# SIMULATED EFFECTS OF PROPOSED RESERVOIR-DEVELOPMENT ALTERNATIVES ON STREAMFLOW QUANTITY IN THE WHITE RIVER, COLORADO AND UTAH

By Gerhard Kuhn and Sherman R. Ellis

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CONTENTS

ILLUSTRATIONS

CONTENTS



TABLES



METRIC CONVERSIONS

| *Multiply inch-pound unit* | *By* | *To obtain metric unit* |
|---|---|---|
| acre-foot (acre-ft) | 0.001233 | cubic hectometer ($hm^3$) |
| acre-foot per year (acre-ft/yr) | 0.001233 | cubic hectometers per year ($hm^3/yr$) |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meters per second ($m^3/s$) |
| foot (ft) | 0.3048 | meter (m) |
| inch (in.) | 25.40 | millimeter (mm) |
| mile (mi) | 1.609 | kilometer (km) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |

# SIMULATED EFFECTS OF PROPOSED RESERVOIR-DEVELOPMENT ALTERATIVES ON STREAMFLOW QUANTITY IN THE WHITE RIVER, COLORADO AND UTAH

By Gerhard Kuhn and Sherman R. Ellis

## ABSTRACT

Numerous reservoirs have been proposed for the White River basin in Colorado and Utah, primarily to provide water for oil-shale development. The effect of streamflow depletion by four of the proposed reservoirs on a period of historical streamflow, the 1932-81 water years, was simulated using a multireservoir-flow model. The proposed reservoirs considered in the study were Avery, Powell Park, Kenney (Taylor Draw Dam), and White River Reservoirs; construction of Taylor Draw Dam was completed during the study.

Four configurations of the proposed reservoirs were simulated. The reservoir configurations were assumed to operate as a combined system, to provide the annual demand of each individual reservoir, while still meeting the minimum streamflow requirements. The current water-use pattern, which depletes about 40,000 acre-feet per year and is dominated by irrigation of hay meadows and pastureland, was maintained in the simulations.

Minimum streamflow requirements were met in the simulation of one two-reservoir configuration, except when historical streamflow was less than the minimum requirement. Average streamflow depletion was about 93,000 acre-feet per year in this simulation. The three-reservoir configuration, which would have depleted an average of 168,000 acre-feet per year, would not have fulfilled the minimum streamflow requirements for 1 or 2 months in 13 different years. Minimum streamflow shortages occurred less often with the four-reservoir simulation, even though average annual streamflow depletion would have been about 222,000 acre-feet. Another two-reservoir configuration, but with a large reservoir used to provide the water-use requirements of three smaller reservoirs, also was simulated. This simulation resulted in no minimum streamflow shortages and an average annual streamflow depletion from the White River of about 226,000 acre-feet. Simulated streamflow throughout the year generally became smaller and more constant as streamflow depletion increased.

Relations between reservoir active capacity and yield applicable to the White River also were developed. These relations show that reservoir storage of about 400,000 acre-feet is the maximum practicable for the White River.

# INTRODUCTION

Historically, the primary use of streamflow in the White River basin, Colorado and Utah (fig. 1), has been agricultural, for the irrigation of hay meadows, pastureland, and some grain fields. Industrial and municipal use of streamflow has been, and still is, small. However, proposed development of the area's oil-shale and coal resources will require considerable quantities of water for industrial, municipal, and recreational uses. In conjunction with energy development, the U.S. Bureau of Reclamation (U.S. Water and Power Resources Service 1980, p. 80-92) estimates annual water needs in the White River basin by the year 2000 could be about 190,000 acre-ft or more, and they list 40 proposed reservoirs for the basin (p. 95-96) which indicate that streamflow from the White River will be a probable source for much of the additional water needs. Average streamflow of the White River during the past 50 years (1932-81 water years) is about 488,000 acre-ft/yr, whereas current water use (depletion) probably is no more than 40,000 acre-ft/yr. Thus, the White River seems to have the potential to supply additional water. However, for the best use of the river's available water resources, the effect of the proposed developments on streamflow and the current agricultural uses of streamflow needs to be determined.

## Purpose and Scope

The primary purpose of this report is to show the ways in which streamflow in the White River may be affected by water-resource developments proposed in conjunction with energy-resource developments. A second objective is to show how much water can be developed from the White River with different reservoir capacities and with annual shortages allowed for an increasing number of years. This study was part of a larger, ongoing study funded by the U.S. Geological Survey to determine the stream water-resource impacts of energy development within the White River basin (Hawkinson and Lystrom, 1983, p. 51-52).

Development of the White River's water-resources will be a complex process, involving many private and governmental entities and will require solutions to several unresolved issues. These aspects of streamflow development are beyond the scope of this report and, by necessity, were largely disregarded in this study. Three of the unresolved issues are discussed briefly in subsequent paragraphs; they are interstate allocation of water from the White River, Indian water rights, and minimum streamflow for endangered species. Two additional aspects also not considered herein are: (1) The ultimate effect of the proposed streamflow depletions on the salinity of the Colorado River; and (2) the effect of sediment deposition on the long-term yield of the proposed reservoirs.

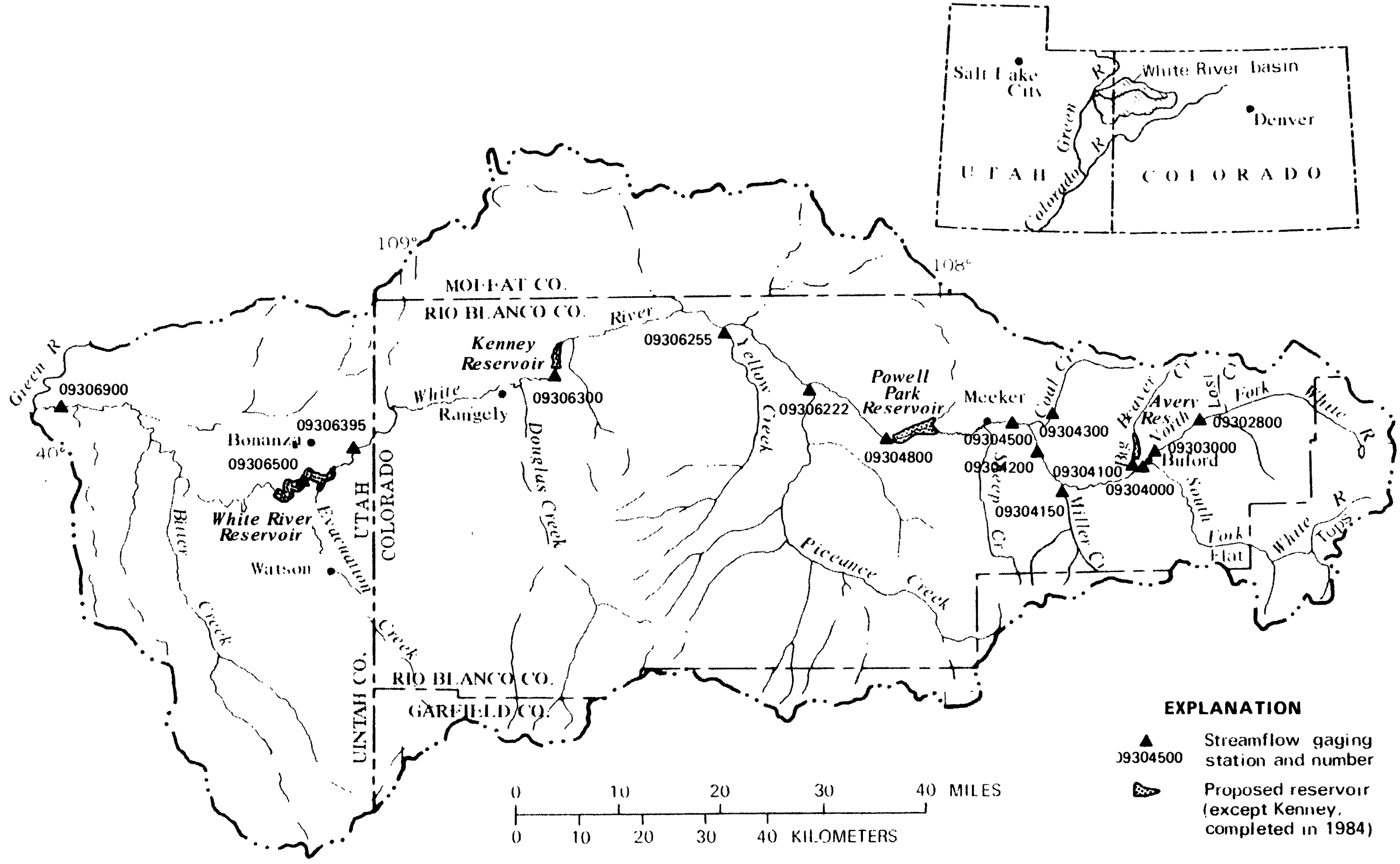



Figure 1.--Location of streamflow-gaging stations and proposed reservoirs, White River basin, used in multireservoir streamflow simulations.

In addition, this report is not to be construed as reflecting the present or future position of any State government of the Upper or Lower Colorado River Basin or of the Federal Government with regard to interpretation and application of the treaties, compacts, and laws, which do or may affect the allocation of water among the States and among private claimants within each State. In particular, nothing in this report is intended to interpret the provisions of the Colorado River Compact (45 Statute 1057), the Upper Colorado River Basin Compact (63 Statute 31), the Water Treaty of 1944 with the United Mexican States (Treaty Series 994, 59 Statute 1219), the decree entered by the Supreme Court of the United States in *Arizona v. California* (376 United States 340), the Boulder Canyon Project Adjustment Act (54 Statute 774; 43 United States Code 618a), the Colorado River Storage Project Act (70 Statute 105; 43 United States Code 620), or the Colorado River Basin Project Act (82 Statute 885; 43 United States Code 1501), or the Endangered Species Act (16 United State Code 16) or to interpret or reach any conclusions regarding future application of the Federal reserved-rights doctrine. Furthermore, nothing in this report shall be taken to represent the present or future position of either the State of Colorado or of the State of Utah, or of the United States, with regard to any matter concerning the use and development of the waters of the White River.

## Approach

In this study, a multireservoir-streamflow model (U.S. Army Corps of Engineers, 1976 and 1981), utilizing four of the proposed reservoirs, was used to simulate the effects on streamflow of various reservoir and water-use configurations. A 50-year period, the 1932 through 1981 water years (a water year is October 1 through September 30), was chosen as the study period. Long-term hydrologic conditions and water-use were assumed not to have changed significantly during this period.

The model was first calibrated to historical streamflow records (those for 1932-81 water years), which were extended in time whenever the records were incomplete during the 50 years. Methods used to extend the records are discussed in a subsequent section of this report. Following calibration, four streamflow simulations were made with four alternative reservoir and water-use configurations, to determine the effects of these configurations on streamflow and current water-use requirements. Also, the amount of any shortages in the annual delivery requirements of each reservoir and water-use configuration was determined. The results of the simulations provide water resource managers and planners some insight into how proposed reservoir development would affect streamflow and diversions in the White River.

Following this, numerous simulations were made with a single reservoir, which was varied in size, with varying water-use demands for each size. These simulations give an indication of the maximum yield for a given reservoir size, and the increase in yield with increases in the number of years with shortages.

## Proposed Reservoirs

The 40 reservoirs proposed for the White River basin (U.S. Water and Power Resources Service, 1980, p. 95-96) have a combined storage capacity of about 2.12 million acre-ft, which is more than four times the average streamflow of the White River. Consequently, it seems reasonable to assume that only a few of these reservoirs will be constructed. The four reservoirs considered in this study (fig. 1), Avery, Powell Park, Kenney (the reservoir created by Taylor Draw Dam), and White River Reservoirs, were selected primarily because they represent the approximate sizes and operational flexibility required to serve the future needs of the basin.

Avery Reservoir, a component of the proposed Yellow Jacket Project (U.S. Water and Power Resources Service, 1980, p. 116-144), is described in some detail in an engineering feasibility report (International Engineering Company, Inc., 1982). Powell Park Reservoir was an interim alternative of the Yellow Jacket Project (International Engineering Company, Inc., 1982, p. IV-8, IV-9) and also is a proposed reservoir in the White River Study (International Engineering Company, Inc., 1983). Kenney Reservoir is described in an environmental impact statement (U.S. Army Corps of Engineers, 1982). Finally, White River Reservoir, proposed by the Utah Division of Water Resources, also is described in an environmental impact statement (U.S. Bureau of Land Management, 1982). Some general data for these reservoirs are presented in table 1.

The primary purpose of these reservoirs, except Kenney Reservoir, would be to provide water for oil-shale development. The primary purposes of Kenney Reservoir are hydroelectric power generation and water supply. Additional purposes indicated in the references cited above include: Coal development (Avery Reservoir only); agriculture (Avery and Kenney Reservoirs); municipal water (all except Powell Park Reservoir); recreation (all reservoirs); flood protection (all except Avery Reservoir); power generation (all except Avery Reservoir). Although the last use is specified in the proposals for three of the reservoirs, power generation was not included in the reservoir operations of this study.

## Unresolved Issues

### Interstate Water Allocation

An examination of alternative plans for water development in the White River basin requires that certain assumptions be made concerning allocation of water between the States of Colorado and Utah. Any interstate allocation of water from the White River would have to comply with provisions of the Upper Colorado River Basin Compact. For study purposes, it was assumed that shortages in the annual diversion requirements of the alternative reservoir configurations would be divided equitably between the States of Colorado and Utah.

Table 1.--*General data for proposed reservoirs used in multireservoir streamflow simulations*

| Proposed reservoir | Principal developer | Suggested active capacity (acre-feet) | Surface area (acres) | Proposed annual water yield (acre-feet)[1] |
|---|---|---|---|---|
| Avery[2] | Yellow Jacket Water Conservancy District. | 55,260 | 675 | [3]87,500 |
| Powell Park (small) | Unknown. | 110,000 | 4,300 | [3] [4]137,000 |
| Powell Park (large) | Unknown. | 300,000 | 5,000 | Unknown |
| Kenney (Taylor Draw Dam) | Colorado River Water Conservancy District. | 11,700 | 615 | 10,200 |
| White River | Utah Division of Water Resources. | 70,700 | 1,980 | 75,000 |

[1]Does not include evaporation losses.
[2]As a single component of the Yellow Jacket Project.
[3]Irrigation and municipal return flows not considered.
[4]In conjunction with Avery Reservoir.

## Indian Water Rights

There are 12,833 acres of irrigable lands within the Ute Indian Reservation in the White River drainage in Utah; water for these lands is claimed by the Ute Tribe under the Winters Doctrine [*Winters v. United States* (207 United States 564)]. Negotiations between the State of Utah and the Ute Tribe resulted in tentative agreement on a duty of 4.80 acre-ft per acre, or a total demand of 61,598 acre-ft; however, the Ute Tribe has not ratified this agreement (State of Utah, Division of Natural Resources, written commun., 1984). The monthly demands under this proposal are summarized in table 2.

In the environmental impact statement for the White River Reservoir, it was assumed that a reservoir release of 250 $ft^3/s$ for the purpose of maintaining fishery habitat also would satisfy the downstream demands for irrigation on the Indian reservation lands (U.S. Bureau of Land Management, 1982, p. 322). The value of 250 $ft^3/s$ also was used in this investigation.

Table 2.--*Proposed Ute Indian water rights from the White River in Utah*
[Source: U.S. Bureau of Land Management, 1982, p. 320]

| Month | Proposed water rights | |
|---|---|---|
| | Acre-feet per month | Cubic feet per second |
| April | 2,041 | 34.3 |
| May | 10,589 | 172.2 |
| June | 13,644 | 229.3 |
| July | 13,491 | 219.4 |
| August | 12,181 | 198.1 |
| September | 7,573 | 127.3 |
| October | 2,079 | 33.8 |
| TOTAL | 61,598 | |

## Minimum Streamflow Requirements for Endangered Species

Any study of the effects of proposed developments on the streamflow of the White River needs to include the flows required for endangered species identified in biological opinions for the Taylor Draw Reservoir Project (Kenney Reservoir) and for the White River Dam Project issued by the U.S. Fish and Wildlife Service. The Taylor Draw Dam biological opinion (U.S. Army Corps of Engineers, 1982, appendix E) states that "The majority of the time, the reservoir would be operated as a run of the river reservoir where the outflow from the dam would be the same as the inflow to the reservoir. During drought years (such as 1977), the dam will release a minimum of 200 cfs, 144,800 af, or natural flow, whichever is less." The White River biological opinion (U.S. Bureau of Land Management, 1982, appendix 4) states that flows downstream from the project would be 250 $ft^3/s$ or natural flows from August 1 to June 14, and an average of 500 $ft^3/s$ from June 15 to July 31 during normal years, but not less than 250 $ft^3/s$ in dry years.

## Acknowledgments

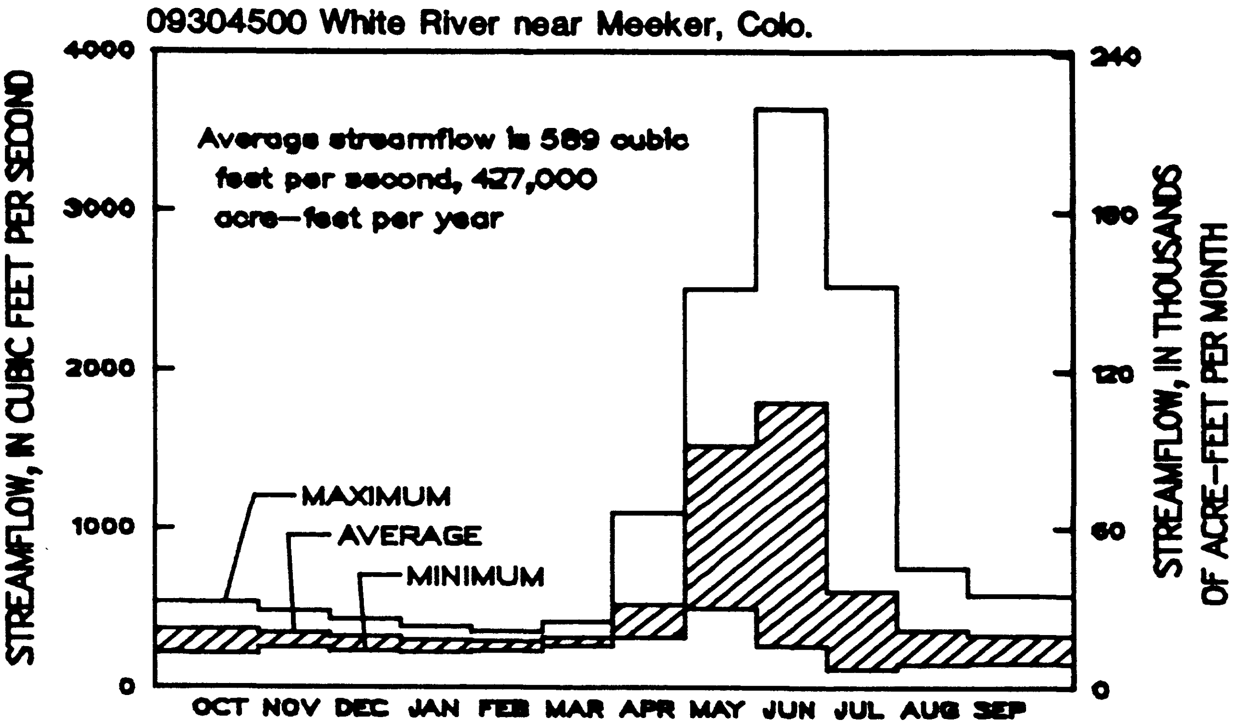
The Utah Department of Natural Resources, Water Resources Division, provided information regarding interstate allocation of water from the White River, the proposed Ute Indian water rights under the Winters Doctrine, minimum streamflow requirements for endangered species, and current water use in Utah. International Engineering Company, Inc., provided information regarding two of the proposed reservoirs and water rights associated with the Yellow Jacket Project. The Colorado Water Conservation Board provided information concerning the instream flow appropriations which were made under Colorado State law. However, this report does not necessarily reflect the views of the States of Colorado and Utah, or International Engineering Company, Inc., and they do not necessarily agree with the assumptions and conclusions stated in the report. Assistance provided by these organizations was very helpful in preparation of this report, and this assistance is gratefully acknowledged.


# HYDROLOGY

The White River basin is an area of highly varied topography and climate, resulting in varied hydrologic conditions. The extreme eastern one-fifth of the basin consists of mountains with elevations from about 8,500 to 12,000 ft above sea level. Precipitation in the higher mountains may be as much as 60 in. annually; therefore, this small, mountainous area produces most of the basin's streamflow. The remaining four-fifths of the basin generally is an area of rolling hills, with elevations from about 5,000 to 8,500 ft. Precipitation in this area is about 8 to 20 in. annually. Because precipitation is so scant, streams originating here usually are ephemeral, or if perennial, have a small average streamflow. The oil-shale and coal areas are in the semiarid part of the basin, near the White River.

## Streamflow Characteristics

Streamflow characteristics of the White River are similar to those of other major perennial streams in the Rocky Mountain region, where most streamflow results from snowmelt during late spring and early summer. The maximum, average, and minimum monthly streamflow at stations 09304500 White River near Meeker, Colo., and 09306500 White River near Watson, Utah, for the 1932-81 water years are shown in figure 2. About 60 percent of the average annual streamflow at these two stations occurs from April through July and about 45 percent occurs during the months of May and June. Within-year streamflow variability at these two stations is further illustrated by hydrographs of average daily streamflows for the 1969 water year, a typical streamflow year (fig. 3). Because the volume of flow is so unevenly distributed throughout the year, it is evident that storage of snowmelt runoff in reservoirs would be necessary to even the distribution of the White River's flow.



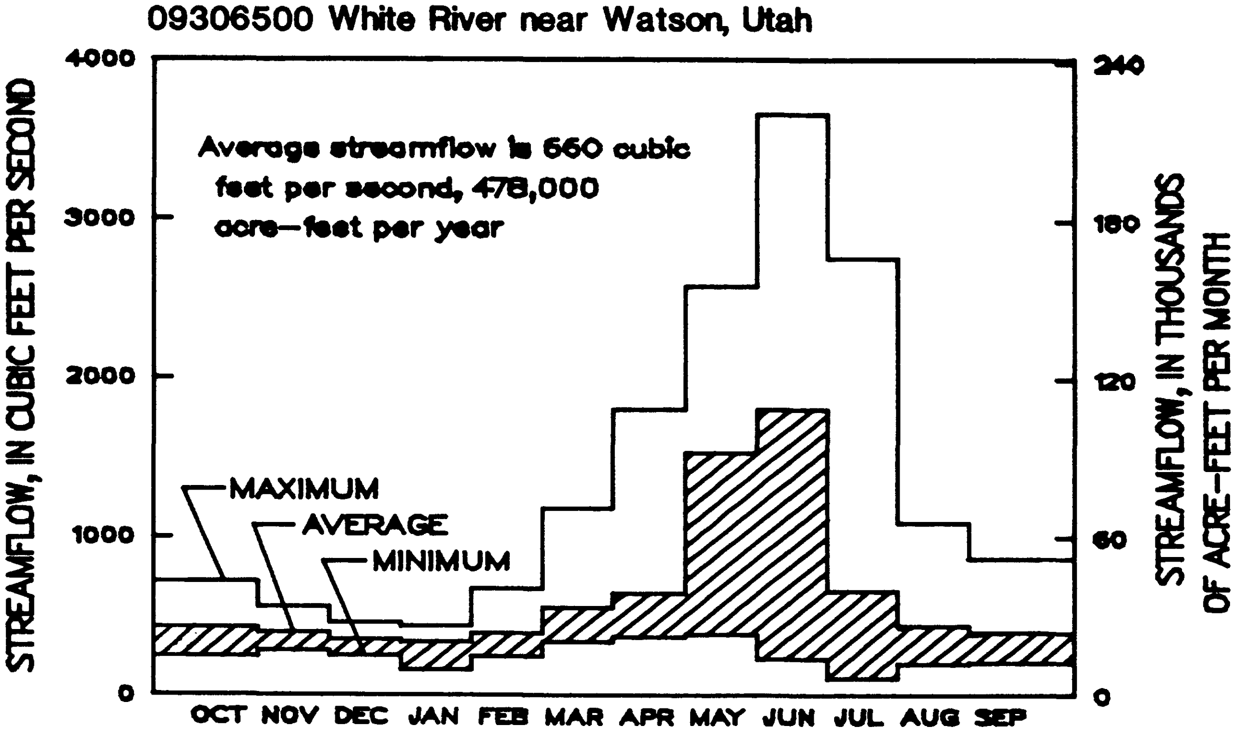




Figure 2.--Maximum, average, and minimum monthly streamflow at stations 09304500 White River near Meeker, Colo., and 09306500 White River near Watson, Utah, 1932-81 water years.

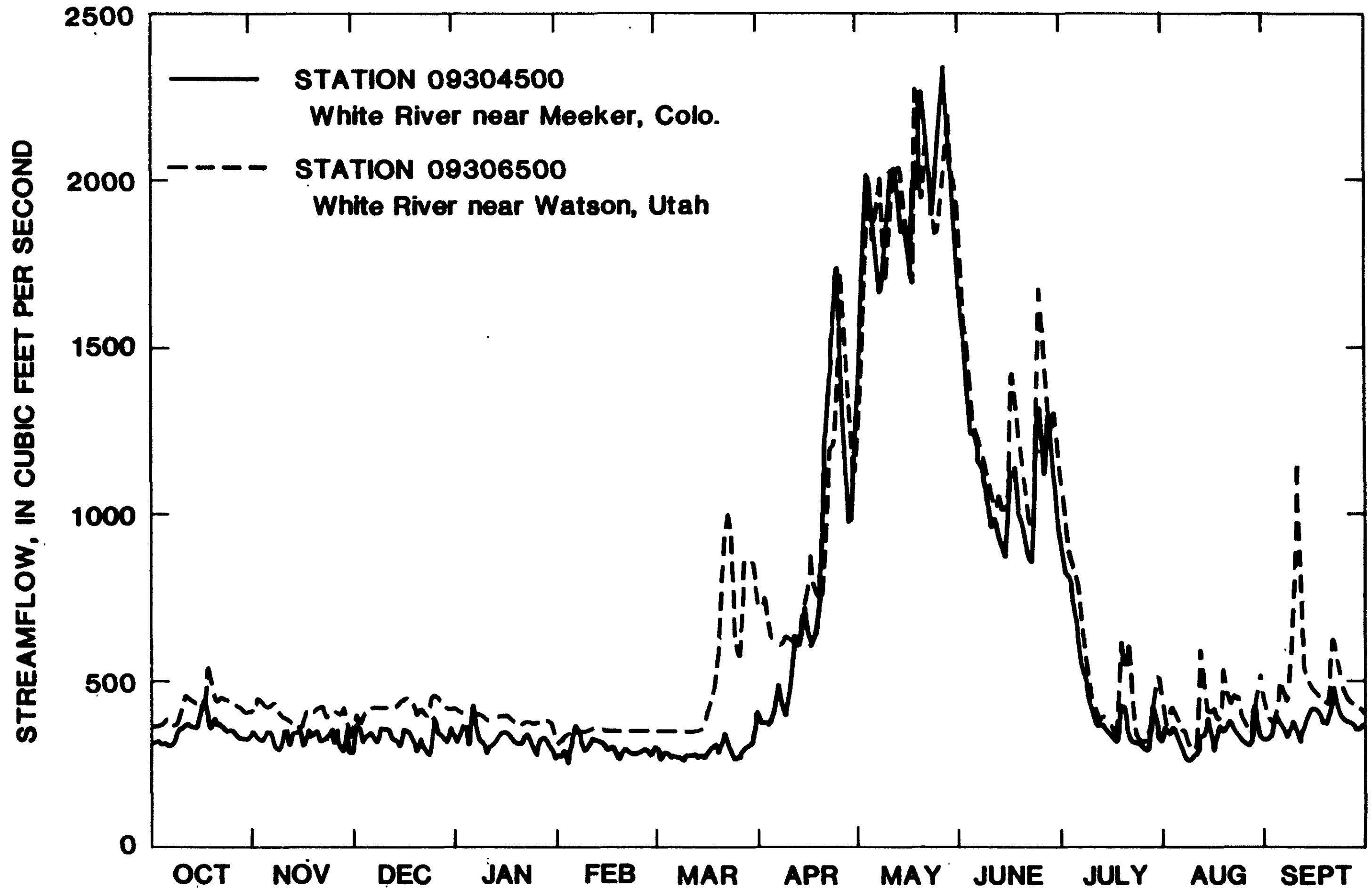



Figure 3.--Hydrographs of average daily streamflow at stations 09304500 White River near Meeker, Colo., and 09306500 White River near Watson, Utah, 1969 water year.

An important aspect of the White River basin's flow characteristics is the areal distribution of the streamflow sources. Approximately 85 percent of the basin's average flow is contributed by only about 10 percent of the drainage area, the headwaters area in The Flat Tops (fig. 1). Station 09304800 White River below Meeker, Colo., gages 20 percent of the basin's drainage area, but has 92 percent of the basin's average discharge. About 3 percent of the basin's average flow is contributed by Piceance Creek, the only significant perennial tributary to the White River downstream from the town of Meeker.

Based on the average streamflow for the study period (see "Streamflow Records" section herein) a graphical relation between streamflow and drainage area was defined for the White River (fig. 4). The relation has a steep slope from the confluence of the North and South Forks of the White River downstream to station 09304800 White River below Meeker, Colo. Streamflow at the confluence of the North and South Forks of the White River is the sum of streamflow at stations 09303000 North Fork White River at Buford, Colo., and 09304000 South Fork White River at Buford, Colo. Although tributary inflow in this reach is not evenly distributed, the extensive amount of streamflow diversion for irrigation and the corresponding return flows tend to distribute the flow increases more uniformly throughout this reach; thus the fairly consistent relation.

Between stations 09304800 White River below Meeker, Colo., and 09306300 White River above Rangely, Colo., the relation is only inferred because data are lacking. Downstream from station 09306300 to the mouth, a good relation is again evident, but with a significant decrease in slope, indicating that streamflow does not increase appreciably in this reach when one considers the amount of additional contributing area. Although two of the stations depicted in figure 4 do not fit the relation as well as the other stations, the differences between the average streamflows at these two stations and those from the relation for the corresponding drainage areas are not significant. These differences are primarily due to somewhat smaller correlation coefficients at these two stations in the streamflow record extension.

## Streamflow Records

Records for 15 streamflow stations (fig. 1) were used in this study. Drainage area and average streamflow for both the period of record and the 1932-81 study period are presented in table 3. Because streamflow records for most of the stations used in the simulations are incomplete for the study period, their records were extended in time to include the entire 50 years. Streamflow records were extended using a least-error linear-regression technique (Alley and Burns, 1983). For the purposes of this study, it was assumed that the streamflow for 1932-81, based on both actual and extended streamflow records, represented historical streamflow.

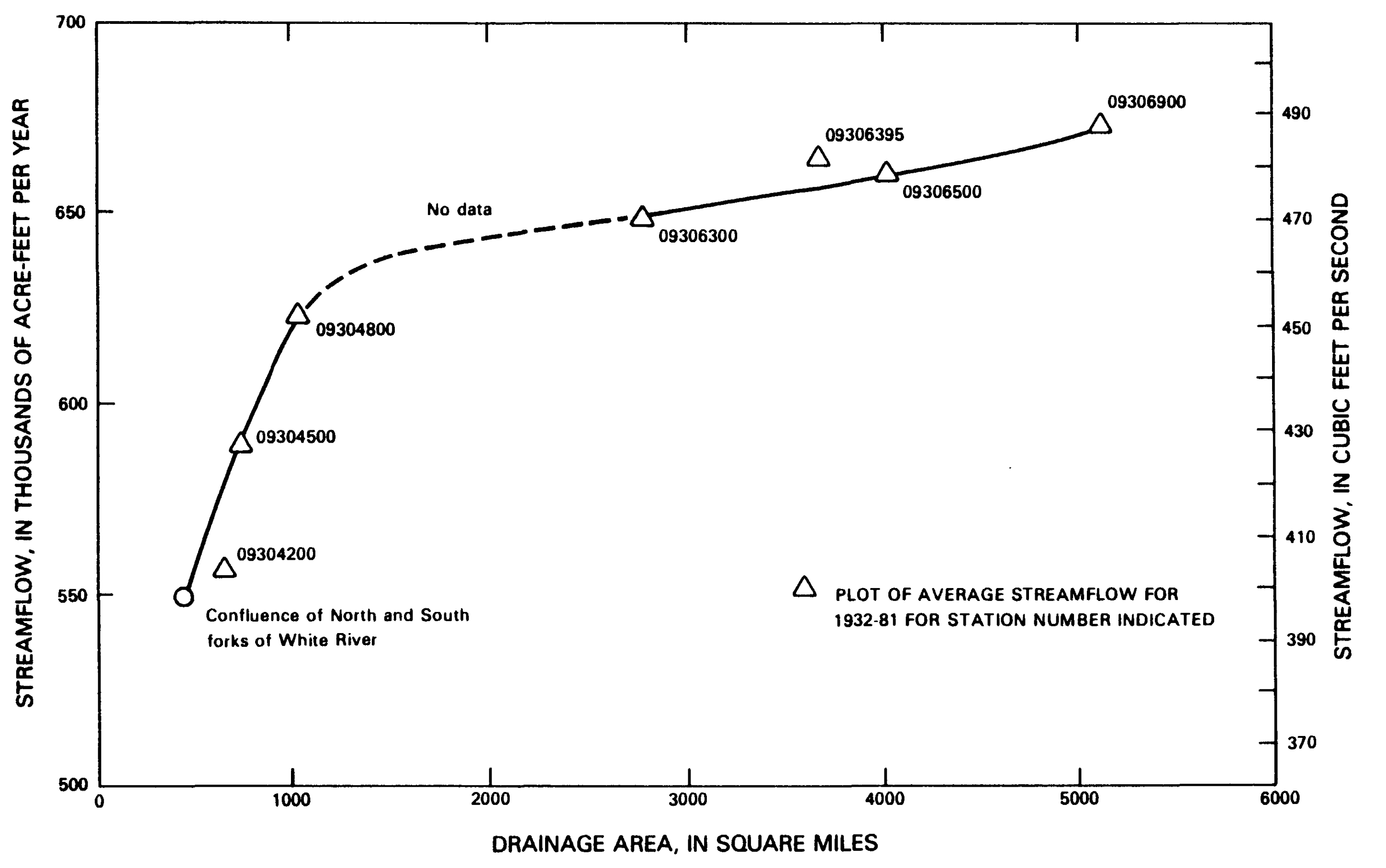



Figure 4.--Relation between average streamflow and drainage area for stations on the White River.

Table 3.--*General data for streamflow-gaging stations used in multireservoir streamflow simulations*

| Station number | Station name | Drainage area (square miles) | Period of streamflow record | Average streamflow for: Period of record, Acre-feet per year | Period of record, Cubic feet per second | 1932-81 water years[1], Acre-feet per year | 1932-81 water years[1], Cubic feet per second |
|---|---|---|---|---|---|---|---|
| 09302800 | North Fork White River near Buford, Colo | 223 | 1903-06<br>1956-73 | 210,000 | 290 | 198,000 | 273 |
| 09303000 | North Fork White River at Buford, Colo | 260 | 1910-15<br>1919-20<br>1951-84 | 221,000 | 305 | 217,000 | 299 |
| 09304000 | South Fork White River at Buford, Colo | 177 | 1951-84 | 183,000 | 252 | 181,000 | 250 |
| 09304100 | Big Beaver Creek near Buford, Colo | 34.6 | 1919-20<br>1955-64 | 10,800 | 14.9 | 10,600 | 14.7 |
| 09304150 | Miller Creek near Meeker, Colo | 57.6 | 1970-84 | 13,300 | 18.4 | 13,500 | 18.7 |
| 09304200 | White River above Coal Creek near Meeker, Colo | 648 | 1961-84 | 388,000 | 536 | 404,000 | 557 |
| 09304300 | Coal Creek near Meeker, Colo | 25 | 1957-68 | 3,790 | 5.23 | 4,020 | 5.55 |
| 09304500 | White River near Meeker, Colo | 755 | 1909-84 | 447,000 | 617 | 427,000 | 589 |
| 09304800 | White River below Meeker, Colo | 1,024 | 1961-84 | 443,000 | 611 | 451,000 | 623 |
| 09306222 | Piceance Creek at White River, Colo | 630 | 1964-66<br>1970-84 | 18,100 | 25.0 | 16,100 | 22.2 |
| 09306255 | Yellow Creek at White River, Colo | 262 | 1972-84 | 1,350 | 1.86 | 1,220 | 1.68 |
| 09306300 | White River above Rangely, Colo | 2,773 | 1972-84 | 459,000 | 633 | 469,000 | 648 |
| 09306395 | White River near Colorado-Utah State line, Utah | 3,680 | 1976-84 | 436,000 | 602 | 482,000 | 666 |
| 09306500 | White River near Watson, Utah | 4,020 | 1904-06<br>1923-76 | 504,000 | 695 | 478,000 | 660 |
| 09306900 | White River at mouth near Ouray, Utah | 5,120 | 1974-84 | 458,000 | 632 | 488,000 | 674 |

[1]Average streamflow based on station records and extended streamflow record.

## Existing Diversions and Return Flows

More than 400 absolute water rights (an absolute right is one which has been developed and put to beneficial use) on the White River have been decreed in Colorado, allowing for streamflow diversions of more than 1,000 $ft^3/s$ (International Engineering Company, Inc., 1982, p. II-9). Nearly all these diversions are for irrigation of hay meadows and pastureland, and generally coincide with the snowmelt runoff season. Also, the full amount of each diversion may not necessarily be used each year. This large quantity of diversion is possible because: (1) A large percentage of the diverted water is readily returned to the river, and (2) the rates of diversion usually are at a maximum during the runoff season and decrease as streamflow decreases.

Thirty major irrigation diversions, with a total water right of about 800 $ft^3/s$ were identified for this study and used in the streamflow simulations. The quantity of streamflow diverted is variable, from month to month and from year to year; records for these diversions often are not available, and if they are, many times they are incomplete, or merely estimated. Therefore, the amount prescribed in the water right decree (Colorado Division of Water Resources, written commun., 1982) was used as the basis of the diversion rates. Furthermore, it was assumed that the diversion rates were 100 percent of the decreed amount during the month of June only, and that they were 14, 86, 57, and 28 percent of the decreed amount during May, July, August, and September, respectively. These diversion rates are similar to those used by International Engineering Company, Inc. (1982, p. V-3, V-4) in their study of the Yellow Jacket Project. No irrigation diversions were used from October through April.

A return-flow rate equal to 80 percent of the streamflow diverted was used for all irrigation months, and it was assumed that all return-flows occurred the same month as the diversion. The above diversion pattern allowed for an annual depletion by irrigation of about 30,000 acre-ft from the White River in Colorado.

Some municipal and industrial uses of streamflow from the White River in Colorado also were identified for this study; these uses are described in the "Current Water Use" section. Constant annual diversion rates, with no return flows, were assumed for these uses to provide the approximate amount of annual depletion required.

Two existing streamflow diversions in Utah were used in the model simulations; these uses also are described briefly in the "Current Water Use" section. A constant annual diversion rate was assumed for the Bonanza, Utah, use, with no return flow. For the current irrigation of Ute Indian lands, a variable diversion rate was assumed for the months of April through October, and no diversion from November through March. However, a 50-percent return-flow rate was assumed for these irrigation diversions.

All these diversions allowed for a total annual depletion of about 36,000 acre-ft of streamflow from the White River. However, this amount was increased by about 1,500 to 7,600 acre-ft/yr from 1963 through 1981 by the diversion for secondary recovery of petroleum in the Rangely oil field.

## Minimum Streamflow Requirements

Two types of minimum streamflow requirements are discussed and used in this report. The first are instream flow appropriations, which are administered by the Colorado Water Conservation Board according to their decreed priority in the same manner as other Colorado water rights. These instream flow appropriations are to protect the natural environment to a reasonable degree, but are not necessarily for the maintenance of flow to protect endangered species which may reside in the stream. The second type of minimum streamflow requirements are those required by Federal Agencies to protect endangered species in the river. These minimum flows are contained in the permits to build and operate dams and are discussed in the "Minimum Streamflow Requirements for Endangered Species" section of this report. The federally required minimum streamflows do not have the status of water rights under Colorado water law (J. William McDonald, Colorado Water Conservation Board, written commun., 1984).

The Colorado Water Conservation Board holds instream flow appropriation on the following reaches of the White River:

1. North Fork of White River from the confluence with Marvine Creek downstream to the confluence with the South Fork of the White River in the amount of 120 $ft^3/s$ (case W-5652-H, District Court, Water District No. 5, State of Colorado; date of appropriation November 15, 1977).

2. South Fork of the White River from the confluence with Swede Creek downstream to confluence with the North Fork of the White River in the amount of 80 $ft^3/s$ (case W-5652-B, District Court, Water District No. 5, State of Colorado; date of appropriation November 15, 1977).

3. White River from the confluence of the North and South Forks downstream to the confluence with Piceance Creek in the amount of 200 $ft^3/s$ (case W-3652-C, District Court, Water District No. 5, State of Colorado; date of appropriation November 15, 1977).

There are no instream flow appropriations for the White River from the confluence with Piceance Creek downstream to the Colorado-Utah State line (J. William McDonald, Colorado Water Conservation Board, written commun., 1984). The State of Utah currently (1984) has not established any minimum streamflow requirements for the White River in Utah (Lloyd Austin, Utah Department of Natural Resources, Water Resources Division, oral commun., 1984).

## Precipitation and Evaporation

Precipitation data for climatological stations at Meeker and Rangely, Colo., and Bonanza, Utah, were used in the reservoir analysis. The average monthly precipitation was used, even though the records used at each station are of a different length and at different times. This was done in favor of extending the precipitation records in time and using individual monthly values for each year because: (1) Precipitation falling on reservoirs represents only a small part of the annual water budget of the reservoirs, (2) evaporation records also are incomplete for the study period, and (3) although precipitation is somewhat variable from one year to the next, the long-term trend has not changed significantly during the study period. Precipitation data used for the above stations are summarized in table 4.

No evaporation data are available within the study area, so data from two nearby stations, Fort Duchesne and Flaming Gorge, Utah, were used. Not every month had record for an equal number of years, and also there were no data for November through April, except that there was some data for April at Fort Duchesne (table 4). Generally, there is no significant difference between the May through October evaporation data at the two stations, so the average of the two stations was used in the reservoir study; the April average at Fort Duchesne alone also was used. The total May through October evaporation used herein compares favorably with estimates of evaporation presented by Farnsworth and others (1982); the pan coefficient used (table 4) is largely based on that report. For purposes of this modeling study, it was further assumed that there was no evaporation from November through March.

## Current Water Use

The combination of streamflow depletion from the White River in the States of Colorado and Utah currently is (1984) less than 10 percent of the average annual flow of the river. The majority of the streamflow use is in the upper reaches of the basin, upstream from Meeker, Colo.

The major use of water from the White River is for irrigation of hay crops and pastureland; this use has not changed significantly during the past 40 years (International Engineering Company, Inc., 1982, p. II-1). Depletion of streamflow by irrigation from the Colorado part of the basin averaged 29,300 acre-ft annually from 1943 through 1960; during this same period the total annual depletion, by all beneficial and nonbeneficial uses averaged only 38,400 acre-ft (U.S. Department of Agriculture, 1966, p. 53).

Beginning in 1963, water from the White River also was used for secondary recovery of petroleum in the Rangely oil field. Annual depletion increased from about 3,000 acre-ft in 1963 to about 7,600 acre-ft in 1969 and 1970, and then decreased to about 1,500 acre-ft in 1981 (Roy Chambers, Chevron U.S.A. Inc., written commun., 1984). In addition, the town of Rangely, Colo., depletes about 1,000 to 1,500 acre-ft of water annually from the White River for municipal use.

Table 4.--*Summary of precipitation and evaporation data used in multireservoir streamflow simulations*

[Dashes indicate no data]

| Station | Elevation (feet) | Period of record used | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
| | | | Average precipitation, in inches | | | | | | | | | | | |
| Meeker, Colo.[1] | 6,242 | 1940-70 | 1.22 | 1.16 | 1.43 | 1.72 | 1.43 | 1.49 | 1.47 | 1.95 | 1.24 | 1.50 | 1.13 | 1.32 |
| Rangely, Colo.[1] | 5,290 | 1950-80 | .60 | .61 | .78 | .83 | .86 | .66 | .77 | .97 | .98 | .89 | .59 | .59 |
| Bonanza, Utah[2] | 5,450 | 1967-78 | .56 | .32 | .55 | .99 | 1.02 | 1.11 | .54 | .52 | .60 | .97 | .51 | .28 |
| | | | Average evaporation, in inches[3] [measured pan evaporation × 0.7 pan coefficient] | | | | | | | | | | | |
| Fort Duchesne, Utah[2]. | 4,990 | 1958-78 | ---- | ---- | ---- | 3.72 | 5.44 | 6.14 | 6.49 | 5.80 | 3.93 | 2.39 | ---- | ---- |
| Flaming Gorge, Utah.[2] | 6,270 | 1958-78 | ---- | ---- | ---- | ---- | 4.71 | 6.11 | 6.94 | 5.84 | 4.14 | 2.84 | ---- | ---- |
| Average used for study area | | | ---- | ---- | ---- | 3.72 | 5.08 | 6.12 | 6.72 | 5.82 | 4.04 | 2.61 | ---- | ---- |

[1]Colorado State Climatologist, (oral commun., 1983).

[2]National Oceanic and Atmospheric Administration (1958-78).

[3]Number of years with data for individual months varied from 4 to 21.

Use of streamflow from the White River in Utah is only a fraction of the use in Colorado. About 1,600 acre-ft/yr are depleted by the town of Bonanza, Utah, for municipal and industrial use. Also, about 2,000 acre-ft are depleted annually by agricultural diversions on the Ute Indian lands (International Engineering Company, Inc., 1981, p. 39; Utah Division of Water Resources, written commun., 1984).

## MODEL DESCRIPTION

The HEC-3 Reservoir System Analysis for Conservation, developed by the U.S. Army Corps of Engineers (1976, 1981) was used in this study; the two references provide a detailed description of the model. HEC-3 is a multipurpose, multireservoir streamflow routing model with the capability of simulating reservoir system operations for purposes such as water supply, navigation, recreation, low-flow augmentation, and hydroelectric power (U.S. Army Corps of Engineers, 1981, p. 1). Only water supply and minimum streamflow requirements were considered in this study. The model routes streamflow through a series of control points, with no streamflow losses or gains other than those specified by the modeler. The White River was simulated by 34 control points, representing either a streamflow, reservoir, diversion, or return-flow point.

## MODEL DATA REQUIREMENTS

Several types of data are required by the HEC-3 model, depending on which of its options are used. For this study, data required at reservoir control points were reservoir geometry, including outlet works and spillway capacities, and reservoir operating rules. Monthly values of precipitation and evaporation also were required for each reservoir. At nonreservoir control points, monthly values of streamflow and diversion or return-flow rates were required. More than one type of data could be specified at a control point; for example, streamflow data could be input at a control point and a diversion also could occur at the same location. Streamflow, diversion or return-flow, precipitation, and evaporation data have been described in the "Hydrology" section herein. The following paragraphs provide additional discussion of the reservoir data requirements.

## Reservoir Geometry

Reservoir geometry data for the reservoirs were obtained from the following sources: Avery Reservoir (International Engineering Company, Inc., 1982); Powell Park Reservoir (small) (International Engineering Company, Inc., 1983); Kenney Reservoir (U.S. Army Corps of Engineers, 1982); and White River Reservoir (U.S. Bureau of Land Management, 1982). The data obtained include storage volume, surface area, elevation-volume and elevation-area curves, and outlet works and spillway capacities. Only elevation-volume and elevation-area relations were available for Powell Park Reservoir (large) (International Engineering Company, Inc., written commun., 1983), so outlet works and spillway capacities were estimated. Proposed values for active capacity, surface area, and water yield of these reservoirs are presented in table 1.

## Reservoir Operating Rules

All reservoirs were divided into five storage levels to facilitate approximate simultaneous adjustment of all reservoir levels. The lowest level is always the bottom of the conservation pool (or top of inactive storage); the second and third levels are intermediate levels in the conservation pool. Level four is the top of the conservation pool and level five is the top of the flood pool (U.S. Army Corps of Engineers, 1981, exhibit 4, p. 23). Other pertinent operating rules also required for each reservoir are downstream diversion and flow requirements. Generalized operating rules for individual reservoirs follow.

### Avery Reservoir

Operation of the proposed Avery Reservoir is presented in some detail by International Engineering Company, Inc. (1982); these operations, including some minor modifications used in this study, are summarized here. The following annual water uses and quantities, in acre-feet, are specified: Oil-shale development (52,500), coal mining (12,000), agriculture (18,000), and municipal (5,000). The water for oil-shale development and municipal use would be released to downstream diversion points, whereas the water for coal mining and agriculture would be diverted directly from Avery Reservoir. For this study it was assumed that one-half of the oil-shale water would be diverted from the White River in the vicinity of Sheep Creek and that the other half would be diverted just upstream from Piceance Creek. Water for municipal use was diverted just upstream from Meeker. A minimum flow of 200 $ft^3/s$ was specified for the White River at these three diversion points.

The monthly diversion rates, and rates of agricultural and municipal return flow, used which were the same as those given by International Engineering Company, Inc. (1982, p. III-2, V-5, V-6). These rates of return flow are different from the rates of return flow for agricultural diversions described in the section on "Existing Diversions and Return Flows" herein. The return-flow rates that were specified allowed for the return of 7,500 acre-ft/yr to the White River, assuming that the full amount of diversion was diverted. In this study, though, it was assumed that all the agricultural and municipal return-flows occurred during the same month as the diversion. Water for oil-shale and coal development, however, was entirely consumed. With return-flows taken into consideration, the above operation of Avery Reservoir would deplete about 80,000 acre-ft annually from the White River, excluding evaporation losses.

This basic operating plan was used for all configurations in which Avery Reservoir was a component, except when Powell Park Reservoir also was a component. In this instance, Avery Reservoir would be operated in conjunction with Powell Park Reservoir (small), and there would be only a single diversion for oil shale, downstream from Powell Park Reservoir. This is described in the operating rules for Powell Park Reservoir.

Water for Avery Reservoir is to be diverted from the North Fork White River approximately 3 mi upstream from Buford, Colo. (International Engineering Company Inc., 1982, p. IV-5), at a maximum rate of 250 $ft^3/s$. The only flow constraint specified at this diversion point was a minimum downstream flow of 120 $ft^3/s$ in the North Fork White River. Herein it was assumed that the streamflow at the diversion point (before diversion to Avery Reservoir) was equal to the flow at station 09303000 North Fork White River at Buford, Colo., about 3 mi downstream. Comparison of the drainage basins at the diversion point and at station 09303000 indicated very little increase in flow between these two points.

Finally, it was assumed that streamflow in Big Beaver Creek would not be passed downstream to the White River, unless Avery Reservoir was full. A small fisheries and recreation lake (Lake Avery, capacity 7,600 acre-ft) is currently in place on Big Beaver Creek at the proposed location of Avery Reservoir; this lake has very little effect on the historical streamflow of Big Beaver Creek.

## Powell Park Reservoir

Operating rules for Powell Park Reservoir (small) are based on the description presented by International Engineering Company, Inc. (1983). This reservoir would be operated in conjunction with Avery Reservoir to provide 102,000 acre-ft of water annually (equivalent to a constant diversion rate of 141 $ft^3/s$) for oil-shale development. This water, which was assumed to be totally consumed, could be provided by either reservoir and would be delivered to a single diversion point on the White River near the mouth of Piceance Creek. A minimum downstream flow of 200 $ft^3/s$ was specified at this location. In addition, the water requirements for coal development, agriculture, and municipal use, as well as the associated operating rules just described for Avery Reservoir, also apply to the joint operation of Avery and Powell Park (small) Reservoirs. For the large version of Powell Park Reservoir, the assumed operating rules were to provide whatever water-use demand was placed on it, while still maintaining the minimum downstream flow requirement of 200 $ft^3/s$. Additional information regarding this reservoir is presented in the "Streamflow Simulations with Alternative Reservoir Configurations" section.

## Kenney Reservoir

For Kenney Reservoir, some municipal use of water is anticipated, but the majority of the water will be used for other, unspecified uses (U.S. Army Corps of Engineers, 1982, p. 15). No projected monthly rates of water use are presented in the above reference, so for Kenney Reservoir the rates of monthly diversion also were largely assumed. The diversion rates assumed ranged from 12 $ft^3/s$ during the winter months to a maximum of 20 $ft^3/s$ in July. Total consumption of the water was presumed, allowing for a annual depletion of 10,200 acre-ft from the White River, excluding evaporation losses. The biological opinion for Kenney Reservoir (U.S. Army Corps of Engineers, 1982, appendix E) states that a minimum streamflow of 200 $ft^3/s$ be maintained in the White River downstream from the dam, unless inflow to the reservoir is less than 200 $ft^3/s$. This requirement was included in this study as a part of the operating rules for this reservoir.

## White River Reservoir

General operating rules for White River Reservoir are presented by the U.S. Bureau of Land Management (1982, p. 27, 318-320); the basic requirement is that a minimum streamflow of 250 $ft^3/s$ be maintained in the White River downstream from this reservoir, unless inflow to the reservoir is less than 250 $ft^3/s$. Additional considerations for streamflow downstream from White River Reservoir are presented in the above reference (p. 318-320) but most of these were not used in this study because of limitations in the HEC-3 model. However, the additional requirement that a minimum streamflow of 500 $ft^3/s$ be released from the reservoir from June 15 to July 31 was included in this study. The time period of that flow, though, was extended to begin on June 1 because the HEC-3 model was used in a monthly mode.

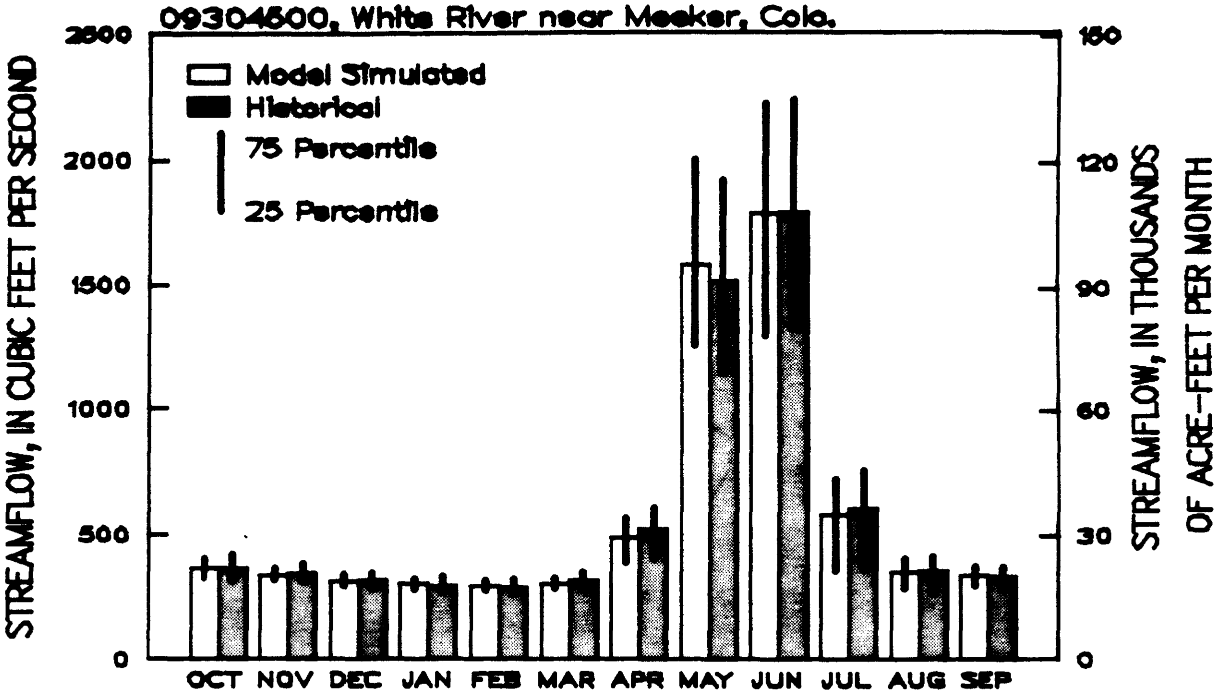
The proposal for White River Reservoir indicates a maximum constant diversion rate of 104 $ft^3/s$, to be used almost exclusively for oil-shale development. Although about 3,000 acre-ft would be for municipal use (U.S. Bureau of Land Management, 1982, p. 9), complete consumption of water diverted from this reservoir was assumed. The proposed yield for White River Reservoir, excluding evaporation loss, is about 75,000 acre-ft annually.

## MODEL CALIBRATION

Historical streamflow, on a monthly basis, was simulated by a series of streamflow, diversion, and return-flow control points, beginning at the confluence of the North and South Forks of the White River, which was the basic starting point for all simulations. This same control point sequence, and the associated streamflows, diversions, and return flows, also was used in the reservoir simulations, but with additional control points for any reservoirs and their associated diversions or return flows.

In the streamflow calibration procedure, the 50-year average simulated streamflow was compared with the historical average streamflow at five streamflow-gaging stations (also control points) on the White River. The five stations used in the calibration were 09304200 White River above Coal Creek near Meeker, Colo., 09304500 White River near Meeker, Colo., 09304800 White River below Meeker, Colo., 09306300 White River above Rangely, Colo., and 09306500 White River near Watson, Utah. In successive simulations the streamflow at these points was adjusted by changing drainage area versus streamflow relations in the model until the simulated average streamflow equaled the historical average streamflow at the streamflow-gaging stations. This procedure was necessary because: (1) Not every tributary to the White River was accounted for in the control point sequence, (2) there undoubtedly is some error in the diversion and return-flow pattern assumed, and (3) there probably are some increases in streamflow due to ground-water discharge.

The monthly averages of the model simulated streamflows and the historical streamflows at stations 09304500 White River near Meeker, Colo., and 09306500 White River near Watson, Utah, are compared in figure 5. Station 09304500 has streamflow record for the entire 1932-81 period and station 09306500 has streamflow record for 48 of the 50 years. Even though there is a noticeable difference between the two streamflows for 2 or 3 months, especially at station 09306500, these differences are inconsequential to the purpose of this study.



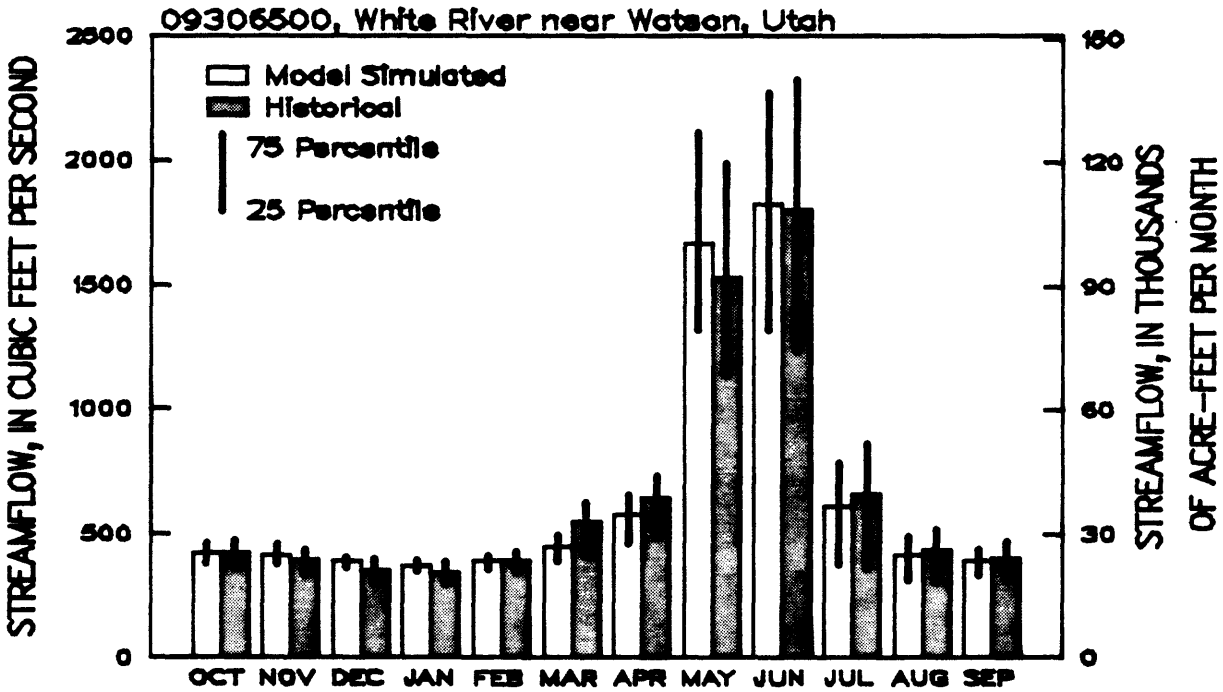




Figure 5.--Comparison of model calibration average streamflow with historical average streamflow, at stations 09304500 White River near Meeker, Colo., and 09306500 White River near Watson, Utah

As a further test of the model calibration, a regression analysis (ordinary least squares) of the historical monthly streamflows versus the model simulated streamflows was done at the above two stations. Ideally, the slope of the regression lines should be 1.00; the y-intercept of the lines should be 0; and the $r^2$ (coefficient of determination) should be 1.00. For station 09304500 White River near Meeker, Colo., the statistics of the regression were: slope = 0.99; y-intercept = 3.4; and $r^2$ = 0.99. For station 09306500 White River near Watson, Utah, the statistics of the regression were: slope = 0.98; y-intercept = 13; $r^2$ = 0.96. The standard errors of estimate were 12 percent at station 09304500 and 18 percent at station 09306500. For both regressions, the slope was not significantly different from 1.00, and the y-intercept was not significantly different from 0; both statistics were taken at the 5-percent level of significance. These results further indicate that the differences between model simulated streamflow and historical streamflow are insignificant. The model simulated streamflow, hereafter referred to as pre-development streamflow, was then used in the reservoir simulations.

## STREAMFLOW SIMULATIONS WITH ALTERNATIVE RESERVOIR CONFIGURATIONS

Four alternative configurations of the four proposed reservoirs were simulated. The first configuration simulated was a two-reservoir system, Avery and Kenney Reservoirs. White River Reservoir was included in the system, in addition to Avery and Kenney Reservoirs, for the second simulation, and all four of the proposed reservoirs considered in this study were used in the third simulation. The last simulation was done with only Powell Park and Kenney Reservoirs, but the size of Powell Park Reservoir was increased greatly (table 1). This configuration was based on the assumptions that: (1) Avery Reservoir water would be stored in Powell Park Reservoir and used exclusively for oil-shale development, and (2) that the water-use requirement for White River Reservoir would be provided by and released from Powell Park Reservoir, with the diversion point being at the same location as the proposed reservoir in Utah. The intent of this configuration was to see if one large reservoir could provide the same amount of water as three smaller ones.

In the simulations, each alternative reservoir configuration was operated as a system to provide all, or as much as possible, of the demands of each individual reservoir, while maintaining the minimum streamflow requirements. If any shortages were incurred, the shortages are described herein in terms of the reservoir system only. It is assumed that if any of the alternative reservoir configurations simulated here would become a reality, the apportionment of the shortages to individual reservoirs would be determined at that time.

## Avery and Kenney Reservoirs

The simulated effects of the Avery and Kenney Reservoirs alternative configuration on average monthly streamflows at four locations on the White River are shown in figure 6. Streamflow depletion, on a percentage basis, would have been greatest at station 09303000 North Fork White River at Buford, Colo. The 50-year average streamflow at this station (table 3) would have been depleted 76,000 acre-ft/yr (105 $ft^3/s$) by the upstream diversion to Avery Reservoir. Streamflow depletion at station 09304500 White River near Meeker, Colo., however, would have been much less than at station 09303000, averaging only 27,000 acre-ft/yr (37 $ft^3/s$). The primary reasons for this are: (1) Water that would have been released from Avery Reservoir for downstream diversion requirements is a component of the flow at this station, and (2) varying amounts of the water that would have been diverted from the North Fork White River are returned directly to the White River by way of Big Beaver Creek when Avery Reservoir is full. White River below Piceance Creek (not a streamflow-gaging station) is downstream from all streamflow diversions served by Avery Reservoir, so the graph for this location shows the maximum effect Avery Reservoir would have had on streamflow in the White River. Streamflow for the White River below Piceance Creek is derived in the model by the following procedure:

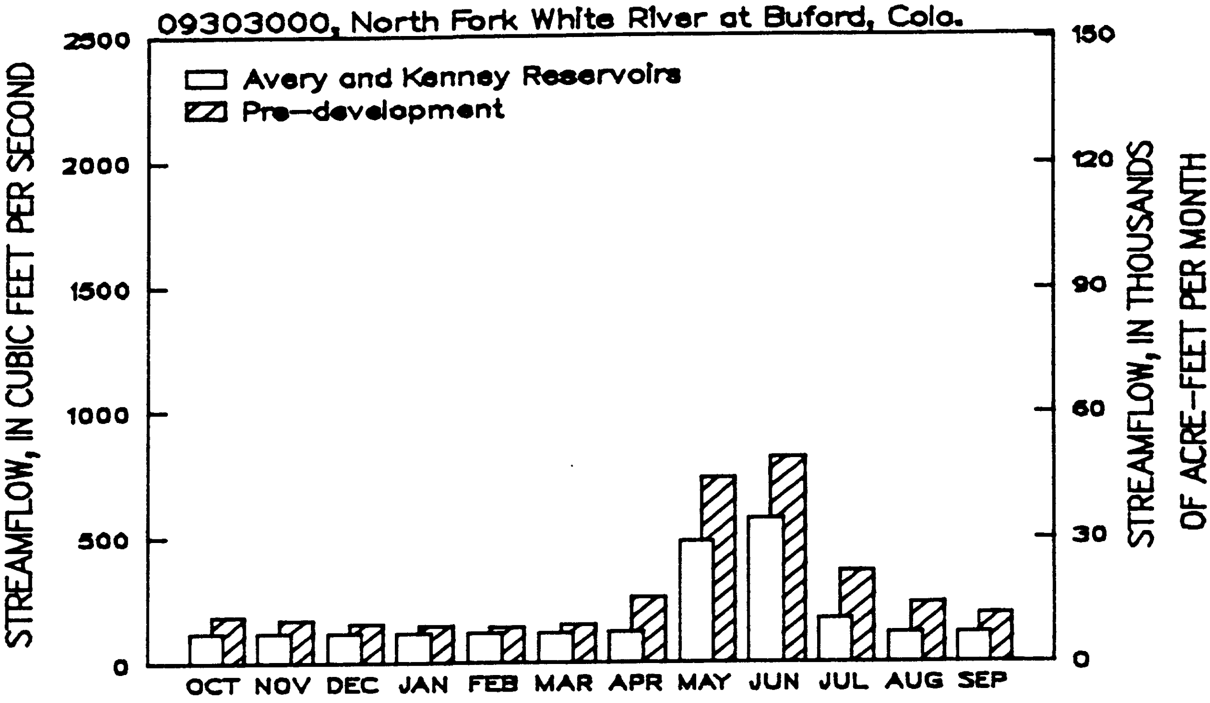
1. Use streamflow at station 09304800 White River below Meeker, Colo., as basic flow;

2. Add any required return-flows between above station and Piceance Creek;

3. Subtract any required diversions between above station and Piceance Creek; and

4. Add flow contributed by Piceance Creek.

The graph (fig. 6) of average monthly streamflow at station 09306900 White River at mouth near Ouray, Utah, shows the added effect Kenney Reservoir would have had on streamflow. The average historical streamflow at this station (table 3) would have been depleted about 93,000 acre-ft/yr (128 $ft^3/s$) by the Avery and Kenney Reservoirs configuration, including evaporation losses at the two reservoirs.



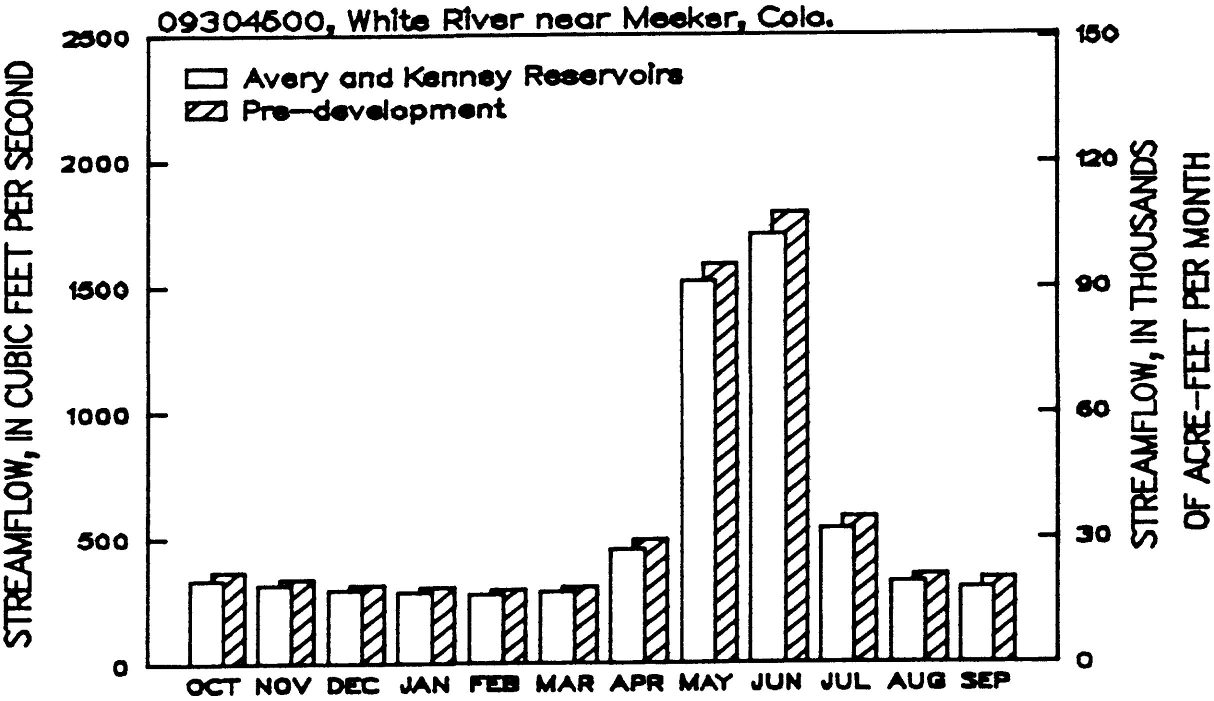
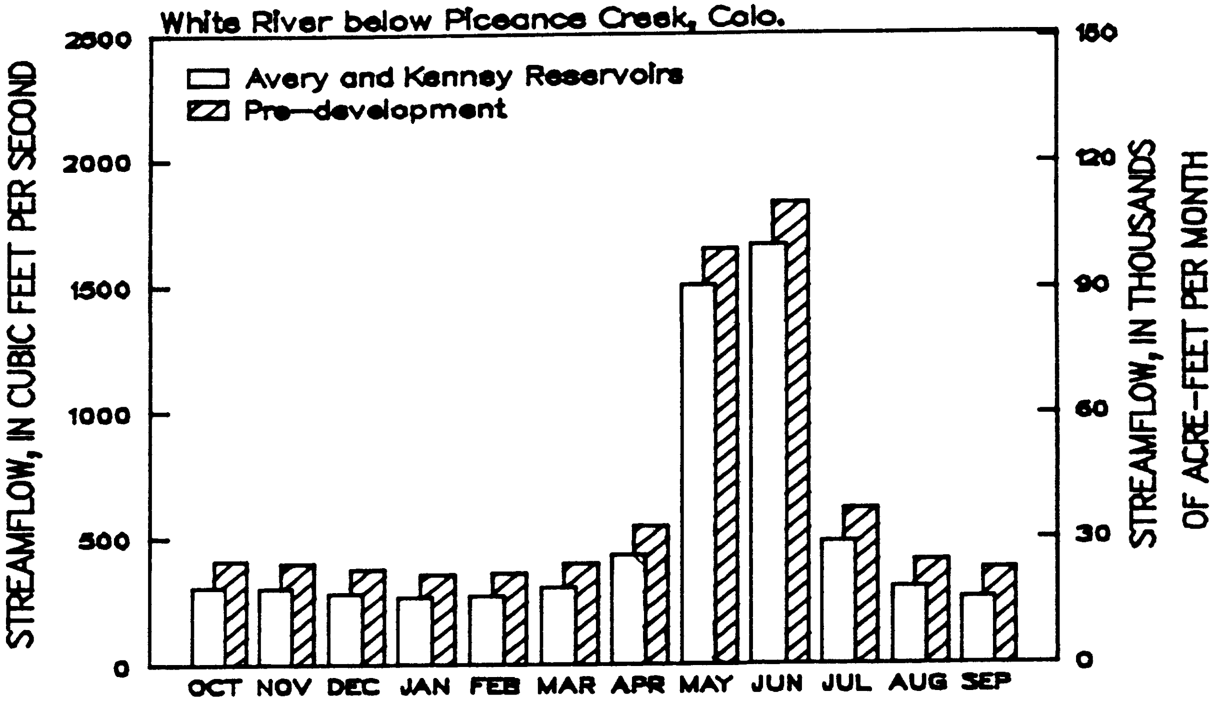




Figure 6.--Comparison of simulated average streamflow with pre-development average streamflow at four locations on the White River for the Avery and Kenney Reservoirs alternative configuration.



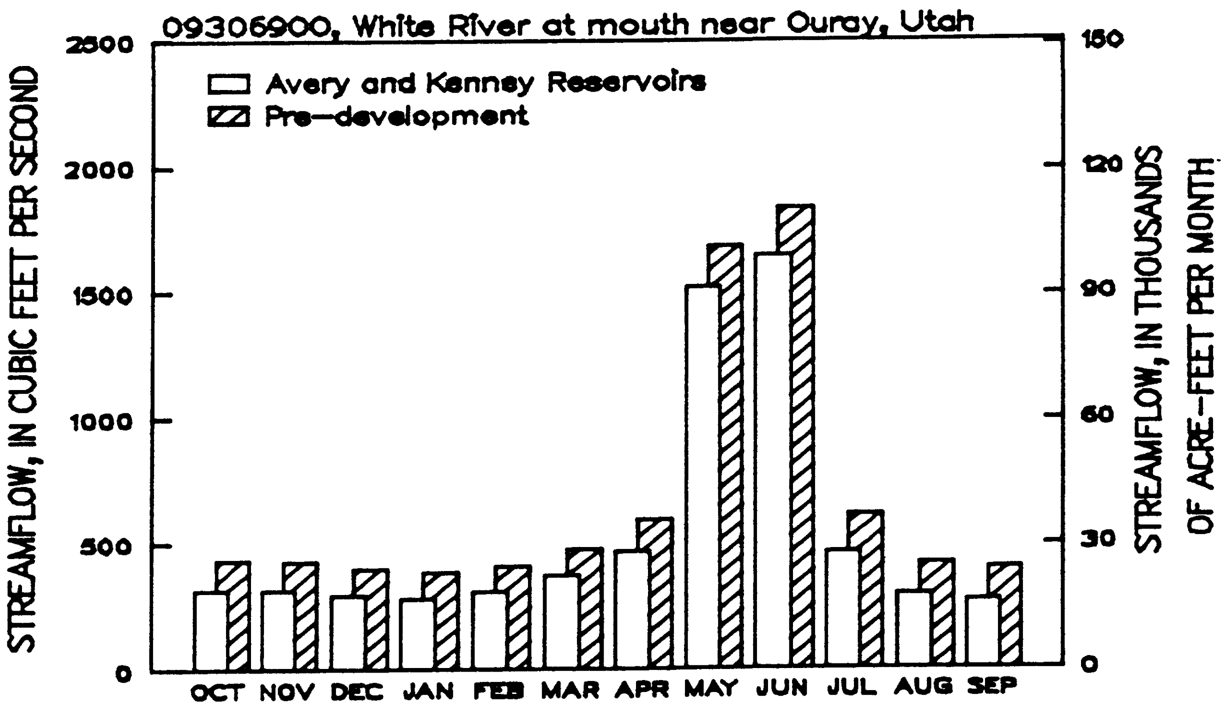




Figure 6.--Comparison of simulated average streamflow with pre-development average streamflow at four locations on the White River for the Avery and Kenney Reservoirs alternative configuration--Continued.

The minimum streamflow requirement of 120 $ft^3/s$ for the North Fork White River at the diversion point to Avery Reservoir would have been satisfied for all but 9 months of the simulation period. Historical streamflows also were less than 120 $ft^3/s$ during those 9 months and no streamflow would have been diverted to the reservoir. At the three diversion points on the White River served by Avery Reservoir upstream from Piceance Creek (see p. 19), the minimum flow requirement of 200 $ft^3/s$, however, would have been satisfied for the entire period. The minimum streamflow requirement of 200 $ft^3/s$ for the White River downstream from Kenney Reservoir also would have been totally satisfied. In this simulation, all the water-use requirements of this two-reservoir configuration were met for the entire 50-year period.

The simulated monthly average quantity of streamflow diverted from the North Fork White River to Avery Reservoir is shown in figure 7. For many months, though, especially the snowmelt months, the quantity of water diverted in the simulation was more than that required by Avery Reservoir because the reservoir was full or nearly full. It was not known if the diversion to Avery Reservoir would be based on the amount of storage available, and, if so, what the diversion rate would be for a given storage in the reservoir. Therefore, the maximum amount of water, but no more than 250 $ft^3/s$, always was diverted from the North Fork White River, while still maintaining the downstream minimum flow requirement of 120 $ft^3/s$. Because of this assumption, an average excess of 36,000 to 43,000 acre-ft/yr (50-60 $ft^3/s$) would have been diverted; however, this excess would have been returned directly to the White River from Avery Reservoir.

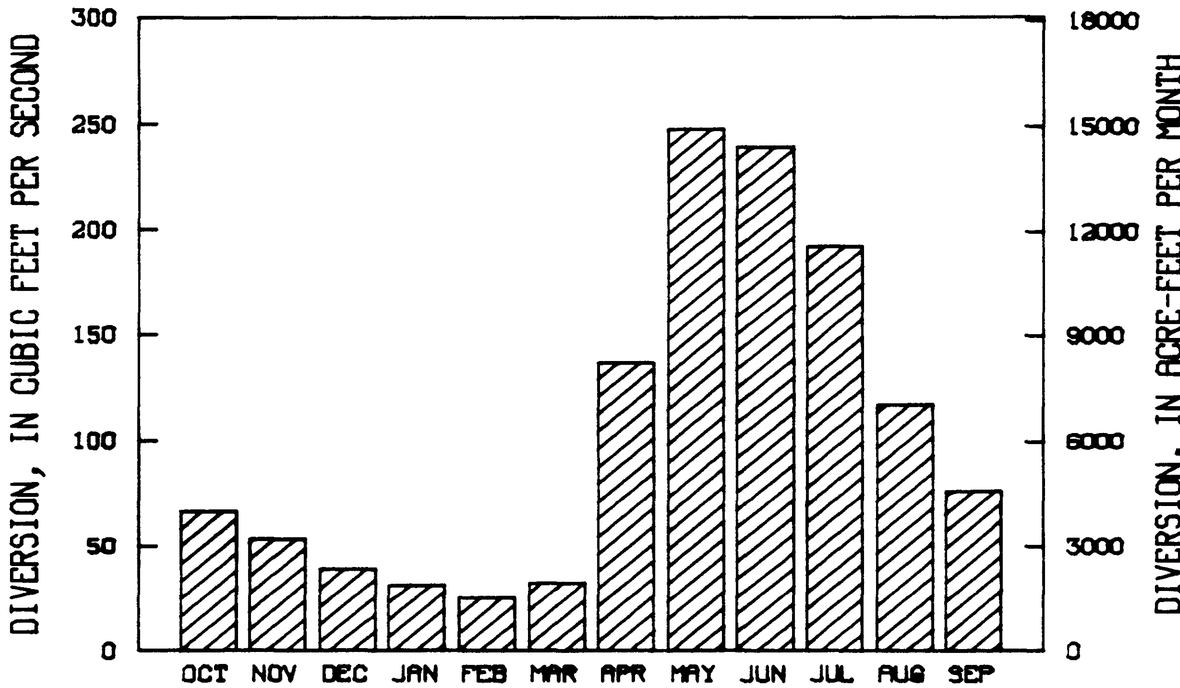



Figure 7.--Simulated average streamflow diversion from North Fork White River to Avery Reservoir

Simulated end-of-month contents for Avery Reservoir are shown in figure 8; the reservoir would have been full at least 1 month every year except 1935. During the very dry year of 1977, which was drier than 1935, the reservoir would have been full only during May. However, the reservoir would have been drawn down during the following months to its lowest level of the simulation period. Kenney Reservoir, because of its small size and small amount of water use, would have remained full for the entire simulation period, so its end-of-month contents are not illustrated.

## Avery, Kenney, and White River Reservoirs

The simulated effects of the Avery, Kenney, and White River Reservoirs alternative configuration on streamflow at three locations on the White River are shown in figure 9. Streamflow effects at station 09303000 North Fork White River at Buford, Colo., were the same in this simulation as in the previous simulation (fig. 6) and are therefore not repeated in figure 9. At station 09304500 White River near Meeker, Colo., and at White River below Piceance Creek, simulated average monthly streamflow (fig. 9) was only slightly different than that simulated for the Avery and Kenney Reservoirs alternative configuration (fig. 6). However, streamflow at station 09306900 White River at mouth near Ouray, Utah, was reduced considerably more in this simulation in comparison to the previous simulation. Average streamflow depletion at this location for the three-reservoir configuration would have been about 168,000 acre-ft/yr (232 $ft^3/s$) including evaporation losses at all three reservoirs.

The minimum streamflow requirements of 200 $ft^3/s$ in the White River at the diversions served by Avery Reservoir which are downstream from Kenney Reservoir, would not have been met 3 months of the 1977 water year. The minimum streamflow requirement of 250 $ft^3/s$ downstream from White River Reservoir would not have been met for 2 months in the 1977 water year and for 5 months in the 1978 water year. Also, the minimum streamflow of 500 $ft^3/s$ during June and July would not have been met in 13 years (15 months total), but never would have been less than 250 $ft^3/s$.

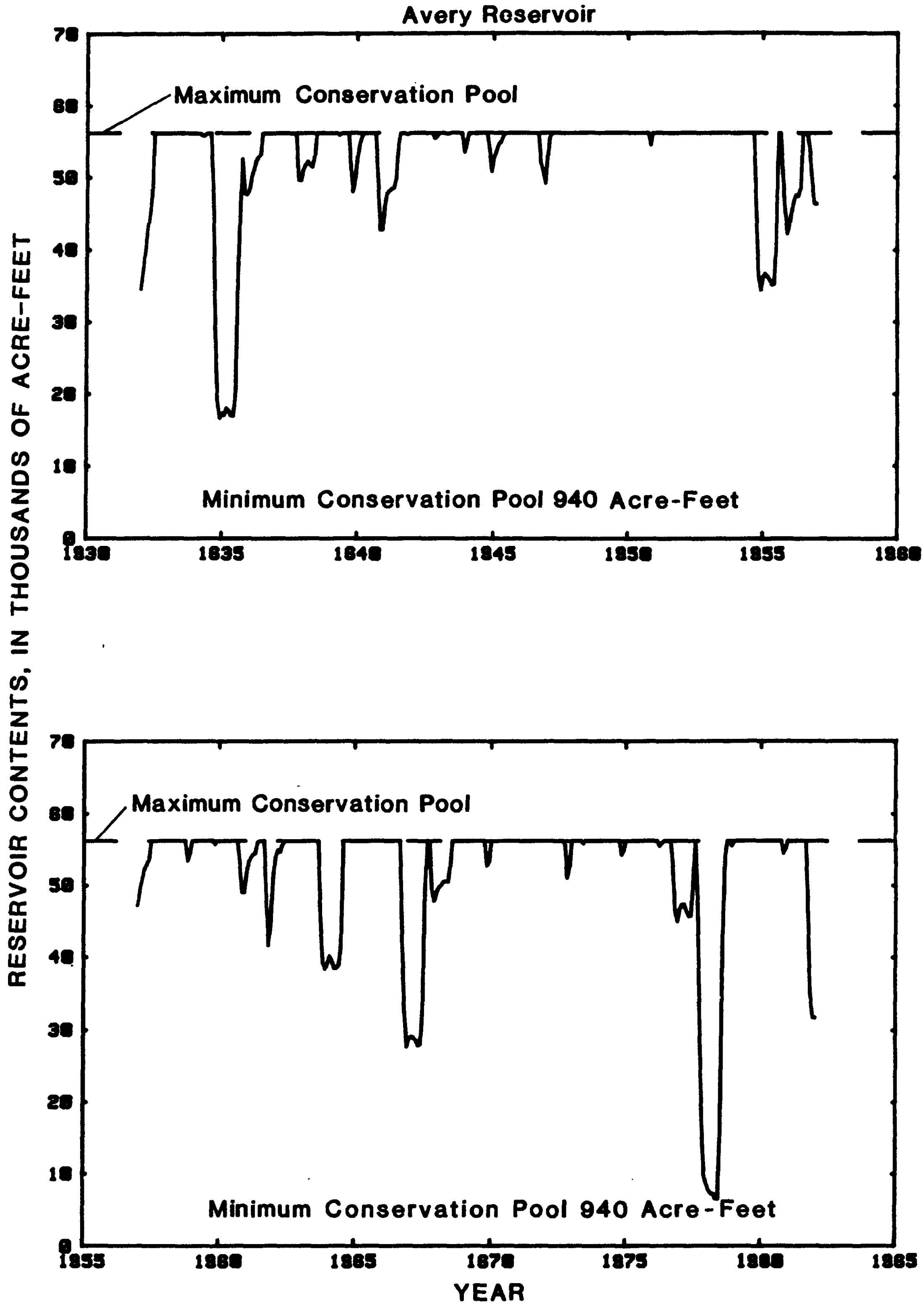
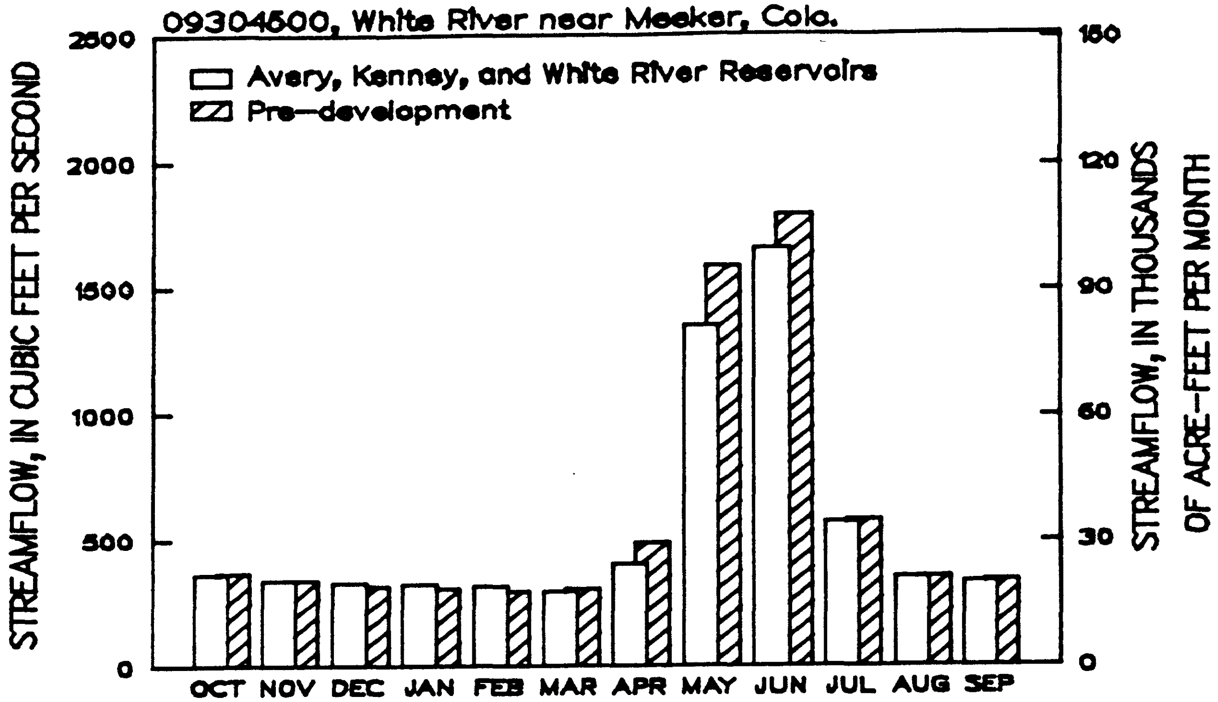



Figure 8.--Simulated end-of-month contents of Avery Reservoir for the Avery and Kenney Reservoirs alternative configuration.



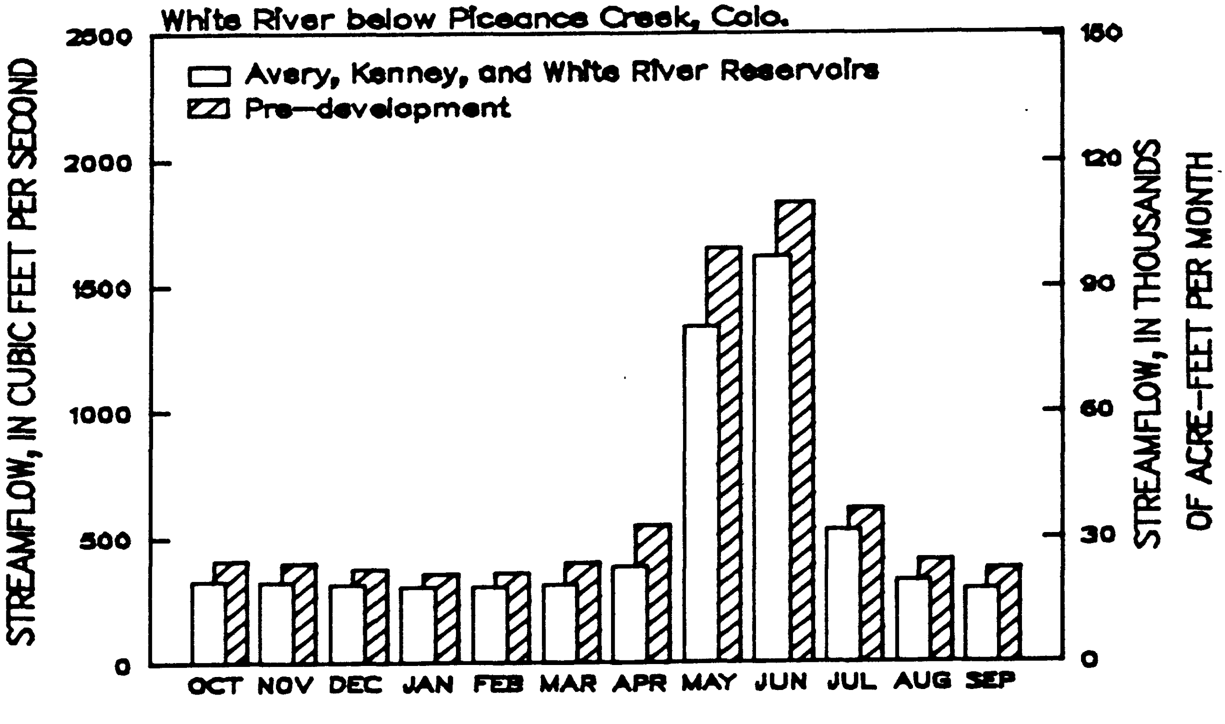




Figure 9.--Comparison of simulated average streamflow with pre-development average streamflow at three locations on the White River for the Avery, Kenney, and White River Reservoirs alternative configuration.

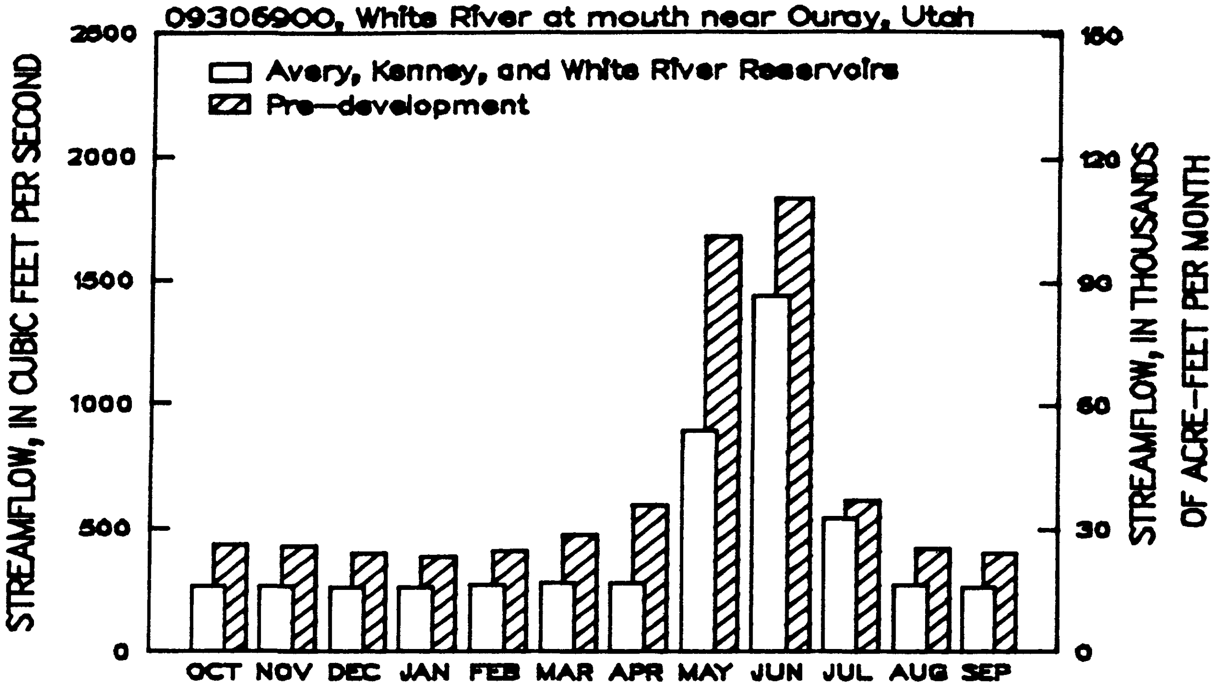



Figure 9.--Comparison of simulated average streamflow with pre-development average streamflow at three locations on the White River for the Avery, Kenney, and White River Reservoirs alternative configuration--Continued.

It should be pointed out that the minimum streamflow requirement of 250 $ft^3/s$ downstream from White River Reservoir only applies if the inflow to the reservoir is 250 $ft^3/s$ or more (U.S. Bureau of Land Management, 1982, appendixes 3 and 4). However, the presence of the reservoirs upstream in Colorado in the simulation would have depleted the streamflow into White River Reservoir considerably, often to about 200 $ft^3/s$, the minimum streamflow requirement downstream from Kenney Reservoir. Therefore, because of the differences in these minimum streamflow requirements, the present modeling effort specified that a minimum streamflow of 250 $ft^3/s$ always was required downstream from White River Reservoir for the entire simulation period. For the purpose of this study, it also was assumed that any of the reservoirs in this configuration could provide water from storage, if available, to fulfill this minimum flow requirement. The above description regarding minimum streamflows also applies to the next two streamflow simulations.

Shortages in the annual diversion requirements of the Avery, Kenney, and White River Reservoirs alternative configuration in this simulation occurred in 3 years: 1968, 1977, and 1978. The simulated shortages were about 12,000 acre-ft/yr (17 $ft^3/s$) in 1968, 21,000 acre-ft/yr (29 $ft^3/s$) in 1977, and 40,000 acre-ft/yr (55 $ft^3/s$) in 1978. The diversion requirement of this system, not including losses for evaporation, would have been about 165,000 acre-ft/yr (228 $ft^3/s$), so the maximum annual shortage was about 24 percent.

Simulated end-of-month contents for Avery, Kenney, and White River Reservoirs for this configuration are shown in figure 10. There is considerably more fluctuation in the contents for Avery Reservoir in this simulation in comparison to the previous simulation; this also is true for Kenney Reservoir, which remained full in the previous simulation. The graphs of the end-of-month contents show that the reservoirs would have filled nearly every year and that all three reservoirs would have been depleted of their active capacity in the 1968, 1977, and 1978 water years.

### Avery, Powell Park (small), Kenney, and White River Reservoirs

Average monthly simulated streamflow for the Avery, Powell Park (small), Kenney, and White River Reservoirs alternative configuration at two locations on the White River is shown in figure 11. In this simulation, streamflow at station 09303000 North Fork White River near Buford, Colo., was identical to that in the previous two simulations (fig. 6), and at station 09304500 White River near Meeker, Colo., simulated streamflow was only very slightly different from that in the three-reservoir simulation just described (fig. 9). However, simulated streamflow for this four-reservoir configuration at White River below Piceance Creek and station 09306900 White River at mouth near Ouray, Utah, is considerably different, because of the greater amount of streamflow depletion by Powell Park Reservoir (small), operated in conjunction with Avery Reservoir. The greatest amount of streamflow depletion would have occurred during the months of May, June, and July. The total streamflow depletion for this configuration at the mouth of the White River would have been about 222,000 acre-ft/yr (306 $ft^3/s$), including evaporation losses at all four reservoirs.

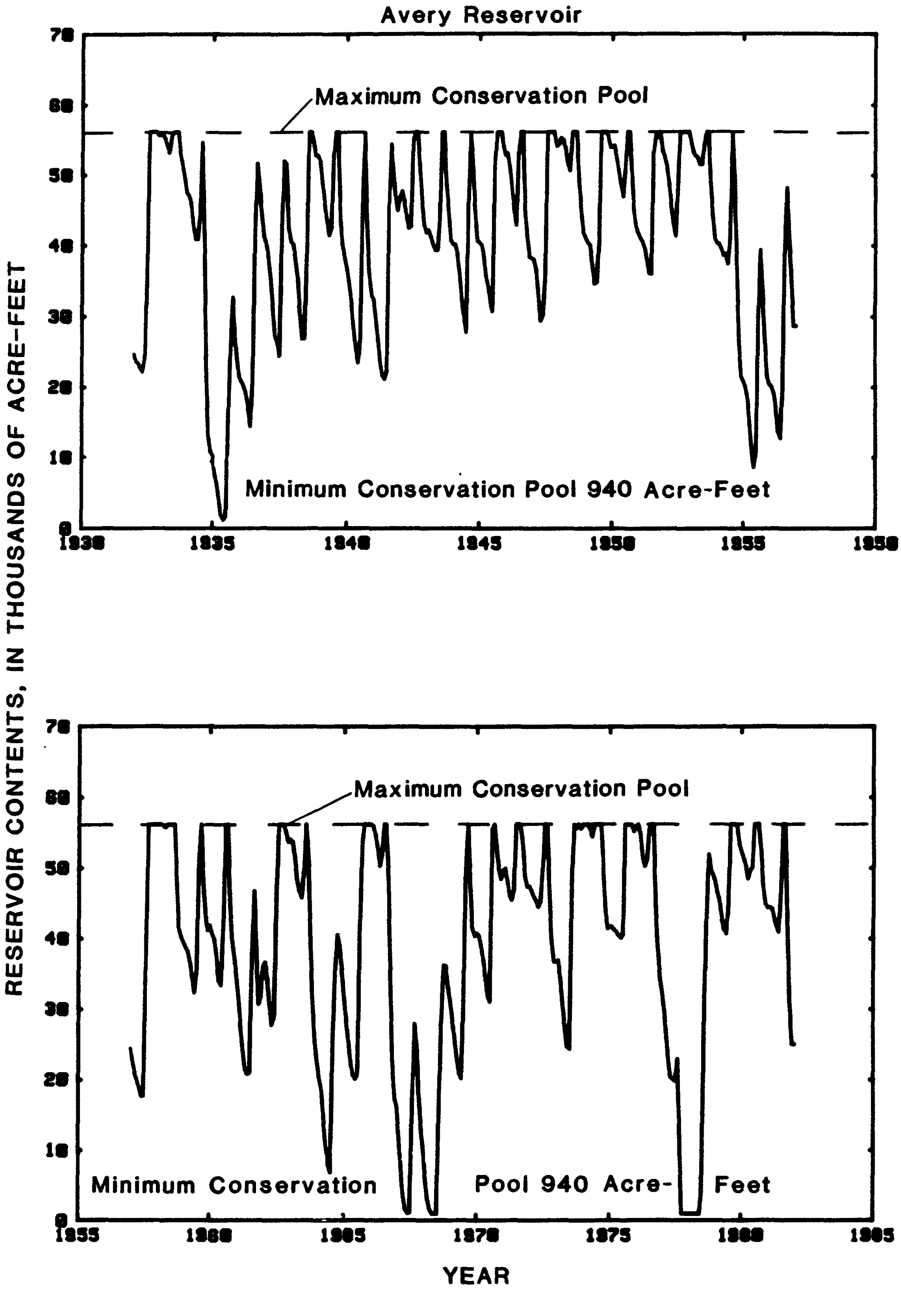



Figure 10.--Simulated end-of-month contents of three reservoirs for the Avery, Kenney, and White River Reservoirs alternative configuration.

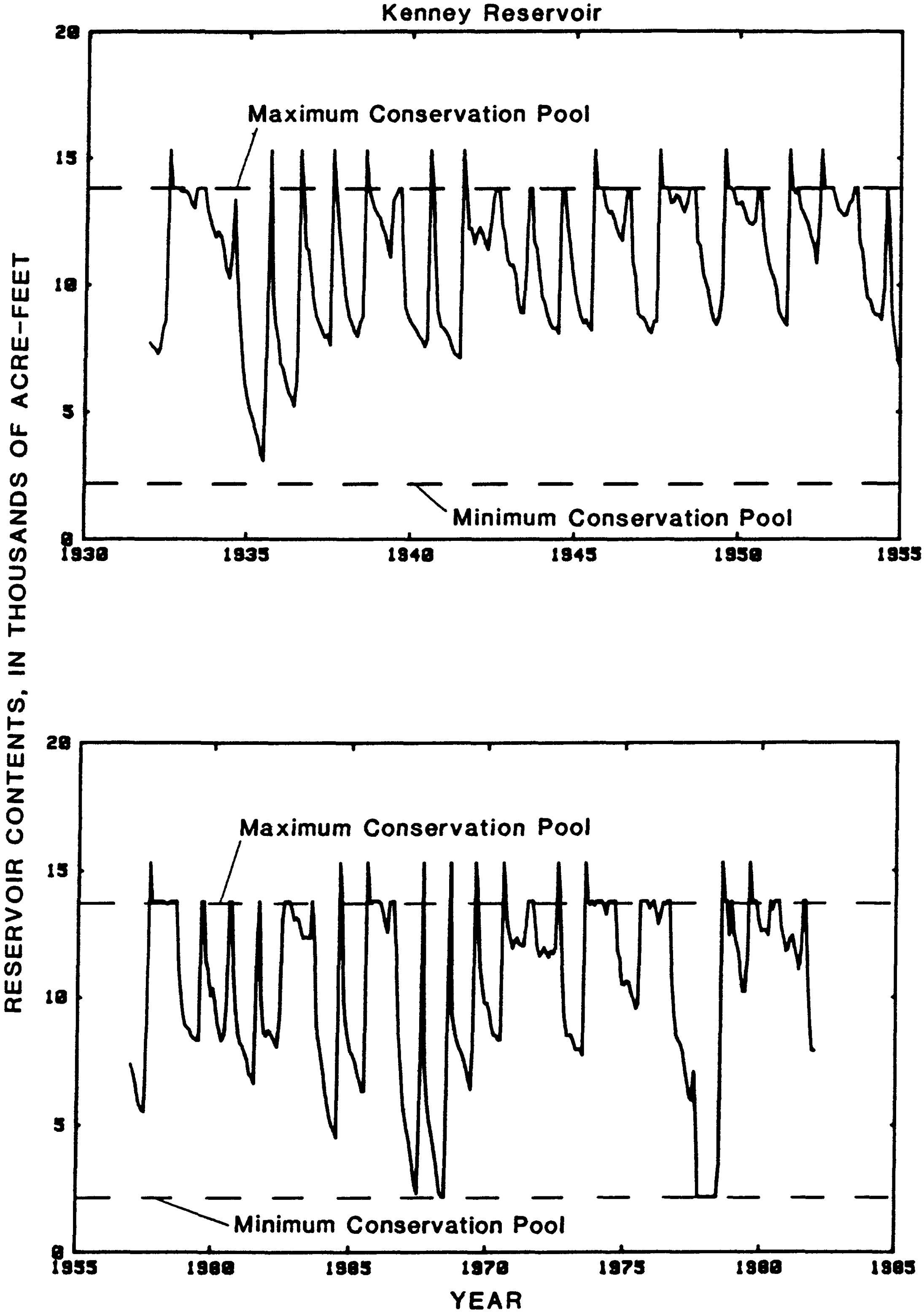



Figure 10.--Simulated end-of-month contents of three reservoirs for the Avery, Kenney, and White River Reservoirs alternative configuration--Continued.

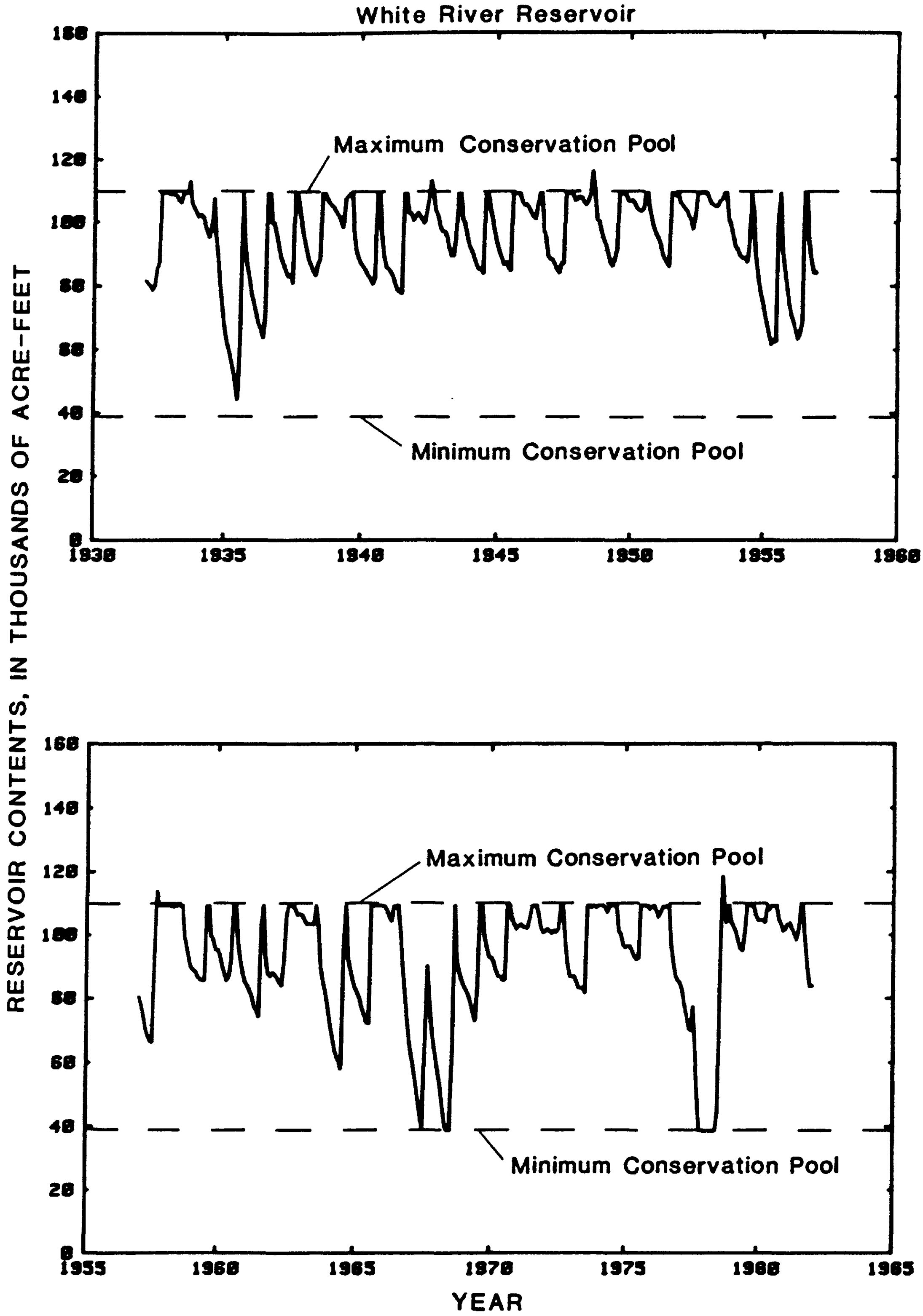
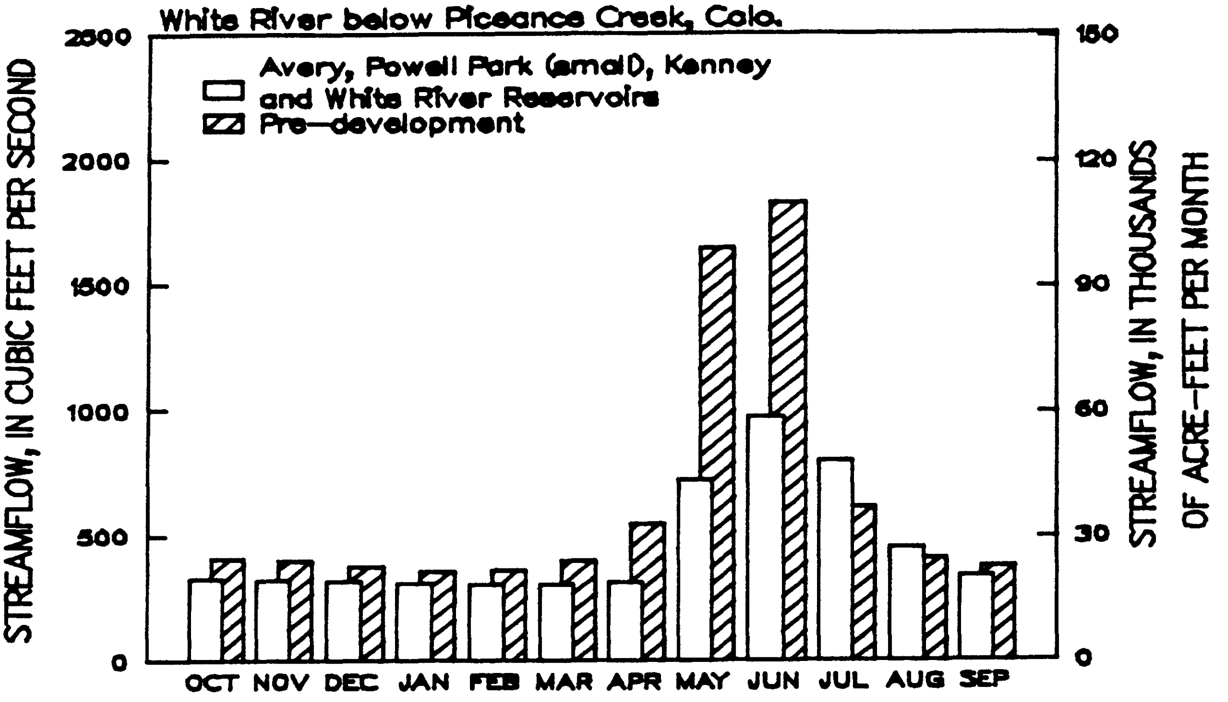



Figure 10.--Simulated end-of-month contents of three reservoirs for the Avery, Kenney, and White River Reservoirs alternative configuration--Continued.



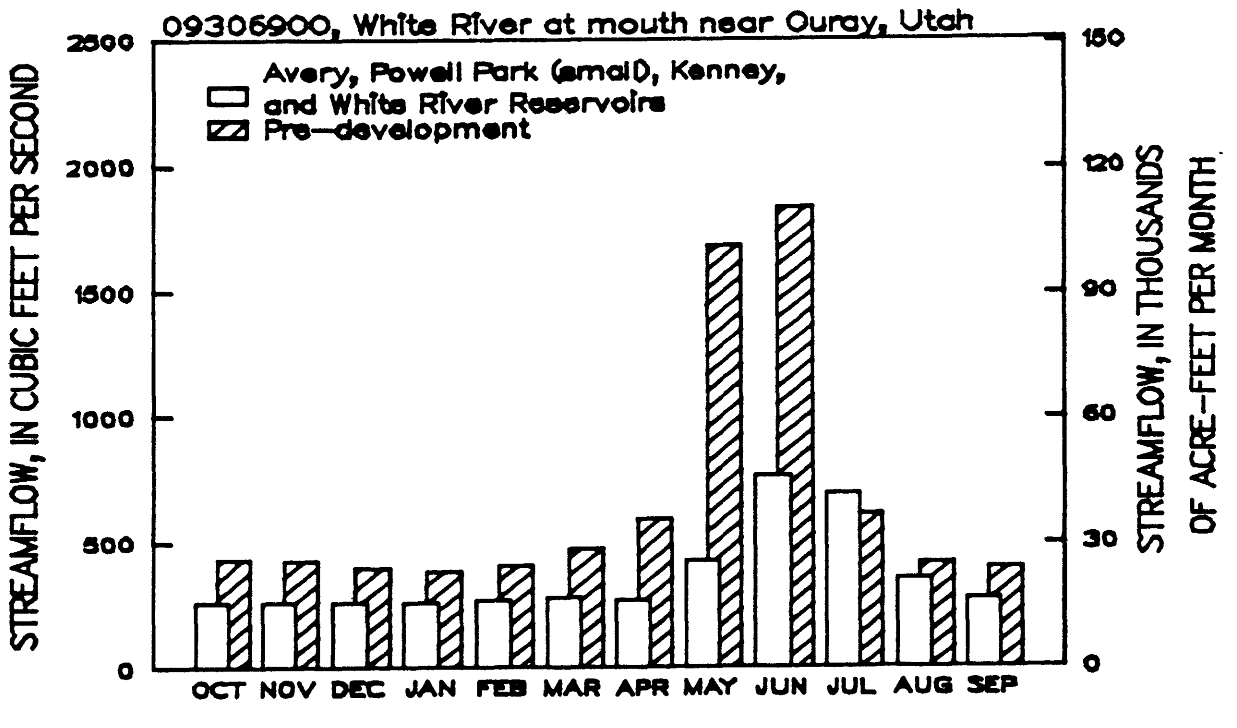




Figure 11.--Comparison of simulated average streamflow with pre-development average streamflow at two locations on the White River for the Avery, Powell Park (small), Kenney, and White River Reservoirs alternative configuration.

The minimum streamflow locations of this configuration basically were the same as for the previous three-reservoir configuration, except that the two oil-shale diversions on the White River upstream from Piceance Creek, and served by Avery Reservoir, are replaced by a single diversion downstream from Powell Park Reservoir. Thus, at the single diversion point remaining upstream from this reservoir, the minimum streamflow requirement of 200 $ft^3/s$ in the White River would not have been met for 2 months in 1977. Downstream from both Powell Park (small) and Kenney Reservoirs, the minimum streamflow of 200 $ft^3/s$ would have been exceeded for the entire 1932-81 period. The 250 $ft^3/s$ minimum flow requirement downstream from White River Reservoir for August through May was met in this simulation, but the 500 $ft^3/s$ requirement for June and July would not have been met in 9 years (11 months total). During those 11 months, though, the flow was not less than 250 $ft^3/s$ in the simulation.

Shortages in the annual diversion requirements of the Avery, Powell Park (small), Kenney, and White River Reservoirs alternative configuration would have occurred only in 1977 and 1978. The shortages would have been about 3,000 acre-ft/yr (4 $ft^3/s$) in 1977 and 62,000 acre-ft/yr (86 $ft^3/s$) in 1978. The diversion requirement of this configuration, not including evaporation losses, would have been about 222,000 acre-ft/yr (306 $ft^3/s$) so the maximum annual shortage would have been about 28 percent.

Simulated end-of-month contents for the four reservoirs in this configuration are shown in figure 12. The graph for Avery Reservoir shows that its contents fluctuated more than in the previous two simulations, because of greater downstream diversion and streamflow requirements. In this simulation, and in all other simulations, the reservoirs were assumed to operate as a conjunctive system. However, the graphs for Kenney and White River Reservoirs show that their contents fluctuated less in this simulation than in the three-reservoir configuration. The primary reason for this is the presence of Powell Park (small) Reservoir upstream, which provides considerable additional regulation of the White River's flow into the two downstream reservoirs. The graphs in figure 12 further illustrate that all four of the reservoirs in this configuration would have been completely depleted of usable storage only in 1977 and 1978.

## Powell Park (large) and Kenney Reservoirs

The effects of Powell Park (large) and Kenney Reservoirs configuration on streamflow at two locations on the White River are shown in figure 13. Monthly average streamflow in the White River upstream from Powell Park (large) Reservoir was the same as historical streamflow. Simulated streamflow at White River below Piceance Creek, and at station 09306900 White River at mouth near Ouray, Utah (fig. 13), for this configuration was somewhat similar to that of the previous configuration (fig. 11). Average streamflow depletion at the White River's mouth for the Powell Park (large) and Kenney Reservoirs configuration would have been about 226,000 acre-ft/yr (312 $ft^3/s$), which is slightly more than that for the previous simulation with four reservoirs.

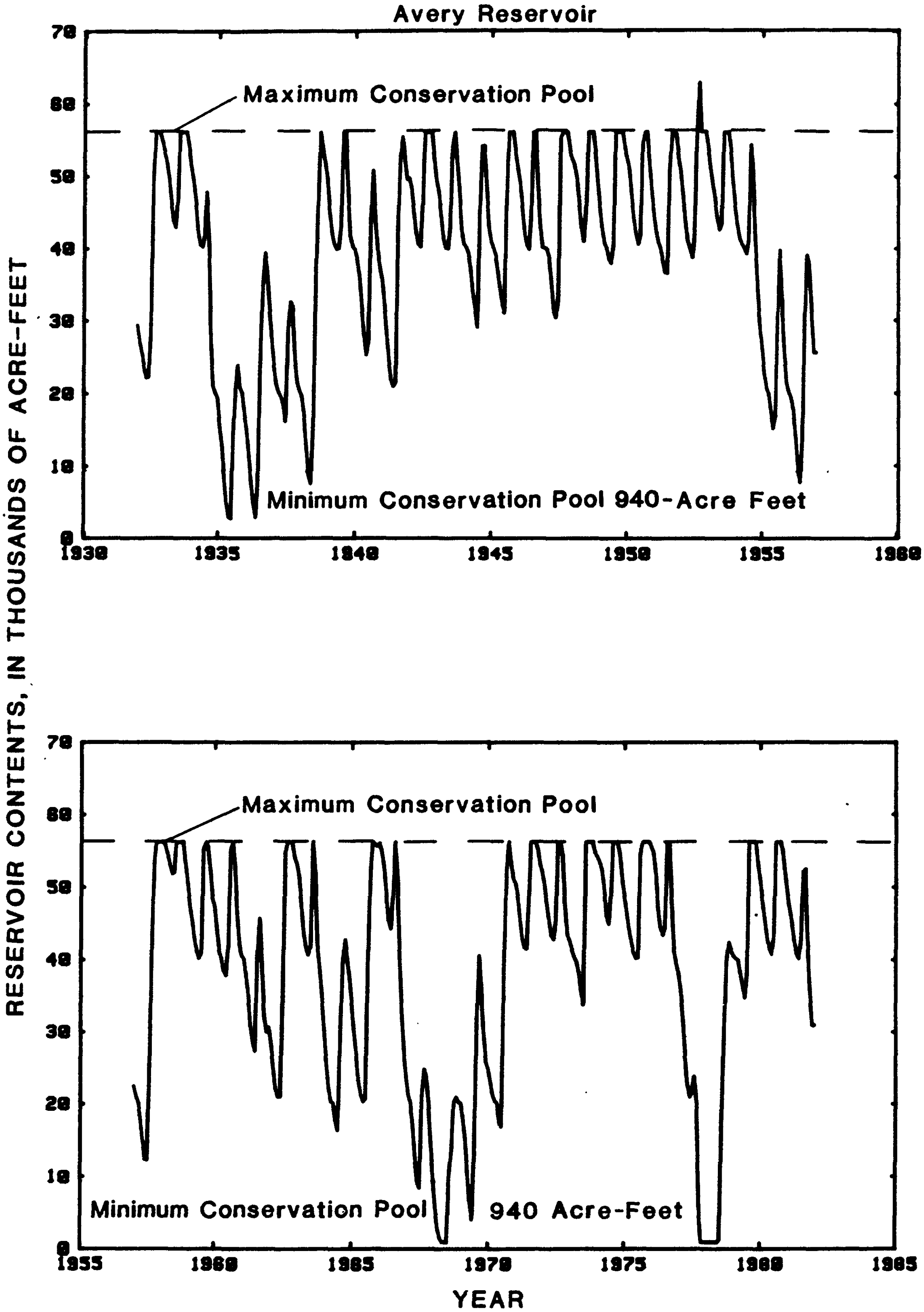



Figure 12.--Simulated end-of-month contents of four reservoirs for the Avery, Powell Park (small), Kenney, and White River Reservoirs alternative configuration.

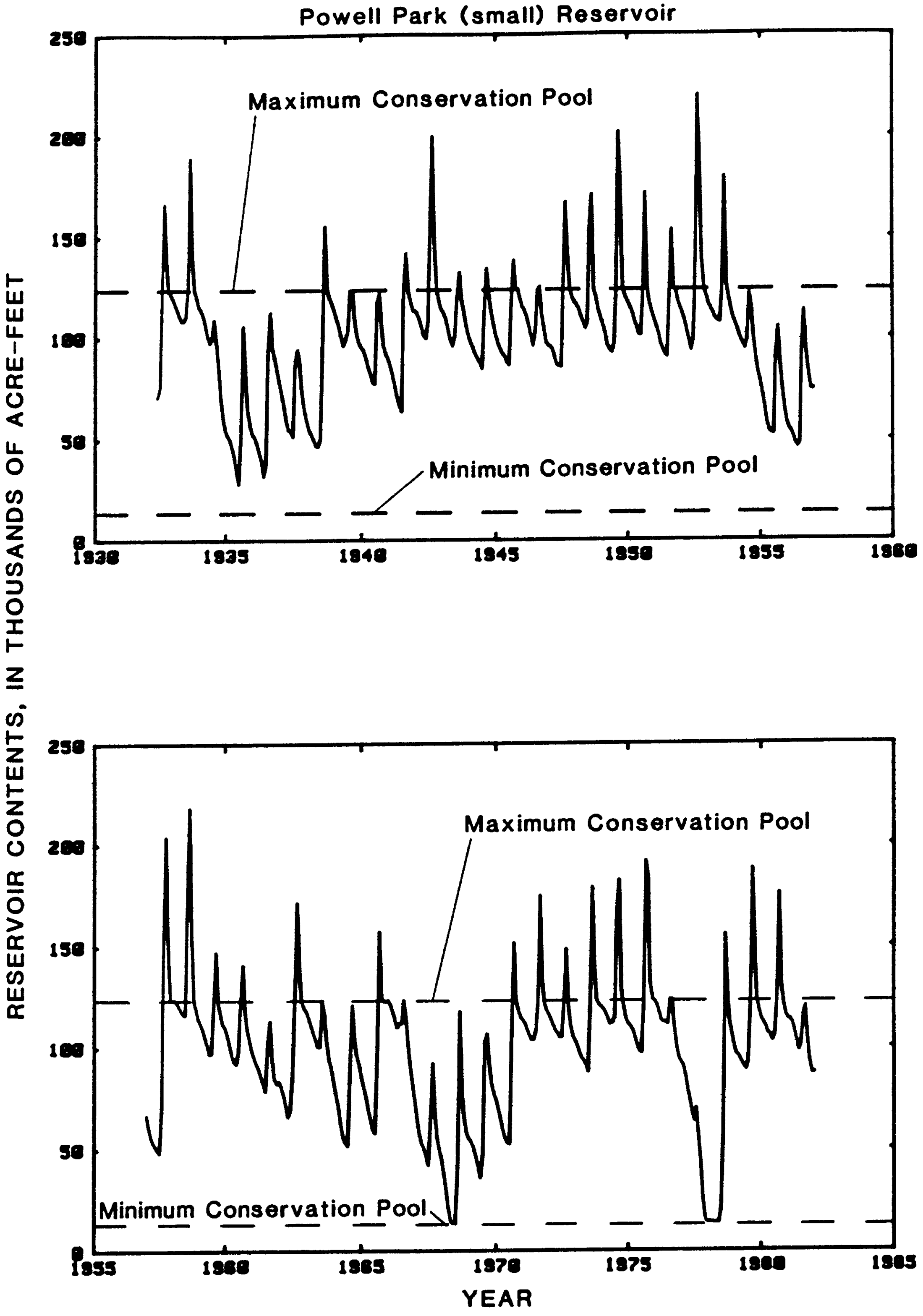



Figure 12.--Simulated end-of-month contents of four reservoirs for the Avery, Powell Park (small), Kenney, and White River Reservoirs alternative configuration--Continued.

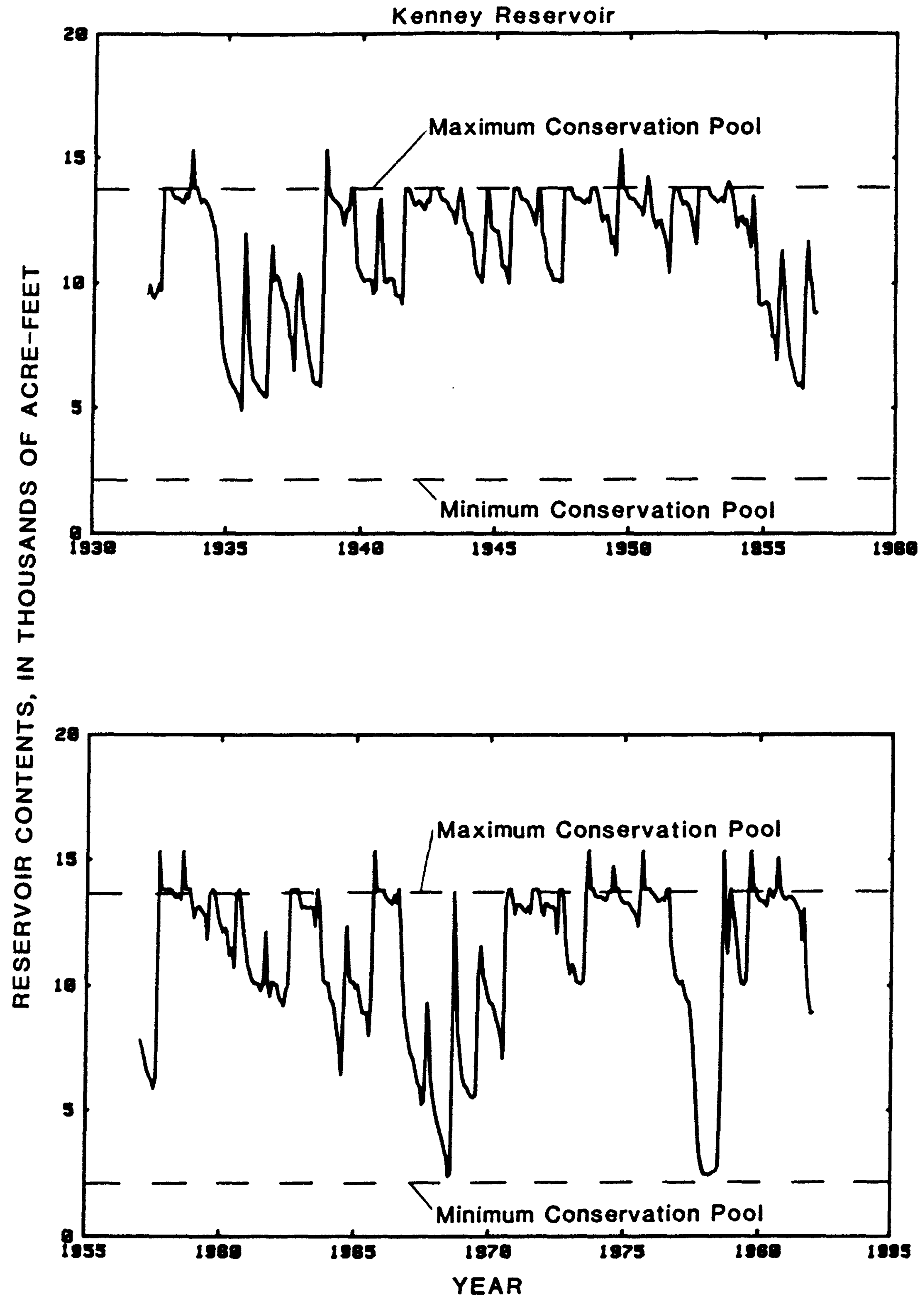



Figure 12.--Simulated end-of-month contents of four reservoirs for the Avery, Powell Park (small), Kenney, and White River Reservoirs alternative configuration--Continued.

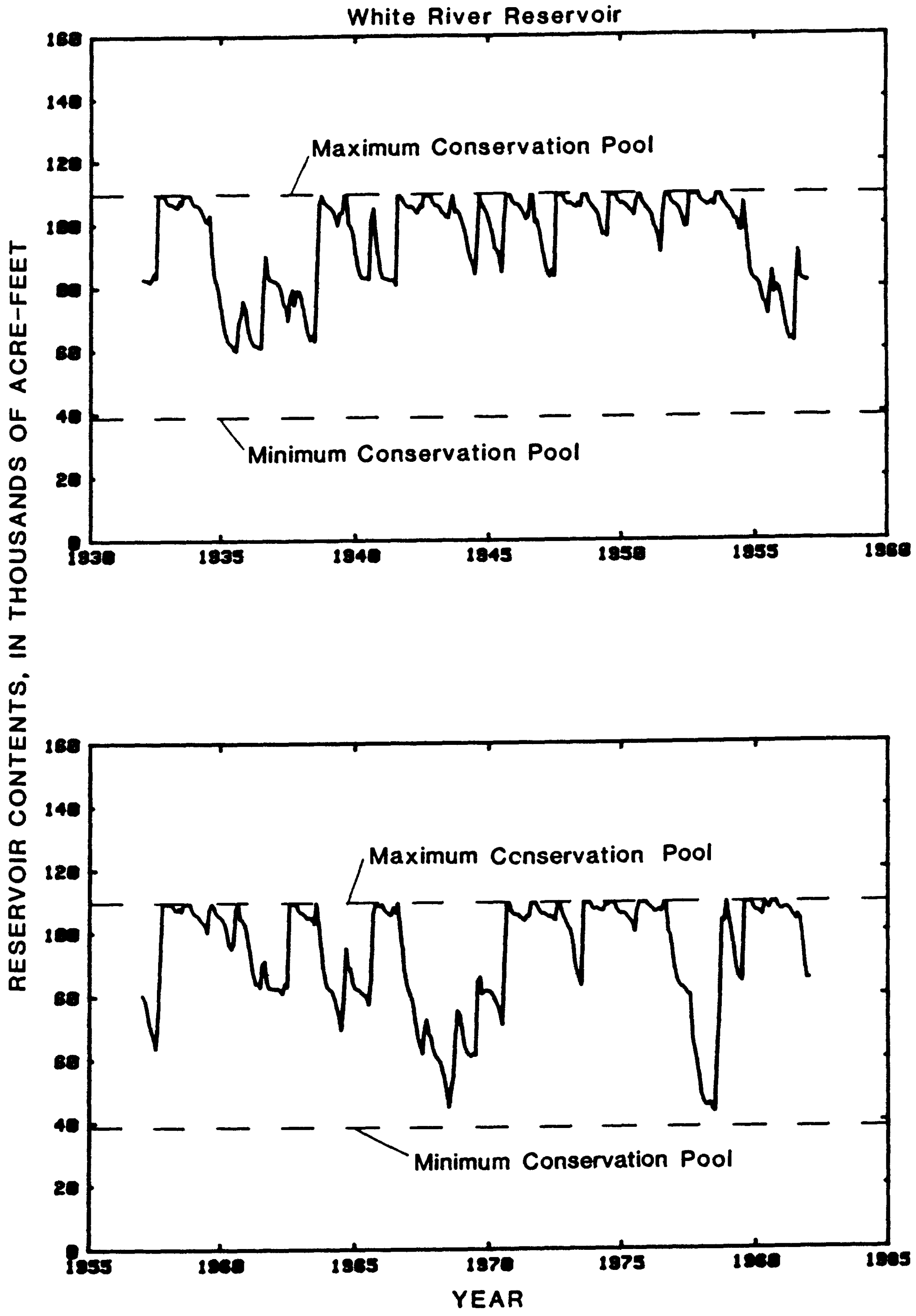
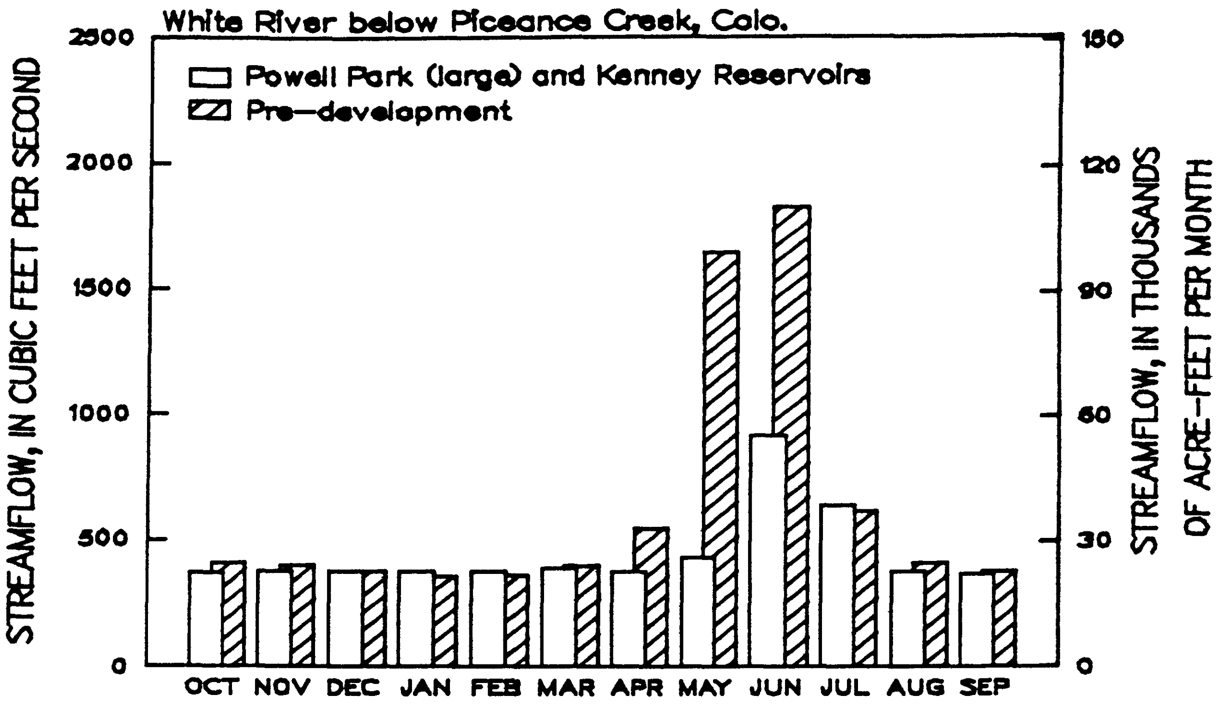



Figure 12.--Simulated end-of-month contents of four reservoirs for the Avery, Powell Park (small), Kenney, and White River Reservoirs alternative configuration--Continued.



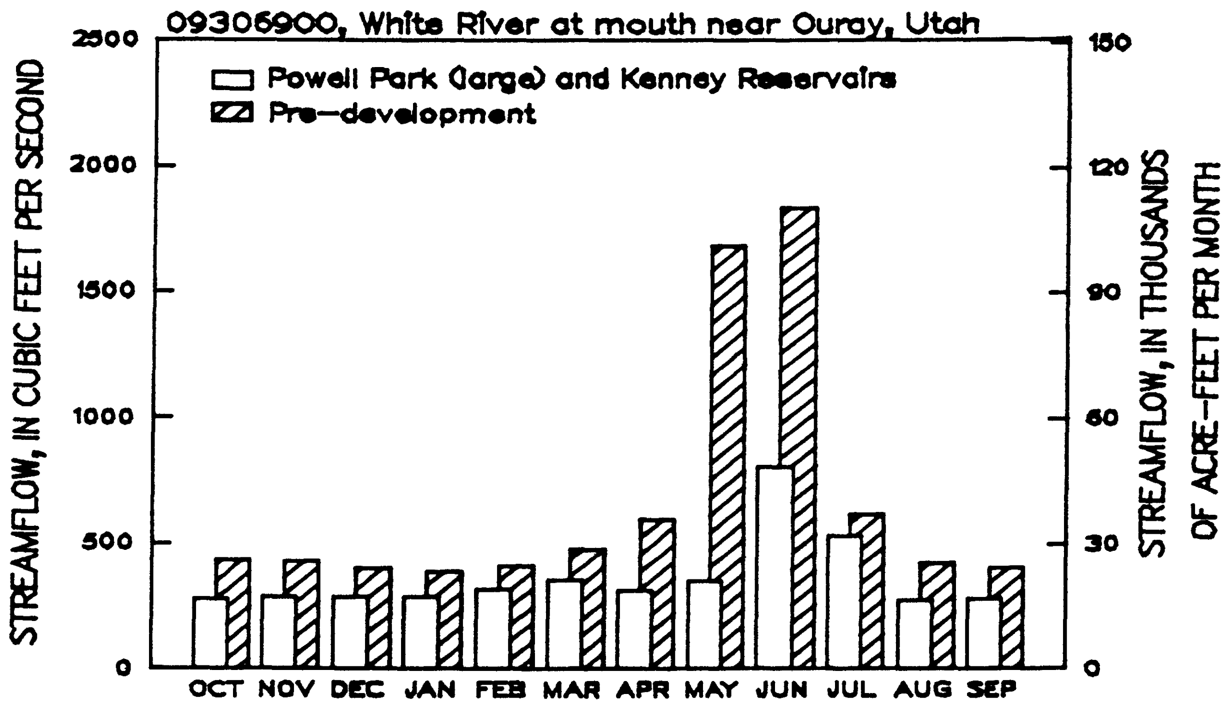




Figure 13.--Comparison of simulated average streamflow with pre-development average streamflow at two locations on the White River for the Powell Park (large) and Kenney Reservoirs alternative configuration.

The minimum streamflow requirements of 200 $ft^3/s$ downstream from Powell Park (large) and Kenney Reservoirs and 250 $ft^3/s$ downstream from the diversion in Utah at the proposed location of White River Reservoir, would have been completely satisfied with this configuration. The additional requirement of 500 $ft^3/s$ during June and July at the latter location also would have been completely satisfied.

Shortages in the annual diversion requirements of the Powell Park (large) and Kenney Reservoirs configuration would have occurred in 1938 and 1978, with shortages of 10,000 acre-ft/yr (14 $ft^3/s$) in 1938 and 61,000 acre-ft/yr (84 $ft^3/s$) in 1978. The diversion requirement of this configuration, not including evaporation losses, would have been 222,000 acre-ft/yr (306 $ft^3/s$), so the maximum annual shortage would have been about 27 percent.

Simulated end-of-month contents for Powell Park (large) and Kenney Reservoirs for this configuration are shown in figure 14. The graph for Powell Park Reservoir shows that its contents would have fluctuated considerably, but the reservoir would have been depleted of its usable contents only in 1938 and 1978. Kenney Reservoir, though, fluctuated less in this simulation than in either of the two previous simulations, primarily because the larger Powell Park Reservoir would have provided more regulation of the White River.

## COMPARISON OF ALTERNATIVE CONFIGURATIONS

The first three streamflow simulations, with two (Avery and Kenney), three (Avery, Kenney, and White River), and four (Avery, Powell Park (small), Kenney, and White River) reservoirs, show the effect of increasing streamflow depletion in the White River resulting from increasing reservoir development. In these three simulations, average annual streamflow depletions were about 93,000, 168,000, and 222,000 acre-ft/yr, respectively. The fourth simulation, with Powell Park (large) and Kenney Reservoirs, was intended to provide the same amount of streamflow depletion as the third simulation, but with a single large reservoir replacing three smaller ones. Average streamflow depletion simulated for this last configuration was about 226,000 acre-ft/yr. Simulated streamflows at three locations on the White River resulting from these configurations are compared in figure 15; results of the simulations also are summarized in table 5.

Simulated monthly streamflow at station 09304500 White River near Meeker, Colo., was somewhat similar for all four configurations (fig. 15). At White River below Piceance Creek, simulated streamflow for the first two configurations nearly was the same, but was reduced considerably in the third and fourth configurations because of streamflow depletion by Powell Park Reservoir. At station 09306900 White River at mouth near Ouray, Utah, streamflow would have been reduced considerably by each of the first three successive configurations, especially during May and June, first by the addition of White River Reservoir and then Powell Park (small) Reservoir. Simulated streamflow at the White River's mouth for the last configuration is somewhat similar to that for the four-reservoir configuration.

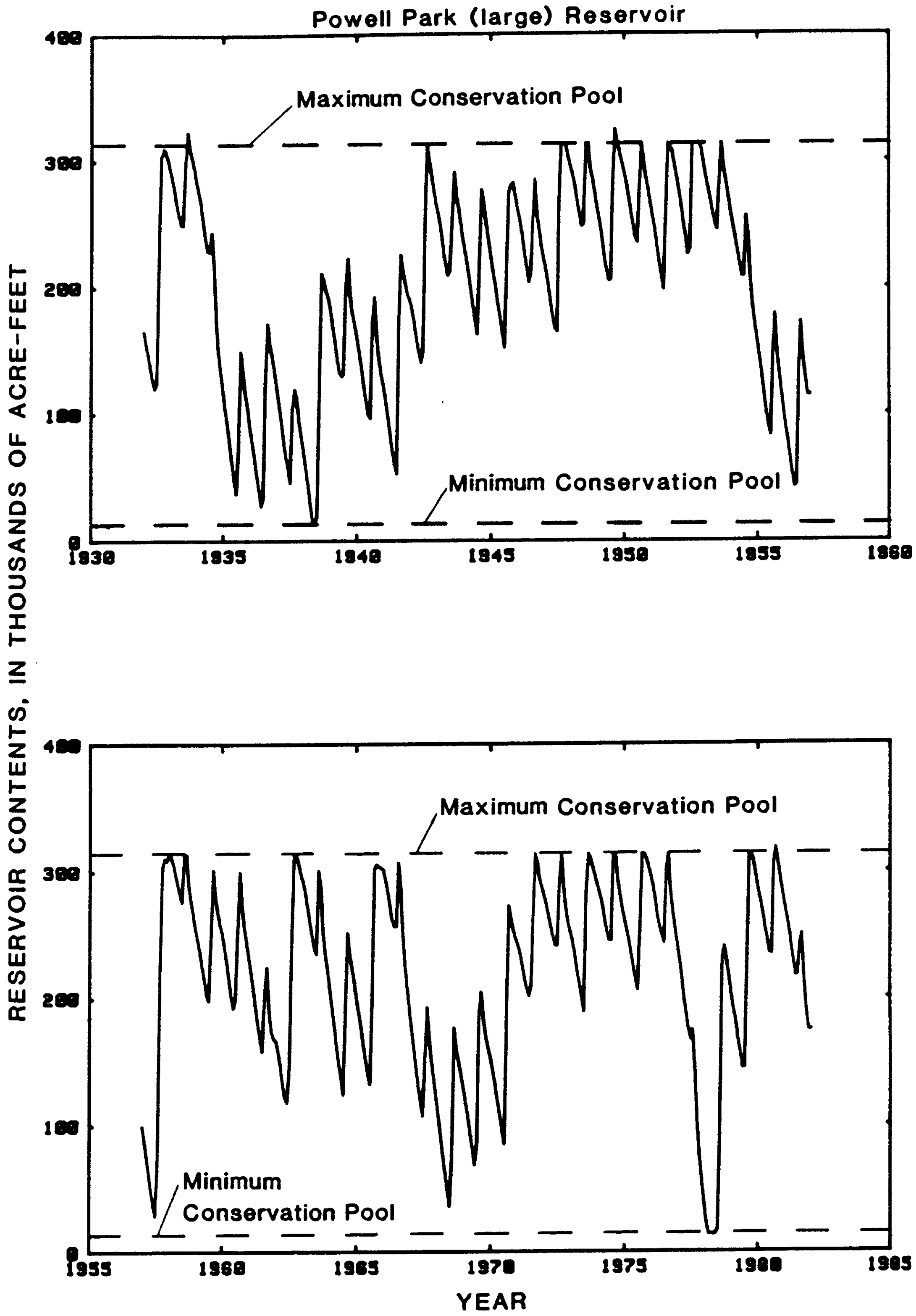



Figure 14.--Simulated end-of-month contents of two reservoirs for the Powell Park (large) and Kenney Reservoirs alternative configuration.

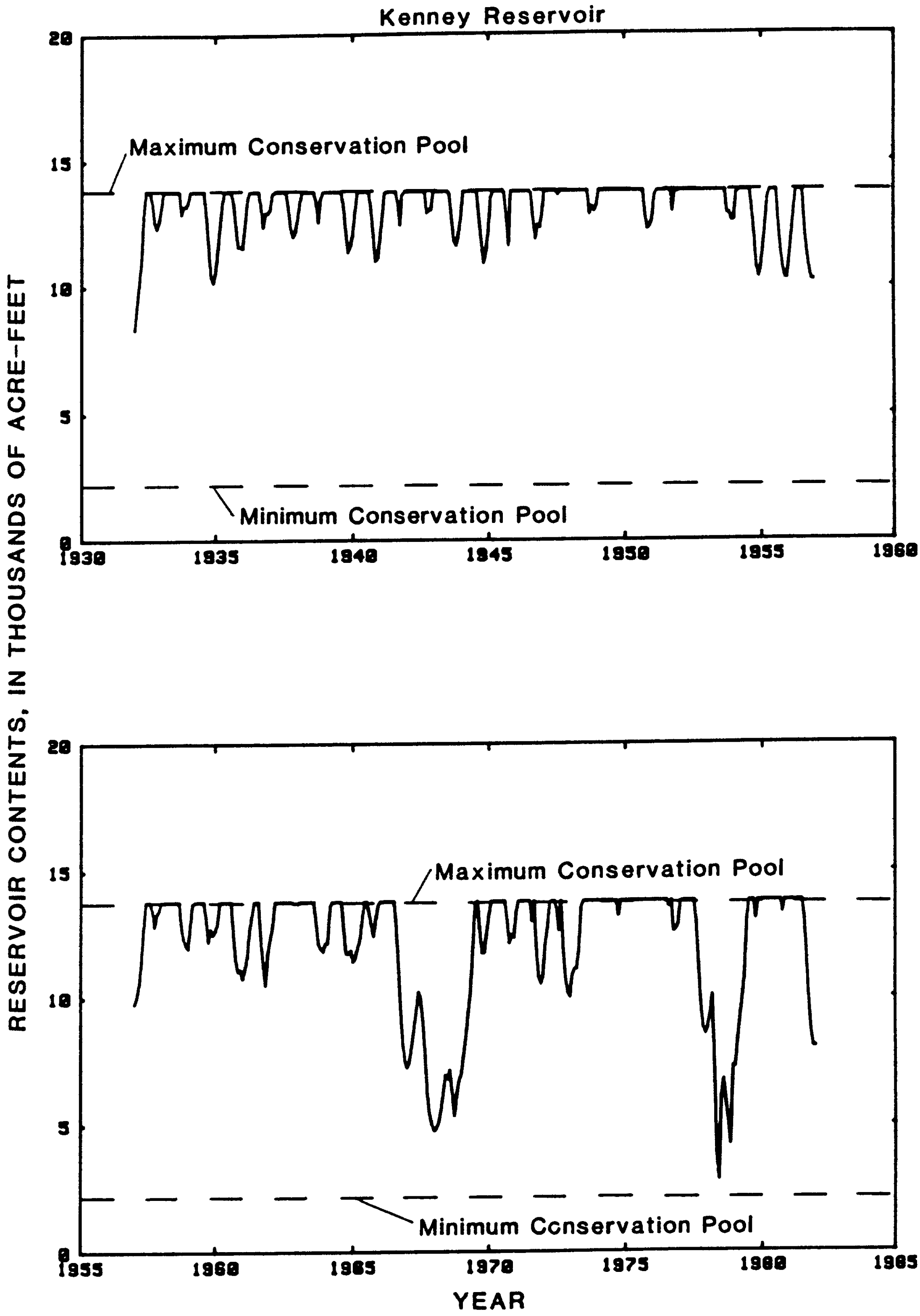
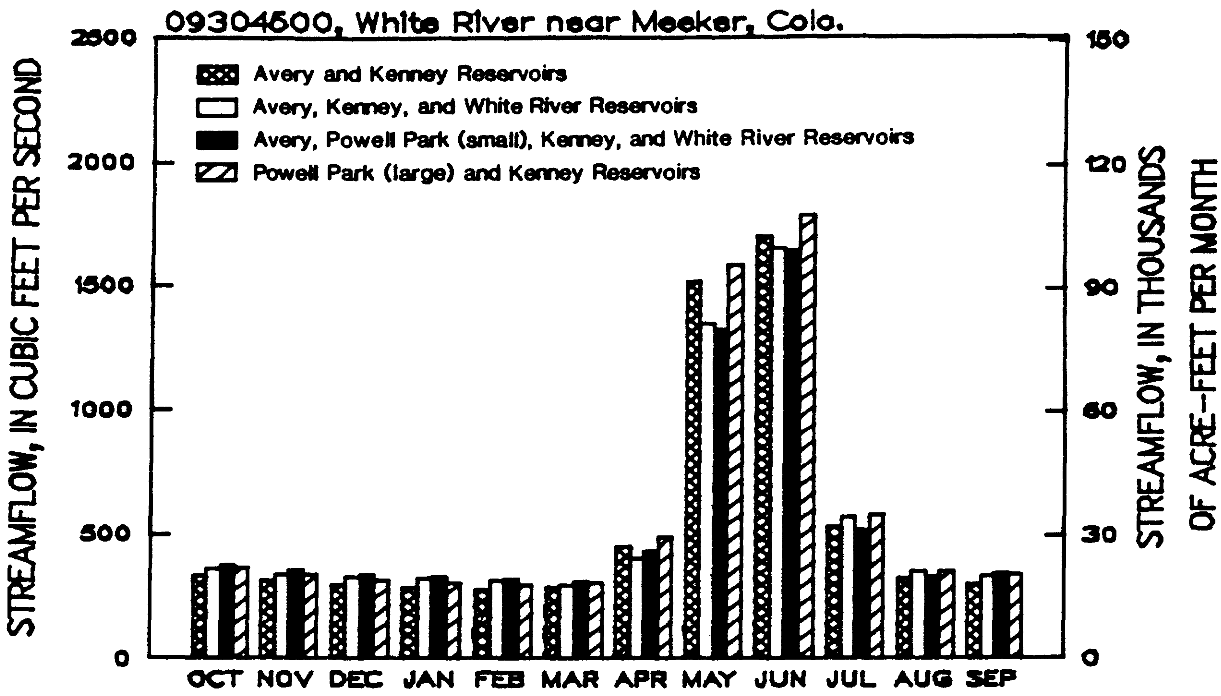



Figure 14.--Simulated end-of-month contents of two reservoirs for the Powell Park (large) and Kenney Reservoirs alternative configuration--Continued.



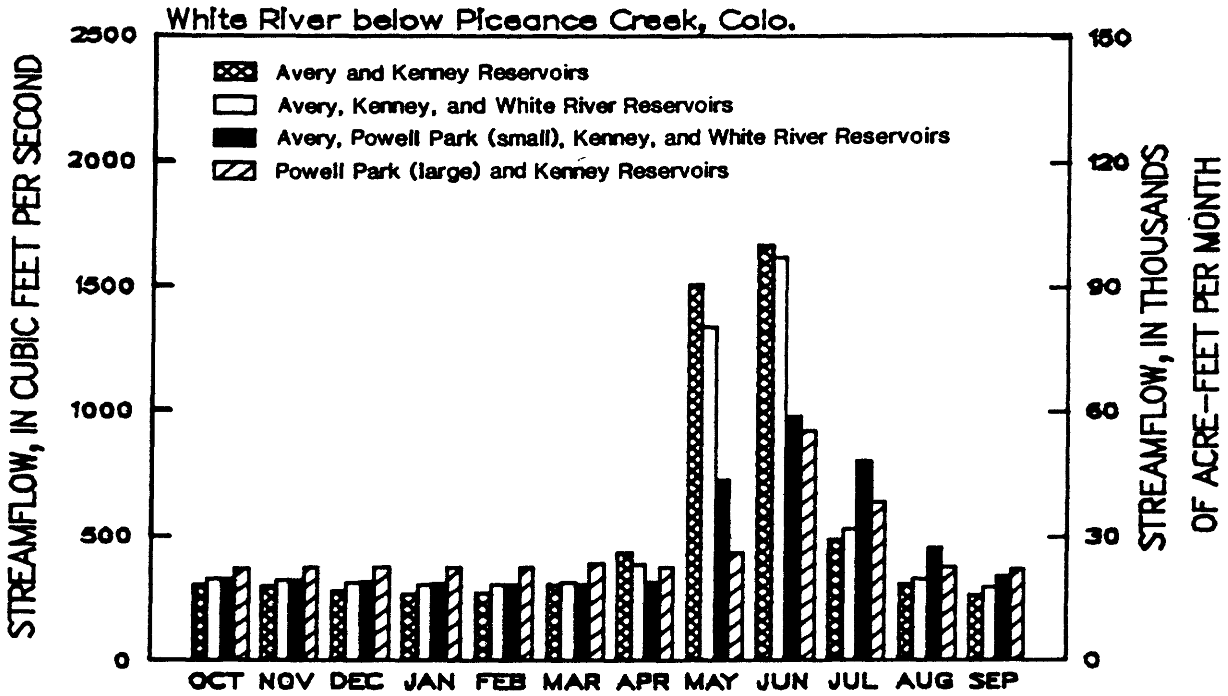




Figure 15.--Comparison of simulated average streamflows at three locations on the White River for four alternative reservoir configurations.

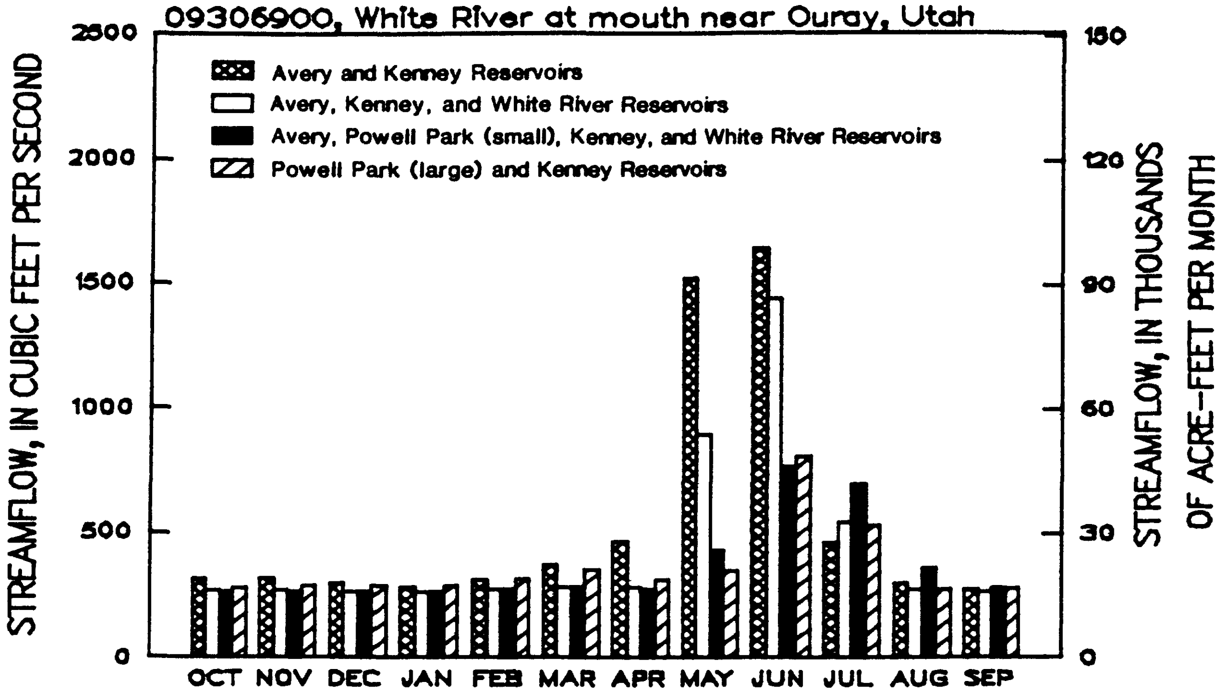



Figure 15.--Comparison of simulated average streamflows at three locations on the White River for four alternative reservoir configurations--Continued.

The simulation with the large version of Powell Park Reservoir did illustrate that one large reservoir could provide the same quantity of water as three smaller reservoirs. Results of that simulation generally indicate that the single, large reservoir seems to be able to regulate the White River and to provide the minimum streamflow requirements throughout the year more effectively than the three smaller reservoirs.

The storage capacity of Powell Park (large) Reservoir was about 10 percent greater than the combined storage of the three smaller reservoirs, but this would not have had a significant effect on the results of that simulation. However, the economic aspect of the single, large reservoir versus three smaller reservoirs, as well as the economics of any of the reservoirs described herein, was not considered in this study.

Table 5.--*Summary of results of multireservoir streamflow simulations*

[Streamflow depletions, evaporations, diversion shortages, and streamflows are in acre-feet per year and cubic feet per second (in parentheses); dashes, not applicable]

| Reservoir configuration | Average annual | | Number of years with | | Average diversion shortage | Average annual simulated streamflow at | | |
|---|---|---|---|---|---|---|---|---|
| | Streamflow depletion | Evaporation | Minimum streamflow shortage | Diversion shortage | | Station 09304500 | White River below Piceance Creek | Station 09306900 |
| Historical | -- | -- | -- | -- | -- | 427,000 (580) | 466,000 (644) | 488,000 (674) |
| Avery and Kenney | 93,000 (128) | 2,300 (3.2) | 0 | 0 | 0 | 400,000 (552) | 385,000 (532) | 396,000 (546) |
| Avery, Kenney, and White River. | 168,000 (232) | 6,100 (8.4) | 13 | 3 | 1,700 (2.4) | 401,000 (553) | 385,000 (532) | 320,000 (442) |
| Avery, Powell Park (small), Kenney, and White River. | 222,000 (306) | 10,000 (14) | 9 | 2 | 1,300 (1.8) | 401,000 (553) | 333,000 (459) | 267,000 (368) |
| Powell Park (large) and Kenney. | 226,000 (312) | 7,200 (9.9) | 0 | 2 | 1,400 (2.0) | 427,000 (589) | 325,000 (448) | 262,000 (362) |

Not every conceivable configuration of the four reservoirs was simulated, but the effect on streamflow of other configurations would be somewhat similar to some of the simulations described herein. For example, two possible configurations could be Avery, Powell Park (small), and Kenney Reservoirs or Kenney and White River Reservoirs. Thus, assuming the same water-use requirements for these reservoirs as described in this report, streamflow depletion for the first possible configuration would be about 137,000 acre-ft/yr (189 $ft^3/s$) at White River below Piceance Creek and about 150,000 acre-ft/yr (207 $ft^3/s$) at the mouth of the White River. For the second possible configuration, streamflow upstream from Kenney Reservoir would be equal to historical streamflow; however, at the mouth of the White River, depletion would be about 90,000 acre-ft/yr (124 $ft^3/s$). From table 5, one can determine which of the four configurations simulated herein had approximately those amounts of streamflow depletion at the appropriate locations, and then can refer back to the illustrations of that simulation. This would give an approximate representation of the streamflow that would result from these other possible reservoir configurations.

In addition, it is quite possible that other reservoirs or water-resource developments could be constructed in the White River basin; even the reservoir configurations used in this study are conjectural. Nevertheless, the effect on streamflow in the White River of any of these developments, regardless of their configuration, generally should be similar to the effects described in this report. The primary reasons for the broad application of these simulations are: (1) Many of the proposed water-resource developments would only affect streamflow downstream from the Meeker vicinity, even though some of the associated reservoirs, such as Avery Reservoir, would be upstream from Meeker; (2) there are very few major irrigation diversions and return flows on the White River between a point a few miles downstream from Meeker and the mouth; and (3) the only tributary contributing any significant flow downstream from Meeker is Piceance Creek, and its flow is small in comparison to that in the White River. Consequently, streamflow, and streamflow depletion, are considerabley related from one location to the next.

## RESERVOIR ACTIVE CAPACITY VERSUS YIELD

A secondary objective of this report was to develop relations between reservoir active capacity and yield applicable to the White River; these were developed for six different reservoir active capacities. The basic assumptions used to develop these relations were: (1) A single hypothetical reservoir, of six different sizes, was used; (2) historical streamflow at station 09306500 White River near Watson, Utah, for the 1932-81 water years was used as inflow to the reservoir; (3) various year-round uniform diversion rates were assumed, with no return flow; and (4) a year-round minimum streamflow of 250 $ft^3/s$ was required in the White River downstream from the reservoir. These relations were developed by numerous streamflow simulations, using the HEC-3 model, but with an abbreviated control point sequence.

The percent of time, in years, that a given annual (water year) demand would not have been met by a particular reservoir capacity is shown in figure 16. The point where each of the curves for the six reservoir sizes intersects the left vertical axis would be the maximum yield, with no shortages during the simulation period, for that capacity. If no shortages are allowed, reservoir capacity of about 400,000 acre-ft seems to be the maximum size practicable for the White River because there is very little increase in yield with a 500,000 acre-ft reservoir. Also, as the percent of time with shortages is increased, the annual yield of a smaller reservoir readily increases to be as much or more as the yield of a larger reservoir with no shortages (fig. 16). For example, a reservoir with active capacity of 200,000 acre-ft would yield about 156,000 acre-ft/yr with no shortage, but if shortages could be allowed for about 10 percent of the time, a 100,000 acre-ft reservoir (fig. 16, table 6) would yield 162,000 acre-ft/yr about 90 percent of the time.

A detailed portrayal of the percent of time the simulated annual demand was not met (fig. 16) is presented in figure 17. Thus, an annual demand of 150,000 acre-ft would not have been met about 29 percent of the time with a 50,000 acre-ft reservoir (fig. 16). The magnitude of those annual shortages, and the frequency with which they would have been equaled or exceeded, are shown in figure 17. For the above annual demand and reservoir capacity, an annual shortage of 17 percent, or 26,000 acre-ft, would have been equaled or exceeded about 11 percent of the time (fig. 17).

These relations are applicable to the White River generally in the vicinity of the streamflow-gaging station near Watson, Utah (fig. 1, table 3). Similar relations applicable to other locations on the White River could be developed, but are not presented here. It is interesting to note that the historical average streamflow at station 09304800 White River below Meeker, Colo. (just downstream from the proposed Powell Park Reservoir, fig. 1), is about 50 $ft^3/s$ less than that at station 09306500 White River near Watson, Utah (table 3). If one assumes a minimum streamflow of 200 $ft^3/s$ downstream from a hypothetical Powell Park Reservoir, it seems possible that the reservoir active capacity-yield relations just described could have some application to this location.

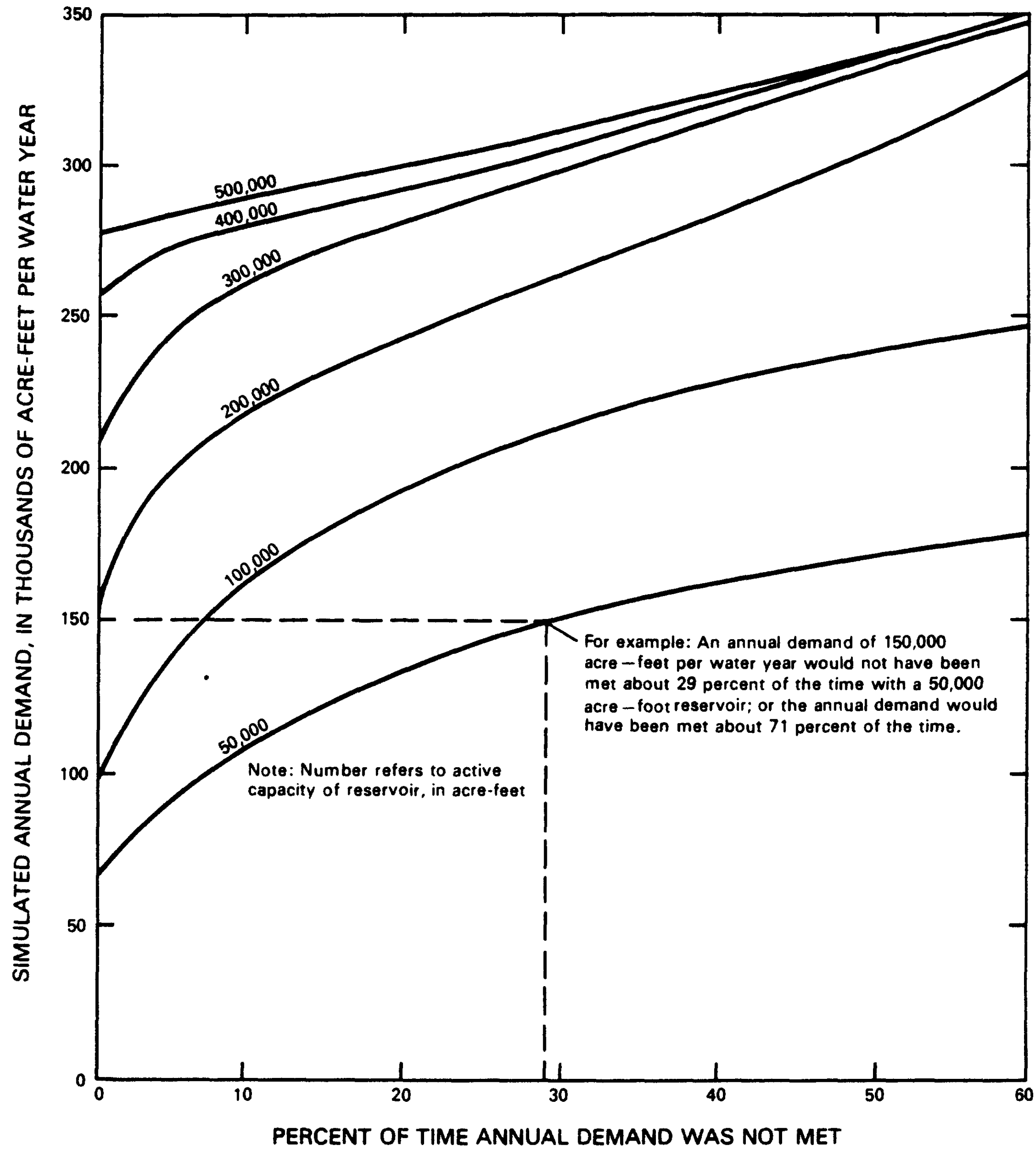



Figure 16.--Simulated annual demand and percent of time that varying annual demand was not met for six sizes of reservoirs on the White River.

Table 6.--*Percent increase in average annual yield for increasing reservoir sizes on the White River for three levels of shortages*

[Reservoir active capacity and average annual yield in thousands of acre-feet; dashes indicate not applicable]

| Reservoir active capacity | Average annual yield | Increase in reservoir active capacity from next smaller reservoir (percent) | Increase in average annual yield from next smaller reservoir (percent) |
|---|---|---|---|
| | No shortages | | |
| 50 | 67 | --- | --- |
| 100 | 98 | 100 | 46 |
| 200 | 156 | 100 | 59 |
| 300 | 212 | 50 | 36 |
| 400 | 258 | 33 | 22 |
| 500 | 278 | 25 | 8 |
| | Shortages 5 percent of time | | |
| 50 | 88 | --- | --- |
| 100 | 140 | 100 | 59 |
| 200 | 202 | 100 | 44 |
| 300 | 245 | 50 | 21 |
| 400 | 272 | 33 | 11 |
| 500 | 283 | 25 | 4 |
| | Shortages 10 percent of time | | |
| 50 | 107 | --- | --- |
| 100 | 162 | 100 | 51 |
| 200 | 220 | 100 | 36 |
| 300 | 261 | 50 | 19 |
| 400 | 281 | 33 | 8 |
| 500 | 288 | 25 | 2 |

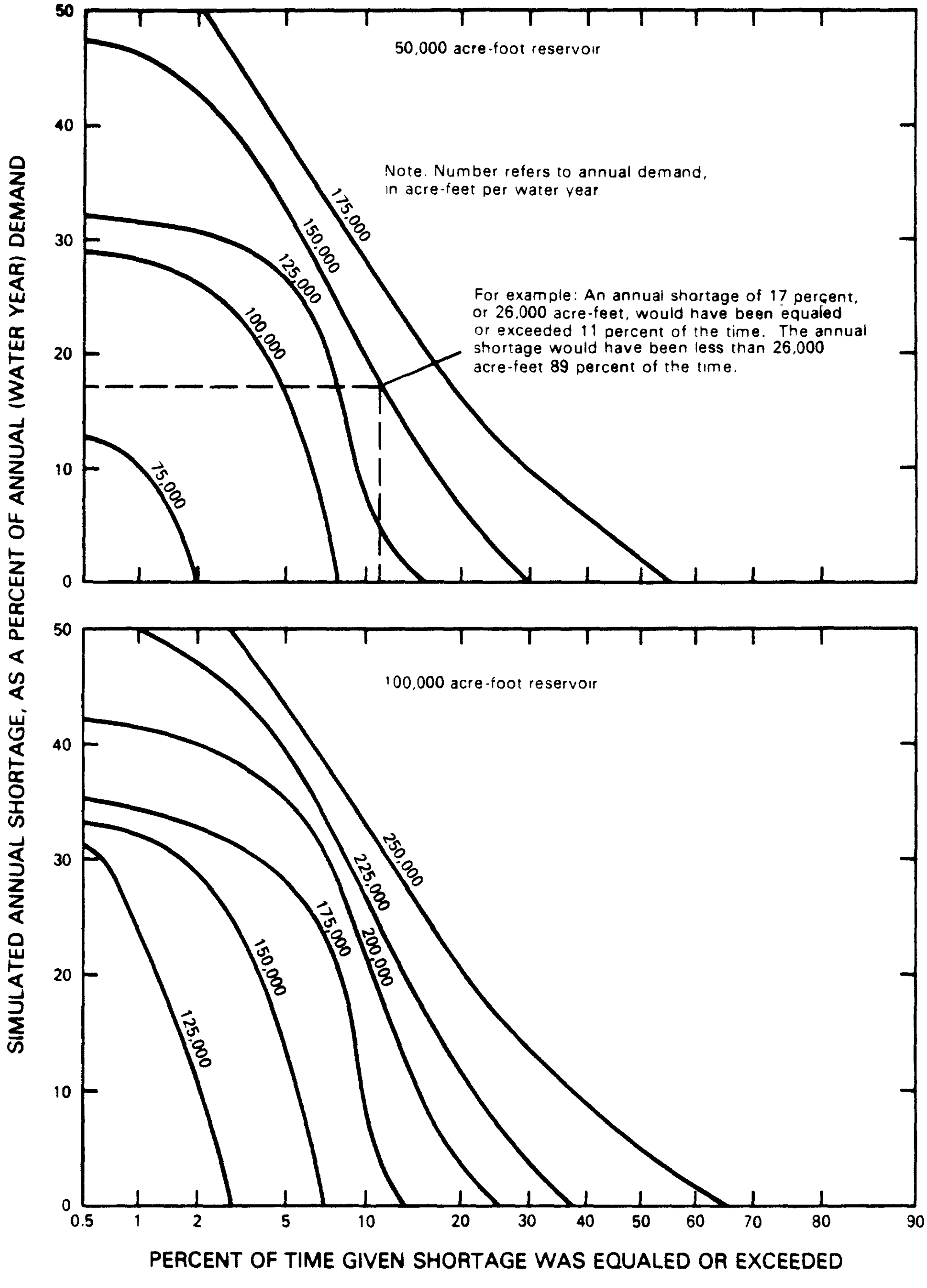



Figure 17.--Duration curves of simulated annual shortages for various annual demands placed on reservoirs of six different capacities on the White River.

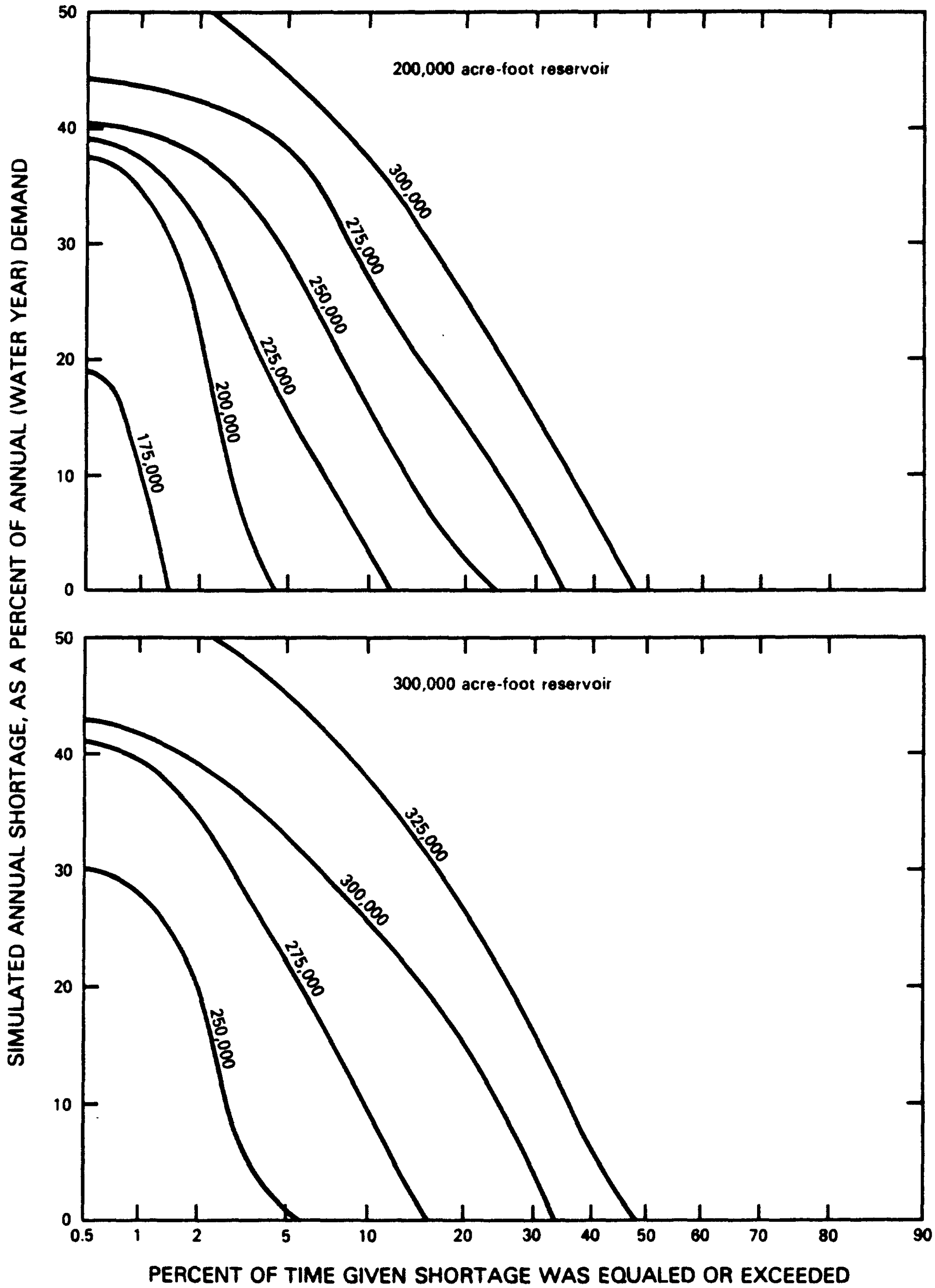



Figure 17.--Duration curves of simulated annual shortages for various annual demands placed on reservoirs of six different capacities on the White River--Continued.

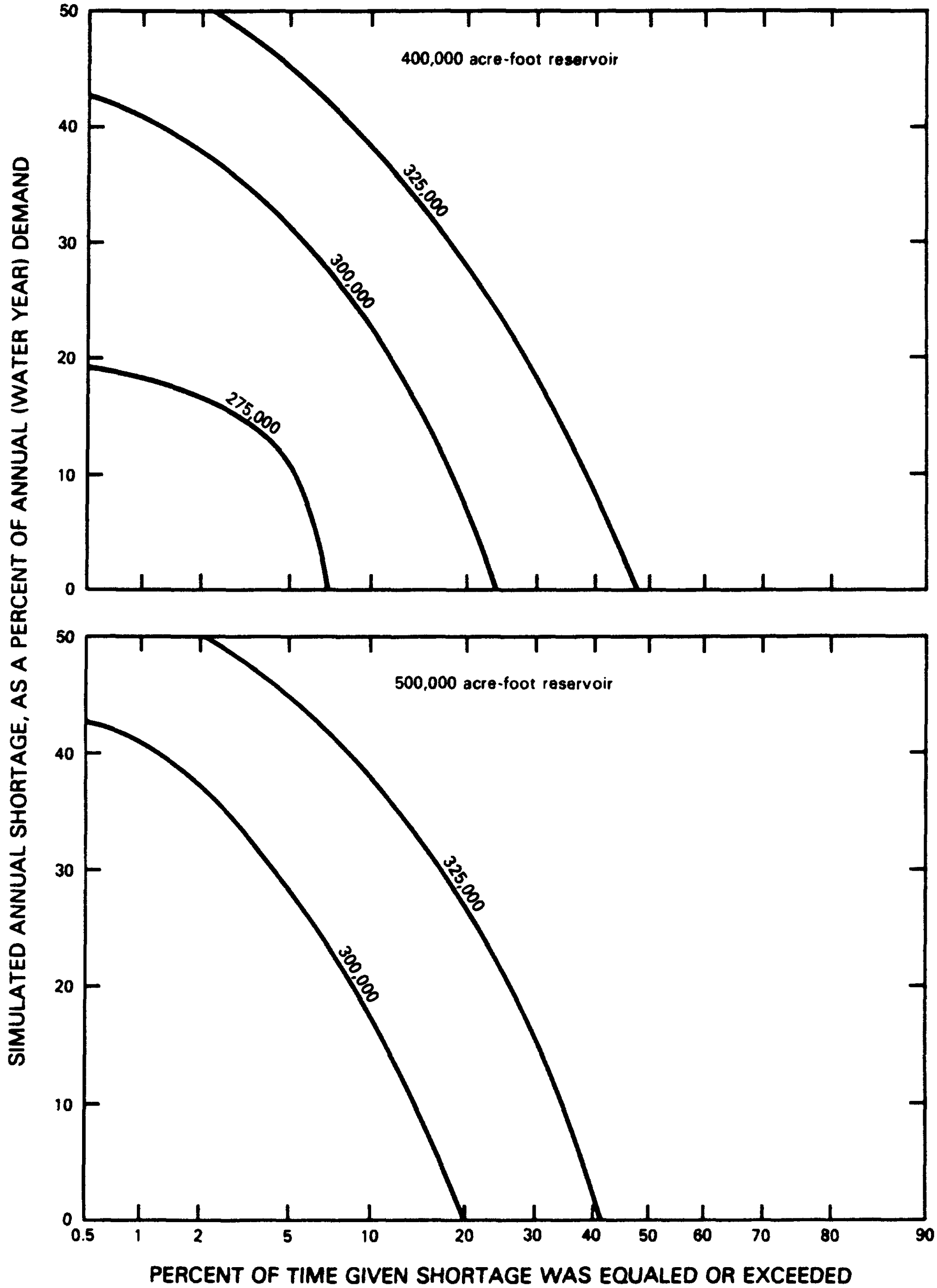



Figure 17.--Duration curves of simulated annual shortages for various annual demands placed on reservoirs of six different capacities on the White River--Continued.

Reservoir active capacity-yield relations should be of some use to the water-resources manager and planner. However, some caution needs to be used in the utilization of these relations for several reasons: (1) They are based on a graphical interpretation of no more than six or seven data points; (2) these data points were derived from computer simulation of streamflow, which has its own inherent error; (3) the assumptions used in developing these relations probably will not be duplicated in actual situations; and (4) it is very unlikely that future streamflow will be the same as historical streamflow.

## SUMMARY


Numerous reservoirs have been proposed for the White River basin in Colorado and Utah, primarily to provide water for oil-shale development. A multireservoir-flow model was used to simulate the effects of streamflow depletion by four of the proposed reservoirs on a 50-year period of historical streamflow, the 1932-81 water years. Results of the simulations provide water-resource managers and planners some insight into the way proposed water-resource developments would affect streamflow in the White River.

Four of the proposed reservoirs (Avery, Powell Park, Kenney, and White River) were considered in this study; construction of Taylor Draw Dam (Kenney Reservoir) was completed during the course of the study. General operating rules for the reservoirs, such as downstream diversion and minimum streamflow requirements, are described in published reports; these rules were used in the streamflow simulations, with some minor changes as needed. The current water-use pattern, which depletes about 40,000 acre-ft annually from the White River and is dominated by irrigation of hay meadows and pastureland, was maintained in the simulations.

Four configurations of the proposed reservoirs were simulated: (1) Avery and Kenney; (2) Avery, Kenney, and White River; (3) Avery, Powell Park (small), Kenney, and White River; and (4) Powell Park (large) and Kenney. These configurations were assumed to operate as a combined system to provide the annual demand of each individual reservoir, while still maintaining the minimum streamflow requirements in the White River. The respective average annual streamflow depletions in the simulations for these configurations were: (1) 93,000 acre-ft; (2) 168,000 acre-ft; (3) 222,000 acre-ft; and (4) 226,000 acre-ft. Simulated streamflow throughout the year generally became smaller and more constant as streamflow depletion increased.

The following minimum streamflow requirements were considered in the streamflow simulations: (1) 120 $ft^3/s$ in the North Fork White River; (2) 200 $ft^3/s$ in the White River upstream from Piceance Creek; (3) 200 $ft^3/s$ in the White River downstream from Powell Park and Kenney Reservoirs; and (4) 250 $ft^3/s$ in the White River downstream from White River Reservoir, except that a minimum flow of 500 $ft^3/s$ was required here during June and July. These minimum flows are required for maintenance of fisheries habitat and protection of endangered species.

These minimum streamflow requirements were met in the simulations nearly all the time; the requirement of 500 $ft^3/s$ downstream from White River Reservoir during June and July was not met most frequently. This requirement was not met for 15 months in 13 different years in the simulation with Avery, Kenney, and White River Reservoirs, and for 11 months in 9 different years in the four-reservoir simulation. The 500 $ft^3/s$ minimum flow requirement was met in the simulation of the Powell Park (large) and Kenney Reservoirs configuration. Results of the simulations generally indicate that one large reservoir may be able to regulate streamflow in the White River and to maintain the minimum streamflow requirements more effectively than two or three smaller reservoirs.

Relations between reservoir active capacity and yield applicable to the White River also were developed. These relations generally indicate that, based only on capacity-yield relations, reservoir storage of about 400,000 acre-ft is the maximum practicable for the White River. If shortages in the annual demand of a given reservoir capacity are allowed for even a small percent of the time, the average yield of the reservoir would increase considerably. Alternatively, a smaller reservoir capacity, with occasional annual shortages, could provide the same average annual yield as a larger reservoir with no shortages allowed.

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