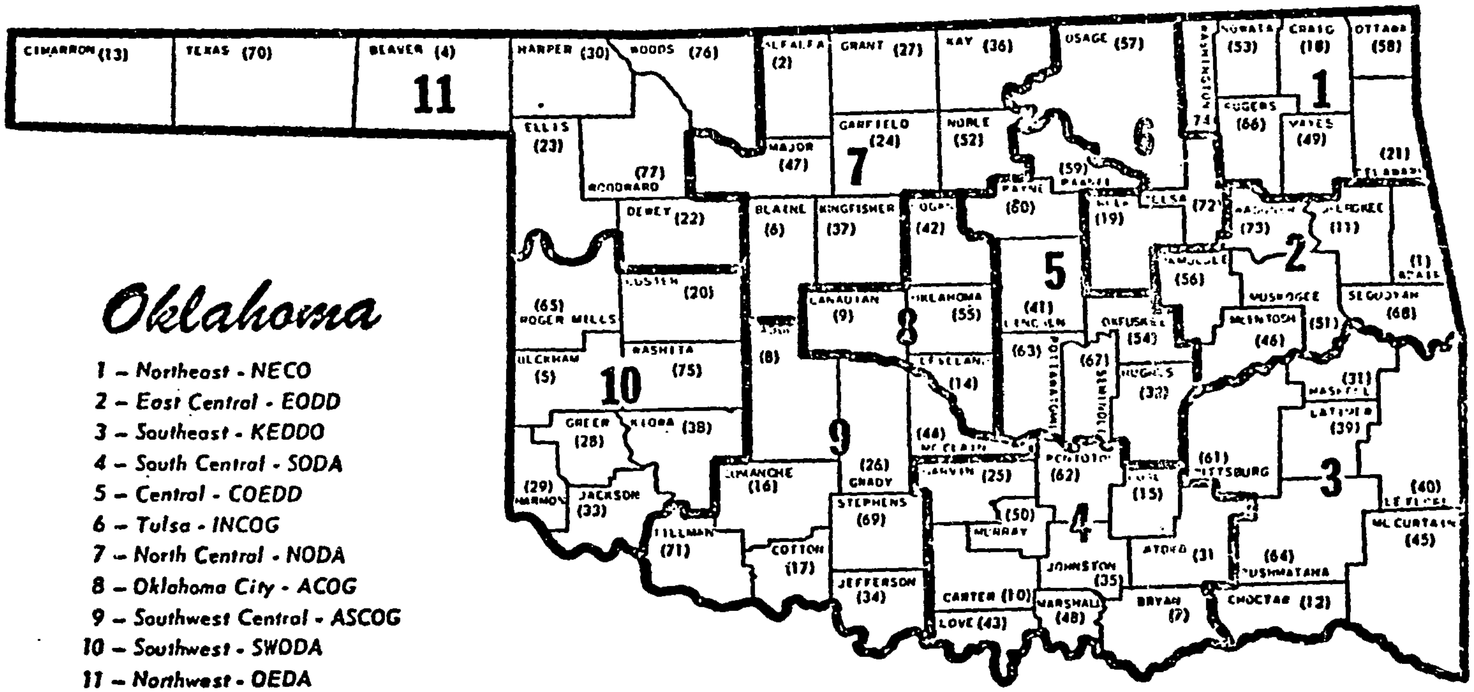
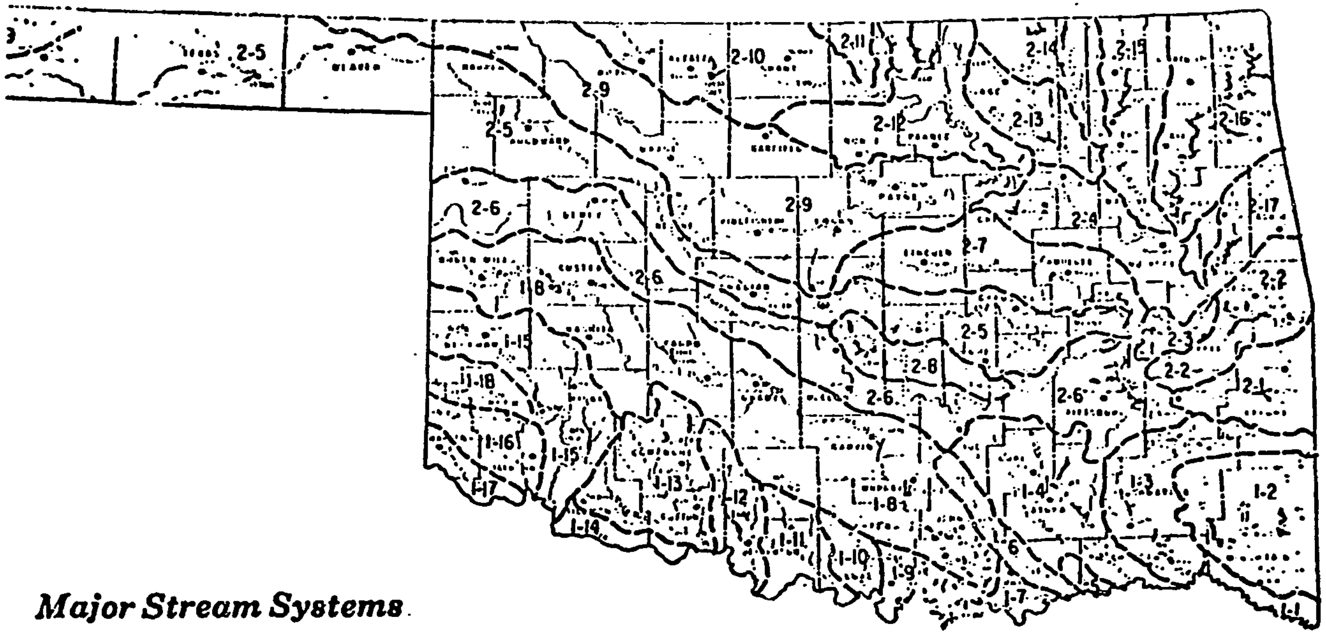


FIGURE 18 State Planning Regions
Source: See Reference 5

A P P E N D I X B

MAJOR STREAM SYSTEMS IN OKLAHOMA



Major Stream Systems

RED RIVER AND TRIBUTARIES

Stream System	
1-1	Main stem from Arkansas state line to mouth of Kiamichi River
1-2	Little River
1-3	Kiamichi River
1-4	Muddy Boggy River
1-5	Main stem from mouth of Muddy Boggy to mouth of Blue River
1-6	Blue River
1-7	Main stem from mouth of Blue River to mouth of Washita River
1-8	Washita River
1-9	Main stem from mouth of Washita River to mouth of Walnut Bayou
1-10	Walnut Bayou
1-11	Mud Creek
1-12	Beaver Creek
1-13	Cache Creek
1-14	Main stem from Cache Creek to North Fork Red River
1-15	North Fork Red River
1-16	Salt Fork Red River
1-17	Prairie Dog Town Fork Red River
1-18*	Elm Fork Red River

ARKANSAS RIVER AND TRIBUTARIES

Stream System	
2-1	Poteau River
2-2	Main stem from Arkansas state line to mouth of Canadian River
2-3	Canadian River from mouth, to mouth of North Canadian River
2-4	Main stem from mouth of Canadian River to Keystone Dam
2-5	North Canadian River
2-6	Canadian River from mouth of North Canadian River to Texas state line
2-7	Deep Fork River
2-8	Little River
2-9	Cimarron River
2-10	Salt Fork Arkansas River
2-11	Chikaskia River
2-12	Main stem from Keystone Dam to Kansas state line
2-13	Bird Creek
2-14	Caney River
2-15	Verdigris River
2-16	Grand (Neosho) River
2-17	Illinois River

FIGURE 19 Map of Major Stream Systems in Oklahoma

See Source 9

MAJOR STREAMS

Arkansas River and Tributaries

2-2 2-4 2-12

Entering the state in Kay Country and extending southeasterly through Kaw Lake as the county line between Osage, Noble and Pawnee Counties, the Arkansas River reaches Lake Keystone. From Keystone, it continues its southeasterly direction through Tulsa County, then once again becomes the county line between Wagoner and Muskogee Counties. Within Muskogee County, the Arkansas flows into Webbers Falls, then into Robert S. Kerr lake and after forming the county line between Sequoyah and LeFlore Counties, it leaves the state at mile 361. A total of 44,815 square miles of drainage and 327.9 miles of its length are in Oklahoma.

2-1

The Poteau River enters the state at the southeast part of LeFlore County at mile 96.6 and travels westerly to Lake Wister. At the confluence of the Fourche Maline it turnes easterly and northerly ending at its confluence with the Arkansas River at mile 362 at the approximate border of Oklahoma and Arkansas. The Poteau River and its tributaries drain an area of 1,888 square miles, 1,328 square miles of which is in Oklahoma.

2-3 2-6

Originating in Colfax County, New Mexico, and flowing southeasterly through New Mexico and easterly through the Texas Panhandle, the Canadian River enters Oklahoma at the boundary between Ellis and Roger Mills Counties. Moving easterly through Dewey County, then southeasterly through the northeast tip of Custer County, and the southwest tip of Blaine County, it crosses the southwest portion of Canadian County and forms the line between Canadaian, Grady, Cleveland, McClain, Pottowatomie, Seminole, Pontotoc, Hughes, Pittsburg and McIntosh Counties. The Canadaian enters the Arkansas River after stretching 410.7 miles across Oklahoma, having a drainage area of 19,487 square miles in the state.

2-5

The North Canadian River has its source in norther Union County, New Mexico, then enters Oklahoma at the southwest corner of Cimarron County, loops south and crosses the Oklahoma-Texas state line for a distance of about twelve miles where it reenters Oklahoma and flows generally east-northeast through Texas and Beaver Counties. After entering Harper County, a southeasterly direction is maintained through Woodward, Major, Dewey, Blaine, Canadian, Oklahoma, Lincoln and Pottawatomie Counties. Then if forms the county line between Pottawatomie, Seminole and Okfuskee Counties. After leaving Okfuskee County's southern border and entering Hughes, the North Canadaian reenters Okfuskee County before entering McIntosh County and then enters Lake Eufaula, flowing southeasterly through the lake. It enters the Canadian River near the town of Eufaula. The North Canadian has approximately 9,100 square miles of drainage.

2-7

The Deep Fork River heads in Oklahoma County and flows easterly throuh Lincoln, Creek, Okfuskee, Okmulgee and McIntosh Counties. After entering McIntosh Counthy, if flows into Lake Eufaula and then to its confluence with the North Canadian river at mile 14.4. The Deep Fork River has a drainage area of 2,548 square miles and a length of 230 miles.

2-8

Little River's source is in Oklahoma and Cleveland Counties. Flowing easterly through Thunderbird Lake, Little River bisects Pottawatomie and Seminole Counties, then flows southeasterly into Hughes County to its confluence with the Canadian River near Holdenville, Little river has a drainage area of 973 square miles and spans 120 miles across central Oklahoma.

2-9

The Cimarron enters Oklahoma at the northeast corner of Beaver County, exists the state in the northwest corner of Harper County, then reenters the state to form part of the eastern portion of the Harper County line. The river flows in a southeasterly direction to form the county line between Woodward, Woods, and Major Counties. Entering Kingfisher County, it flows eastward through Logan County to form a portion of the county line between Logan and Payne Counties. After entering Creek County it continues eastward to its termination in the Keystone Reservoir. The Cimarron River has 18,927 square miles of drainage area and covers a river distance of about 698 miles, about 410 miles of which are in Oklahoma.

2-10

The Salt Fork of the Arkansas River enters Oklahoma from Kansas in the northeast section of Woods County and flows eastward through Alfalfa

County to the Great Salt Plains Reservoir. Then the Salt Fork continues eastward through Grant and Kay Counties and terminates at the confluence with the Arkansas River in Kay County at mile 637.8, draining a total area of 6,764 square miles and meandering 160 miles across northern Oklahoma.

2-11

The Chikaskia river heads in south central Pratt County, Kansas, and flowing southeasterly, it enters Oklahoma between Grant and Kay Counties, then continues southeasterly to its confluence with the Salf Fork Arkansas River in Kay County. The Chikaskia River has 340 square miles of drainage in Oklahoma and has a total length of 145 miles, 49 of which are in Oklahoma.

2-13

Bird Creek is 84 miles long, located mostly in Osage and Tulsa Counties, and has its 1,147 square mile drainage area entirely within Oklahoma, Bird Creek enters the Verdigris River at mile 78.3.

2-14

The Caney River originates in southwestern Elk County, Kansas, flows southerly and southeasterly where it enters Oklahoma in the northwest portion of Osage County. It continues easterly into Washington and Rogers Counties to its confluence with the Verdigris River in central Rogers County. The Caney River has a total length of 117 miles and a total drainage area of 1,616 square miles within Oklahoma.

MAJOR STREAMS

Red River and Tributaries

1-1 1-5 1-7 1-9 1-14

Red River -- the Red River is more or less the southern boundary of Oklahoma. Flowing from west to east the Red River is one of the two major drainage basins of Oklahoma. About 517 miles of the Red River lies between Oklahoma and Texas. Oklahoma contributes 25,104 square miles of drainage to the Red River. South of the drainage area of the principal creeks and along the Red River, several small creeks drain directly into the Red River.

1-2

Little River heads in the southern portion of LeFlore County, extends into eastern Pushmataha County and southerly and southeasterly into McCurtain County, turning easterly near Idabel and continuing in the same general direction leaving the state at river mile 78. With its tributaries, Mountain Fork River and Glover Creek, it has a total combined drainage area of 3,449 square miles.

1-3

Kiamichi River has it source in the Kiamichi and Wichita mountain ranges in southeastern LeFlore County, Oklahoma. It extends westerly into Latimer and Pittsburg Counties, then south through Atoka, Pushmataha and Choctaw Counties, entering the Red River at mile 607. It has a drainage are of 1,830 square miles and is a major tributary to the Red River.

1-4

Muddy Boggy River heads in eastern Pontotoc and southwestern Hughes Counties, and flows in a southerly and southeasterly direction to its confluence with the Red River at about mile 644, near Hugo, Oklahoma. The Muddy Boggy and its two main tributaries, the Muddy Boggy Creek and the Clear Boggy Creek, make up a total of 2,429 square miles of drainage area.

1-6

Blue River heads in Pontotoc County near Roff and flows in a southeasterly direction to its confluence with the Red River near Wage in Bryan County, Oklahoma. It has a total length of about 118 miles. The basin is long and narrow with a maximum width of about 14 miles, and has a total drainage area of 676 square miles.

1-8

Washita River heads in southeastern Roberts County, Texas, and flows in an easteraly direction to the Texas-Oklahoma state line, enters in Rogers Mills County in Oklahoma and extends southeasterly through Beckham, Dewey, Custer, Washita, Kiowa, Caddo, Canadaian, Comanche, Grady, Stephens, McClain, Garvin, Murray, Carter, Pontotoc, Johnston, Marshall and Bryan Counties, to its confluence with the Red River, in Texoma Lake at mile 732. It extends 554 miles and covers a total of 9,110 square miles of drainage area.

1-10

Walnut Bayou heads in Carter County and extends south through Love County to its confluence with the Red River at mile 808. It has a drainage area of 334 square miles and an average annual flow of approximately 59,500 acre feet.

1-11

Mud Creek orginates in the southwest corner of Stephens County and runs in a southeasterly direction across Jefferson County to its confluence with Red River in the southwestern corner of Love County. It has a drainage area of 688 square miles.

1-12

Beaver Creek orginates in the northwestern section of Comanche County and the southwestern section of Grady County. It flows in a southerly direction to its confluence with the main stem of Red River at mile 882. Beaver Creek has a drainage area of 865 square miles.

1-13

Cache Creek is located in Caddo, Comanche, Tillman and Cotton Counties and consists of only a very short main stem and several large tributaries. The total drainage are of Cache Creek is 1,920 square miles of which 641 square miles is in the Deep Red Run tributary drainage. It flows southerly and southwesterly to its confluence with the main stem of Red River at mile 912.

1-15

North Fork of Red River orginates in Carson County, Texas, and flows eastward for a river distance of 72 miles where it enters the state near Texola, Oklahoma. After passing near Sayre, it turns southeasterly and southerly to its confluence with the main stem of the Red River near Davidson, a total distance of 220 river miles. The North Fork has a 4,828 square mile drainage in Texas and Oklahoma, of which 3,605 square miles is in Oklahoma. three hundred-ninety-nine square miles of the total drainage area is non-contributing.

1-16

Salt fork of the Red River heads in southern Carson County and northern Armstrong County, Texas, in the High Plains area and flows in a southeasterly direction for 97 miles, where it enters Oklahoma near Wellington, Texas. It continues in the same general direction for a distance of 70 miles, to its confluence with the main stem of the Red River near Elmer, Oklahoma, a total of 167 miles. A total of 2,088 square miles is in the Salt Fork drainage. Oklahoma contains 708 square miles of the drainage, with probably 209 square miles of non-contributing area in the High Plains.

1-17

Prairie Dog Town fork of Red River heads near the New Mexico Texas state line and flows in an easterly direction to its confluence with Buck Creek just inside the boundary of Oklahoma where it becomes the Red River, continuing to the mouth of the North Fork of the Red River. The principal tributaries in Oklahma are Lebos Creek and Gypsum Creek. Lebos

Creek has a drainage area of 323 square miles, 201 square miles of this is in Oklahoma. Gypsum Creek has a drainage are of 110 square miles, all in Oklahoma.

1-18

Elm Fork of the North Fork of the Red River begins in the southwestern part of Wheeler County, Texas, and flows east-southeasterly where it enters Oklahoma near the Harmon-Beckham county line, then continues in the same general direction where it entres the North Fork at a river mile 70. Elm Fork has a total drainage area of 915 square miles, of which 540 square miles are in Oklahoma.

2-15

From its source in Greenwood County, Kansas, the Verdigris River flows southerly where it enters Oklahoma along the northern portion of Nowata County. It flows in a southerly direction through Oologah Reservoir into Rogers and Wagoner Counties, then enters Muskogee County and joins the Arkansas River at mile 460.2. The Verdigris has 4,290 square miles of drainage within Oklahoma and a total length in Oklahoma of 162 miles.

2-16

The Grand (Neosho) River has its source in Mavis County, Kansas, flows southerly and southeasterly where it enters Oklahoma between Craig and Ottawa Counties and forms a portion of the county line. Forming the Lake O' the Cherokees, Lake Wash Hudson and Fort Gibson Lake, the Grand River winds through Delaware, Mayes, Wagoner and Cherokee Counties before joining the Arkansas River in Muskogee County at mile 459.5. The Grand

River has approximately 12,520 square miles of total drainage, 6,781 square miles in Oklahoma. It has a total length of 450 miles, 164.4 miles of this in Oklahoma.

2-17

The Illinois River has its source in Washington County, Arkansas, enters Adair County and travels southwesterly through Cherokee and Sequoyah Counties before its confluence with the Arkansas River at mile 426.7, completing its 109 mile stretch through eastern Oklahoma. Tenkiller Reservoir is formed on the Illinois River and utilizes a large part of the approximate 1,660 square miles of total drainage area of the river.

APPENDIX C

Calculation Procedure of the Net Arkansas River and Red River Basin Average Dishcarge.

Appendix C

Arkansas River, Basin No. 13, Computed as follows:

Van Buren, Arkansas gage No. 07250550 has drainage area of 30652 C.F.S. The drainage area at Oklahoma Arkansas state line is 149,977 square miles. The drainage area ratio is 0.996 and the average annual flow at state line is 30529 C.F.S. However, the drainage area for basin number 13 is the area in Oklahoma on the Arkansas River downstream of basins 1 through 7. Therefore, the drainage area for basin 13 is 149,977 minus 97,561 = 52,416 square miles. The average annual flow for area number 13 is 30529 minus 22904 = 7623 C.F.S. Table 21 shows the detail calculation.

Red River, Basin No. 14 Computed as follows:

Index, Arkansas gage No. 07337000 has a drainage area of 48,030 square miles and an average annual flow of 11479 C.F.s. The drainage area at Oklahoma-Arkansas state line is 47,555 square miles. The drainage area ratio is 0.990 and the average annual flow at the state line is 11364 C.F.S. However, the drainage area for basin 14 is for the area in Oklahoma on the Red River downstream of basin 8 through 12, Therefore, the drainage area for basin 14 is 47.555 minus 19,301 = 28,254 square miles. The average annual flow for area number 14 is 11,364 - 9,262 = 2102. The summarize procedure will be shown on Table 26.

Appendix C

Table 24 Calculation Procedure of the Net Average Discharge of the Arkansas River and Red River Basins.

Arkansas River
0725550

Basin 13	Drainage Area sq. mile	Average Discharge C.F.S.
1	6558	973
2	18927	1240
3	8303	4262
4	12520	7548
5	1660	1548
6	47705	5179
7	1888	2154
Total	9,7561	22,904

Red River
0733.7000

Basin 14	Drainage Area sq. mile	Average Discharge C.F.S.
8	4828	329
9	7945	1491
10	2429	1820
11	1830	2425
12	2269	3197
Total	19,301	9262

Appendix D

Construction Cost Indexes and

Construction Review Inflation in Construction Material

Builders' construction cost indexes

Name, area & type	1977 AV	1978 AV	1979 AV.	1980 AV	1980 Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	1981 Jan.	Feb.	Mar.	Apr.	May	June
GENERAL PURPOSE COST INDEXES																			
ENR 20-cities Construction cost	240	256	280	302	293	292	298	304	308	309r	310r	312r	314	314	314	315	321	323	32[illegible]
ENR 20-cities Building cost	225	248	269	288	283	282	284	289	292	293r	292r	296r	299	298	298	298	306	307	308
U.S. Commerce Department	216	243	276	306	299	302	307	309	310	310	310	311	312	314	314	319	321	—	—
WPRS, Denver, bldgs.	273	241	266	288	283	—	—	291	—	—	296	—	—	297	—	—	302	—	—
Dodge bldg. cost	na	299	333	364	—	—	—	—	—	313	—	—	—	—	—	381	—	—	—
Factory Mutual indus. bldg.	226	246	268	295	—	—	—	299	—	—	—	—	—	311	—	—	—	—	—
Lee Saylor Inc.: labor/material	242	263	285	—	292	296	299	303	306	307	308	308	310	312	310	310	310	—	—
Means: const. cost	209	224	242	265	261	—	—	267	—	—	275	—	—	281	—	—	280	—	—
CONTRACTOR PRICE INDEXES—BUILDING																			
Austin: central & eastern U.S., indus.	208	228	255	289	—	—	287	—	—	292	—	—	299	—	—	307	—	—	—
Fruin-Colnon, St. Louis, industrial	234	258	285	307	298	308	309	310	311	313	314	316	316	317	317	—	—	—	—
Geo. A. Fuller	234	262	292	325	—	—	—	321	—	—	331	—	—	341	—	—	343	—	—
Lee Saylor Inc.: subcontractor	209	241	282	—	287	288	289	291	292	293	292	295	296	298	298	296	296	—	—
Turner: general	209	222	246	273	270	—	—	276	—	—	283	—	—	290	—	—	297	—	—
Smith, Hinchman & Grylls general**	213	229	246	264	259	261	262	264	266	267	270	271	273	274	275	275	278	278	—
E.F. Campbell: 17-cities, mfg.	216	233	256	282	278	279	280	286	286	288	288	289	289	294	294	294	304	304	—
VALUATION INDEXES																			
American Appraisal, 20-cities, indus.	220	239	259	274	266	267	275	278	281	280	280	281	281	284	284	283	288	—	—
Boeckh index: 20-cities, comm'l & mfg	221	238	259	283	275	277	279	285	291	292	293	294	296	296	297	299	303	305	312
Marshall & Swift: industrial	209	231	257	281	278	280	281	280	281	283	285	287	289	293	295	296	297	298	301
SPECIAL PURPOSE INDEXES																			
Nelson Refinery Cost: "inflation" index	223	244	264	287	279	280	284	288	291	294	296	298	299	301	302	—	—	—	—
Chemical Engineering plant cost	186	201	217	232	234	235	236	240	242	243	245	246	248	—	—	—	—	—	—
Port Authority of N.Y. & N.J., hangar cost	217	233	256	280	279	280	281	284	283	283	283	283	284	290	293	295	305	—	—

Base 1967 = 100

**Smith, Hinchman & Grylls is an A-E firm. Water and Power Resource Services (formerly BuRec) †Adjusted for productivity. Prepared by E.H. Boeckh Co., div. of American Appraisal Assoc., Inc. p-preliminary * na-not available *For latest 12 mo period recorded r revised.

84 *ENR / June 18, 1981*

[a] Source: Engineering News-Record. (The indexes shown here reflect data as of 1st of the indicated month; also, they have been shifted from the 1913=100 to the 1967=100 base by the U.S. Department of Commerce.

The Construction Cost Index and the Building Cost Index have 4 components each, three material items and labor. The material items for both indexes are: (1) The base price of structural steel shapes, which from 1913 (the ENR base period) through July 1938 is at Pittsburgh only and since then is a three-mill average for Pittsburgh, Gary, and Birmingham; (2) consumers' net price of cement exclusive of bags, f.o.b. Chicago, from 1913 through June 1948, and since then a 20-city average of f.o.b. bulk prices; (3) lumber, which in 1913 and through 1935 was 3" x 12" to 12" x 12" long leaf yellow pine, wholesale, at New York, and beginning 1936 is 2" x 4" S4S pine and fir in carload lots (ENR 20-city average). The labor component of the Construction Cost Index, which is designed to show the movement of construction cost in general, is the common labor rate, ENR 20-city average, while the labor component of the Building Cost Index is the ENR 20-city average for skilled labor. The labor rates are shown on p. 75 under construction wages.

The component series are weighted according to their relative importance as determined by the compilers. As a step in arriving at proper weights, the average production of steel and cement in the years 1913, 1916, and 1919, average production of lumber for 1913 and 1916, and the number of common industrial laborers, according to the 1910 Census, were placed on a dollar-value basis using 1913 average prices as compiled by ENR wherever possible. These data are shown in the following table:

	Value	Percent
33,000,000 short tons steel at $30	$ 990,000,000	24
90,000,000 barrels cement at $1.19	107,100,000	3
42,000,000 M board feet lumber at $28.50.	1,197,000,000	29
1,200,000,000 man-days at $1.52 (8 hours).	1,822,000,000	44
Total	4,116,000,000	1

It should be noted that these data represent total production in the United States and not amounts used in the construction industry. According to the Engineering News-Record, they were used as a guide, but the proportions of the items were adjusted to their importance in the construction industry with the aid of experienced construction men. An expenditure of approximately $100 on the four items in these proportions was assumed for 1913 (the ENR base period) and the quantities of the three materials and the man-hours of labor that could be purchased for these amounts were computed. Purchases of similar quantities of these four items were assumed to be made at each successive period.

The expenditure of $100, at 1913 prices, for the proper quantities of each item in the Construction Cost Index is given below, and it may be noted that the "adjustment" mentioned above is an important factor.

2,500 pounds of structural steel at $0.015 (Pittsburgh base) (see next paragraph below)	$37.50
6 barrels of cement at $1.19 (net barrel, f.o.b. Chicago) (see 2d paragraph below)	7.14
600 board feet, Southern pine, 3" x 12" to 12" x 12" at $28.50 per M ft. (New York base) (see 3d paragraph below)	17.10
200 man-hours at $0.19 (common labor, average for country)	38.00
Total.	99.74

The adoption of the three-mill average for structural steel shapes in August 1938 did not necessitate any change in the weighting of this component.

In July 1948, when cement went off basing point pricing 20-city average cement price was substituted; no adjustment in the weight factor was necessary.

For the Southern pine lumber series prior to 1936 the weight was 600 board feet. In linking this series with the series for 2" x 4" pine and fir, the 1936 average value of lumber of the old type as included in the index was first determined (quantity weight, 600 board feet, times the average price for the year). The equivalent 1936 average value of the new type was represented by 1,088 board feet of lumber, which quantity is now used as the weighting factor.

The Building Cost Index is computed in the same manner as the Construction Cost Index, except that the skilled labor trend is substituted for common labor. Since the skilled rate is considerably higher than the common rate, a weight of 68.38 man-hours was substituted for the common labor weight of 200 man-hours used in the Construction Cost Index, as shown in the table above, in order to have the same labor component in the base period when the rate was multiplied by the weight. The computation for labor in 1913 for the Building Cost Index is 68.38 x $0.555, which gives approximately $38.00. The trends of the two indexes reflect the divergent movements of wage rates for common and skilled labor.

Monthly data for 1967-74 for Building and Construction Cost Indexes appear in the 1971 and subsequent editions of BUSINESS STATISTICS (see reference note, p. 1 of this section; data for 1951-66 are available upon request.

TABLE 25 - 1979 STATISTICAL SUPPLEMENT TO THE SURVEY OF CURRENT BUSINESS

CONSTRUCTION AND REAL ESTATE—CONSTRUCTION COST INDEXES AND CONSTRUCTION MATERIALS

YEAR AND MONTH	CONSTRUCTION COST INDEXES: Boeckh indexes[1], Average, 20 cities: Apartments, hotels, and office buildings	Commercial and factory buildings	Residences	Engineering News-Record[2]: Building	Construction	Federal Highway Administration[1]: Federal-aid highway construction, composite index (average for year or quarter)	CONSTRUCTION MATERIALS OUTPUT[4]: Composite index: Unadjusted for seasonal variation	Adjusted for seasonal variation	Selected components, unadjusted for seasonal variation: Iron and steel products	Lumber and wood products	Portland cement
	1972 = 100			1967 = 100			1947–49 = 100				
1947	33.4	33.0	37.4	44.60	38.80	....	98.8	....	98.4	98.1	93.0
1948	37.7	37.3	42.1	51.30	43.04	....	103.1	....	102.1	106.2	107.4
1949	38.2	37.7	41.0	52.38	44.56	....	97.8	....	101.3	98.0	104.6
1950	39.8	38.2	43.2	55.91	47.61	80.8	117.0	....	120.9	118.2	112.7
1951	43.0	42.4	46.6	60.86	50.09	81.8	115.5	....	125.8	114.2	122.7
1952	44.4	43.8	47.8	61.88	53.20	84.1	111.6	....	113.8	114.5	124.2
1953	45.8	45.4	48.7	64.16	56.06	81.0	118.4	....	120.8	115.7	131.8
1954	46.2	45.9	48.3	68.37	58.67	76.4	120.3	....	121.2	117.3	138.2
1955	47.6	47.4	49.7	69.91	61.83	74.3	132.8	....	139.6	128.8	147.9
1956	49.8	49.9	51.9	73.08	64.68	84.0	134.7	....	145.8	128.0	157.7
1957	51.4	51.7	52.9	75.75	67.62	87.7	127.3	....	148.7	118.7	148.5
1958	52.3	52.8	53.4	78.13	70.82	86.8	126.4	....	129.8	122.0	155.3
1959	54.1	54.6	56.2	81.58	74.45	82.0	138.2	....	121.4	130.8	160.0
1960	56.2	56.5	58.1	83.31	76.04	80.1	130.2	....	128.6	127.0	160.0
1961	56.8	56.0	56.2	84.61	78.13	80.7	129.6	....	130.2	128.0	161.6
1962	57.7	57.2	57.2	86.36	81.45	84.3	134.5	....	131.6	134.6	167.7
1963	58.6	58.4	58.4	88.47	84.15	86.4	142.6	....	140.7	140.4	175.7
1964	60.3	60.2	60.1	91.10	87.48	86.9	153.5	....	154.2	152.8	182.6
1965	62.4	62.2	62.0	93.31	90.73	80.3	157.8	....	161.1	157.0	186.5
1966	64.8	64.8	64.7	96.86	95.21	86.1	150.8	....	160.0	158.2	189.8
1967	68.8	69.1	68.8	100.00	100.00	100.0	156.2	....	163.0	151.8	186.6
1968	73.8	73.8	73.6	107.38	107.81	103.4	159.1	....	171.1	168.2	188.1
1969	79.8	79.1	79.7	117.86	118.69	111.8	168.7	....	167.8	164.5	204.2
1970	85.8	85.0	84.0	124.37	128.89	125.6	164.3	....	166.4	162.3	194.3
1971	92.8	92.5	91.1	140.49	146.74	131.7	175.7	....	163.8	182.7	200.0
1972	100.0	100.0	100.0	155.18	163.04	138.2	[8]189.7	....	175.0	193.8	219.4
1973	105.9	106.6	109.2	168.47	176.52	152.4	184.1	....	183.1	194.6	225.4
1974	115.8	118.1	118.0	178.31	187.09	201.8	181.1	....	181.8	171.6	215.3
1975	127.2	130.4	125.8	193.30	205.97	203.8	180.4	....	140.9	166.9	182.9
1976	137.3	141.6	138.2	210.34	223.43	199.3	176.4	....	141.9	181.2	182.3
1977	148.8	152.8	148.6	229.58	230.95	218.4	180.4	....	147.3	199.8	208.7
1978	158.2	164.3	161.8	247.72	258.43	294.9	....	....	158.6	198.8	226.2
1975. January	122.8	128.2	122.1	183.81	195.78		137.0	144.8	152.7	133.5	114.9
February				187.23	198.08	207.3	136.3	152.4	138.5	138.7	106.0
March	125.6	130.4	123.8	187.26	198.07		148.8	153.2	142.8	164.8	131.4
April				187.84	198.76		182.3	158.1	147.0	172.3	172.1
May	126.8	128.7	125.1	190.64	201.43	198.3	187.7	154.2	136.4	175.7	204.0
June				193.48	204.80		150.7	155.3	128.9	170.3	213.8
July	129.0	131.3	128.4	196.01	208.85		170.5	177.2	135.8	172.7	232.3
August				196.93	211.31	203.0	178.7	181.8	148.0	178.2	234.3
September	129.4	132.6	127.9	197.25	211.41		179.8	176.0	157.1	186.8	232.7
October				200.05	213.06		185.8	167.5	161.9	187.8	248.8
November	131.1	134.4	128.8	198.81	212.92	208.8	147.2	154.6	122.1	157.7	188.6
December				200.48	213.43		144.2	165.8	123.3	162.3	136.3
1976. January	131.8	136.4	130.5	201.61	214.18		151.3	158.2	173.8	178.9	108.2
February				202.82	219.05	200.3	154.6	174.0	170.5	175.9	172.7
March	133.7	138.5	131.6	204.04	215.72		183.0	188.9	157.2	202.2	188.0
April				206.65	216.66		164.5	180.9	153.3	198.5	198.2
May	137.4	141.8	138.9	208.97	219.40	200.4	178.2	186.0	153.3	183.3	205.5
June				209.53	224.32		182.2	178.4	185.7	190.0	238.7
July	139.8	142.7	137.7	210.99	224.70		179.3	186.8	142.4	182.4	230.9
August				215.30	227.81	199.0	181.1	174.9	147.7	202.2	251.1
September	139.5	143.7	139.0	217.46	229.80		183.9	178.9	147.7	199.5	233.6
October				218.45	230.71		182.0	164.0	139.8	204.2	272.7
November	142.6	147.0	142.8	218.92	231.47	200.4	168.3	176.6	129.0	188.7	180.4
December				219.67	231.78		155.3	178.9	122.7	186.9	138.6
1977. January	143.6	147.9	143.3	220.36	232.21		144.5	161.8	106.5	185.5	83.5
February				221.87	233.18	202.2	152.9	172.5	118.8	184.2	125.0
March	146.3	150.1	145.3	222.80	232.85		184.7	200.9	180.2	217.3	187.6
April				222.88	235.06		182.6	180.1	148.0	201.4	213.6
May	147.8	151.8	147.0	223.01	234.11	218.4	182.9	177.7	156.8	203.1	238.3
June				225.16	234.61		199.2	188.0	187.0	201.4	268.6
July	149.8	154.2	149.8	227.86	240.11		176.4	184.3	148.5	182.1	243.9
August				229.79	243.06	215.9	204.8	187.5	170.5	234.8	272.3
September	151.5	155.7	152.2	234.88	246.16		182.1	187.9	101.1	207.9	250.9
October				239.37	248.03		187.5	187.5	149.4	206.8	285.5
November	152.5	157.5	153.7	237.21	247.58	233.0	172.8	180.7	142.2	186.7	206.1
December				237.88	248.51		183.3	187.3	139.1	186.5	154.3
1978. January	154.0	168.5	155.6	237.74	248.78		148.4	166.9	124.9	187.1	81.7
February				238.99	248.63	219.5	153.6	174.1	129.2	186.8	110.8
March	156.3	160.9	157.5	239.49	250.66		136.8	193.9	161.9	212.7	188.1
April				239.88	251.18		....	....	168.9	194.2	226.6
May	156.7	163.0	158.8	244.59	254.45	258.1	....	....	176.4	209.6	268.6
June				246.15	256.34		....	....	180.9	206.0	297.8
July	158.6	166.2	162.0	251.00	262.59		....	....	153.2	177.6	261.8
August				252.34	263.34	296.1	....	....	173.8	207.2	301.2
September	160.7	167.5	166.4	254.54	265.38		....	....	159.4	198.7	296.4
October				254.76	265.38		....	....	173.2	204.8	289.9
November	163.8	170.9	170.9	256.31	266.30	302.7	....	....	158.8	193.4	276.4
December				258.70	267.04		....	....	152.8	181.8	173.2

[illegible]

See Reference 70

TABLE 25 - Construction Cost Indexes, 1915-78

(1972=100)

Year	Department of Commerce composite cost index*	American Appraisal Company	Engineering-News Record		Environmental Protection Agency		Federal Highway Administration		Bureau of the Census new one family houses excluding Census lot value	Bureau of Reclamation
			Building	Construction	Sewers	Plant	Structures	Composite		
1915	13	8	9.1	5.3						
1916	15	9	12.4	7.4						
1917	19	11	15.9	10.3						
1918	23	13	15.2	10.8						
1919	26	17	15.2	11.3						
1920	33	20	19.8	14.4						
1921	26	16	15.9	11.5						
1922	24	15	14.8	9.9			21.4	38.9		
1923	26	16	17.7	12.2			24.5	43.3		
1924	26	16	17.8	12.3			24.2	41.6		
1925	26	16	17.5	11.8			23.4	39.5		
1926	26	16	17.7	11.9			23.4	38.1		
1927	26	16	17.7	11.8			22.9	37.5		
1928	26	16	17.9	11.8			21.7	35.0		
1929	26	16	18.3	11.9			21.4	33.9		
1930	25	15	17.8	11.7			20.2	31.5		
1931	23	13	16.2	10.4			18.1	28.2		
1932	20	12	13.4	9.0			15.4	22.4		
1933	22	11	14.0	9.7			16.3	28.1		
1934	24	12	16.0	11.3			18.2	30.9		
1935	24	12	15.9	11.2			18.4	29.6		
1936	24	12	16.4	11.8			20.3	30.5		
1937	26	14	18.7	13.4			20.6	29.2		
1938	26	14	18.7	13.4			19.6	26.8		
1939	24	15	18.9	13.5			19.3	26.7		
1940	25	15	19.5	13.9			19.8	26.3		24
1941	27	16	20.2	14.7			22.7	29.9		27
1942	31	18	21.2	15.8			27.5	40.0		32
1943	33	18	21.8	16.6			30.3	45.9		38
1944	33	20	22.6	17.1			30.8	41.6		37
1945	34	20	22.9	17.7			29.9	40.1		39
1946	40	23	25.0	19.8			37.1	43.8		39
1947	47.7	32	29.8	23.6			44.4	49.6		45
1948	52.4	36	32.9	26.3			50.5	55.6		50
1949	52.3	36	33.8	27.3			47.4	53.6		52
1950	53.2	36	36.0	29.3			42.8	48.2		49
1951	58.0	39	38.5	31.1			53.2	59.2		53
1952	59.6	40	39.9	32.6			54.3	60.9		56
1953	59.9	42	41.3	34.4			54.2	58.6		58
1954	59.4	43	42.8	36.0			50.7	55.3		56
1955	60.5	44	45.0	37.8			50.4	53.8		55
1956	64.1	46	47.1	39.7			58.8	60.8		60
1957	65.8	48	48.8	41.5	52.2	57.0	62.2	63.5		64
1958	65.2	50	50.3	43.5	54.1	59.0	56.8	61.9		64
1959	65.0	51	52.6	45.6	56.5	61.4	54.3	59.3		64
1960	64.8	53	53.7	47.2	57.2	61.0	52.8	58.0		63
1961	64.7	54	54.5	48.5	58.3	61.6	53.3	58.4		63
1962	65.5	55	55.7	49.9	59.1	62.2	53.8	61.0		65
1963	66.0	57	57.0	51.6	61.0	63.1	57.0	62.5	70.2	66
1964	65.9	59	58.7	53.7	61.8	64.0	58.0	62.9	69.9	67
1965	67.2	60	60.1	55.6	62.8	65.1	60.7	65.3	70.5	69
1966	69.8	63	62.4	58.4	64.9	67.5	65.0	69.5	73.4	70
1967	72.4	66	64.4	61.3	67.1	69.4	71.1	72.4	75.7	73
1968	76.1	71	69.2	66.1	69.8	71.9	72.2	74.8	76.7	76
1969	82.7	77	75.8	72.8	74.7	77.2	84.1	80.9	85.3	80
1970	88.6	83	80.2	79.1	80.7	83.5	94.0	90.9	89.1	86
1971	94.8	92	90.5	90.0	90.1	92.9	98.5	95.3	94.0	93
1972	100.0	100	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100
1973	108.7	111	108.5	108.3	107.5	106.2	111.3	110.3	109.5	106
1974	126.9	117	114.9	115.5	124.2	126.3	152.6	146.0	120.8	119
1975	138.4	125	124.5	126.2	139.5	145.3	149.7	147.5	131.6	139
1976	143.9	137	135.9	137.1	148.2	152.5	140.5	144.2	141.1	149
1977	156.5	146	147.3	147.2	157.6	161.8	147.1	156.6	158.1	158
1978	175.7	159	159.6	158.5	172.6	177.1	173.5	191.7	180.2	167

See footnotes at end of table.

See Reference 72

April 19, 1982

In 1959 we were paying \$10.00 per sq. ft.

In 1982 we estimate cost to be \$30.00 per sq. ft.

1980

1979 we were paying \$50 - 45 per sq. ft. based on competition.

H. G. Plato Jr., P.E.

Assistant Bridge Engineer

Appendix E

Existing or Under Construction Reservoirs with Their Median Capacities in Oklahoma

TABLE 26 - Existing or Under Construction Reservoirs with Their Median Capacities in Oklahoma

Basin No.	Major River Basin	Name Stream or Creek	Name of Storage	Flood Control Storage Acre Ft.	Water Supply Storage Acre Ft.	Water Supply Yield Acre Ft.	Date of Completion
1	Arkansas River Basin (Main Stem & Minor & Tributaries	Polecat Creek	Hejburn Lake	48400	2000	1900	1950
		Arkansas River	Kaw Lake	866,000	203,000	230,700	1976
		Arkansas River	Keystown Lake	1,218,500	20,000	22,400	1964
		Big & Little Turkey Creek	Lake Ponca	0	15,300	9,000	1935
		Main Stem of Arkansas River	Robert S. Kerr	0	0	0	1970
		Greasy Creek	Sooner Lake	47,500	149,000	3,600	1976
		Arkansas	Webbers Falls	0	0	0	1970
			Total	2,180,400	389,300	267,600	
		Median = 457,200 (AC-Ft/Yr)					
2	Salt Fork River Basin	Salt Fork of Ark. River	Greet Salt Plains Lake	240,000	0	0	1940
			Total	240,000	0	0	
		Median = 240,000 (Ac-Ft/Yr)					
3	Cimarron River Basin	Still-water Creek	Lake Carl Blackwell	0	55,000	7,000	1948
		North Still-water Creek	Lake McMurtry	5,000	135,000	3,000	1971
			Total	5,000	190,000	10,000	

TABLE 26 - Continued

Basin No.	Major River Basin	Name Stream or Creek	Name of Storage	Flood Control Storage Acre Ft.	Water Supply Storage Acre Ft.	Water Supply Yield Acre Ft.	Date of Completion
4	Verdigris River Basin	Birch Creek	Birch Lake	39,000	15,200	6,700	1977
		Candy Creek	Candy Lake	312,600	43,100	8,620	1982
		Little Caney River	Copan Lake	184,300	33,600	21,300	1981
		Caney River	Hulah Lake	257,900	27,000	19,000	1951
		Verdigris River	Oologah Lake	965,600	342,600	172,500	1974
		Homing Creek	Skiatook Lake	182,300	304,800	85,100	1982
			Total	1,941,700	766,300	313,220	
			Median = 221,100 (Ac-Ft/Yr.)				
5	Grand (Neosho) River Basin	Spovinaw Creek	Eucha Lake	0	79,600	84,000	1952
		Grand (Neosho) River	Fort Gibson Lake	919,200	0	0	1953
		Grand (Neosho) River	Grand Lake O'The Cherokees	525,000	0	0	1940
		Spavinaw Creek	Spaninaw Lake	0	30,600	0	1924
		Butler Creek	Wash Hudson Lake	244,200	0	0	1964
			Total	1,688,400	110,200	84,000	
			Median = 244,200 (AC-Ft/Yr.)				
6	Ill. River Basin	Illinois River	Tenkiller Lake	576,700	25,400	17,900	1953
			Total	576,700	25,400	17,900	
			Median = 576,700 (AC-Ft.Yr.)				

TABLE 26 - Continued

Basin No.	Major River Basin	Name Stream or Creek	Name of Storage	Flood Control Storage Acre Ft.	Water Supply Storage Acre Ft.	Water Supply Yield Acre Ft.	Date of Completion
7	Canadian River Basin	Deep Fork	Arcadia Lake	70,700	27,380	12,100	1984
		North Canadian River	Canton Lake	267,800	107,000	13,440	1948
		East Elm Creek	Draper Lake	0	100,000	86,000	1962
		Wolf Creek	Fort Supply Lake	86,800	400	220	1942
		Canadian River	Lake Eufaula	1,470,000	56,000	56,000	1964
		Bluff Creek	Lake Hefner	0	75,000	17,000	1943
		North Canadian River	Lake Overholser	0	17,000	5,000	1967
		Little River	Lake Thunderbird	76,600	105,900	21,700	1965
		North Canadian River	Optima Lake	71,800	76,200	5,400	1978
		South Deer Creek	Shawnee Lakes	0	34,000	4,400	1935
			Total	2,043,700	598,880	221,260	
		Median = 81,700 (AC-Ft/Yr.)					
8	Poteau River Basin	Poteau River	Wister Lake	400,000	9,600	6,700	1949
			Total	400,00	9,600	6,700	
		Median = 400,000 (AC-Ft/Yr.)					
9	Red River Basin (Main Stem and Minor Tributaries	East Cache Creek	Lake Ellsworth	0	68,700	9,500	1962
		Cache Creek	Lake Lawtonka	0	64,000	8,500	1905
		Tributary of Hichory Creek	Lake Murray	0	0	0	1937
		Red River	Lake Texoma	2,669,000	22,100	23,700	1944
		Beaver Creek	Waurika Lake	131,900	170,200	44,800	1977
			Total	2,800,900	325,000	86,500	
		Median - 1,400,540 (AC-Ft/Yr.)					

TABLE 26 - Continued

Basin No.	Major River Basin	Name Stream or Creek	Name of Storage	Flood Control Storage Acre Ft.	Water Supply Storage Acre Ft.	Water Supply Yield Acre Ft.	Date of Completion
10	North Fork of Red River Basin	North Fork of Red River	Altus Lake	19,600	146,000	18,600	1948
		Otter Creek	Tom Steed Lake	19,500	88,160	16,000	
			Total	39,100	234,160	34,600	
		Median = 117,808 (AC-Ft/Yr.)					
11	Washita River Basin	Rock Creek	Arbuckle Lake	36,400	62,600	22,700	1967
		Cobb Creek	Fort Cobb Lake	63,330	78,350	13,300	1959
		Washita River	Foss Lake	180,400	203,700	18,000	1961
			Total	280,130	344,640	54,00	
		Median = 62,600 (AC-Ft/Yr.)					
12	Boggy Creek Basin	North Boggy Creek	Atoka Lake	0	123,500	65,000	1964
		McGee Creek	McGee Creek Lake	85,000	109,800	71,800	1985
			Total	85,000	233,300	370,100	
		Median - 116,650 (AC-Ft/Yr.)					
13	Kiamachi River Basin	Jack Fork Creek	Clayton Lake	128,200	297,200	156,800	1981
		Kiamichi River	Hug Lake	809,100	121,500	165,800	1947
			Total	937,300	418,700	322,600	
		Median = 468,650 (AC-Ft/Yr.)					
14	Little River Basin	Mountain Fork River	Broken Bow Lake	450,000	152,500	196,000	1970
		Little River	Pine Creek Lake	388,100	70,500	134,400	1969
			Total	838,100	223,000	330,400	
		Median = 419,050 (AC-Ft/Yr.)					
			State Total	13,816,430	3,868,090	2,034880	

Source Adapted from Reference 2

Appendix F

An Analytical Storage Procedure to Accompany and Explain Tables 12, 13, 14, and 15 on the Cimarron River in the Basin 2 with Compare to Table 29.

TABLE 27 - An Analytical Storage Procedure to Accompany and Explain Tables 12, 13, 14 and 16 on the Cimarron River on the Basin 2

	Period of Record	Annual Flow C.F.S.	60% of M.A.F. C.F.S.	Cumulative 60% of M.A.F. C.F.S.	90% of Mean Annual Flow Draft 0 C.F.S.	Deficiency 0-I C.F.S.	Cumulative C(0-I) C.F.S.	70% Mean Annual Flow Draft 0 C.F.S.	Deficiency 0-I C.F.S.	Deficiency ε(0-I) C.F.S.	50% of Mean Annual Flow Draft 0 C.F.S.	Deficiency 0-I C.F.S.	Deficiency ε(0-I) C.F.S.
1	1940	307	184	184	632	448	52	491	307	307	351	167	167
2	1941	1255	753	937	632	-121	0	491	-262	0	351	-402	0
3	1942	2603	1562	2499	632	-930	0	491	-1071	0	351	-1211	0
4	1943	882	529	3028	632	103	103	491	-38	0	351	-178	0
5	1944	1111	667	3695	632	-35	68	491	-176	0	351	-316	0
6	1945	1509	905	4600	632	-273	0	491	-414	0	351	-554	0
7	1946	521	313	4913	632	319	319	491	178	178	351	38	38
8	1947	1482	889	5802	632	-257	62	491	-398	0	351	-538	0
9	1948	822	493	6295	632	139	201	491	-2	0	351	-142	0
10	1949	2317	1390	7685	632	-758	0	491	-899	0	351	-1039	0
11	1950	1453	872	8557	632	-240	0	491	-381	0	351	-521	0
12	1951	1986	1192	9749	632	-560	0	491	-701	0	351	-841	0
13	1952	454	274	10023	632	358	358	491	217	217	351	77	77
14	1953	235	141	10164	632	491	849	491	350	567	351	210	287
15	1954	305	183	10347	632	449	1298	491	308	875	351	168	455
16	1955	1349	809	11156	632	-177	1121	491	-318	557	351	-458	0
17	1956	543	326	11482	632	306	1427	491	165	722	351	25	25
18	1957	3450	2070	13552	632	-1438	0	491	-1579	0	351	-1719	0
19	1958	950	570	14122	632	62	62	491	-79	0	351	-219	0
20	1959	695	417	14539	632	215	215	491	74	74	351	-66	0
21	1960	2705	1623	16162	632	-991	0	491	-1132	0	351	-1272	0
22	1961	1449	869	17031	632	-237	0	491	-378	0	351	-918	0
23	1962	1345	807	17838	632	-175	0	491	-316	0	351	-456	0
24	1963	929	557	18395	632	75	75	491	-66	0	351	-206	0
25	1964	426	256	18651	632	376	451	491	235	235	351	95	95
26	1965	981	584	19240	632	43	494	491	-98	137	351	-238	0
27	1966	371	223	19463	632	409	903	491	268	405	351	128	128
28	1967	514	308	19771	632	324	1227	491	183	588	351	43	171
29	1968	559	330	20101	632	302	1529	491	161	749	351	21	192
30	1969	1055	633	20734	632	-1	1528	491	-142	607	351	-282	0
31	1970	375	237	20971	632	395	1923	491	254	861	351	114	114
32	1971	294	176	21147	632	456	2379	491	315	1176	351	175	288
33	1972	438	263	21410	632	369	2748	491	228	1404	351	88	376
34	1973	2039	1273	22633	632	-591	2157	491	-732	672	351	-872	0
35	1974	2306	1384	24017	632	-752	1405	491	-893	0	351	-1033	0
36	1975	3605	2163	26180	632	-1531	0	491	-1672	0	351	-1812	0
37	1976	551	331	26511	632	301	301	491	160	160	351	20	20
38	1977	721	433	26944	632	199	500	491	58	218	351	-82	0
39	1978	525	315	27259	632	317	817	491	176	394	351	36	36
40	1979	886	532	27791	632	100	917	491	-41	353	351	-181	0
41	1980	1658	995	28786	[illegible]	-363	554	491	-504	0	351	-644	0
	Ave.	1170	702										

Table 28 A Comparison of the results from Tables 12, 13, 14, and 16 with the Analytical Procedure from Table 29 on the Cimarron River at mouth.

Comparison Results	90% of (60% of Mean Annual Flow) AC-Ft/Yr	70% of 60% of Mean Annual Flow) AC-Ft/Yr	50% of 60% of Mean Annual Flow) AC-Ft/Yr
Results from Tables 12, 13, 14 and 16	2,046,893	1,023,446	301,647
Results of Analytical Procedure from Table 29	2,108,925	1,077,486	288,557
Percentage of Difference	3%	5%	4%