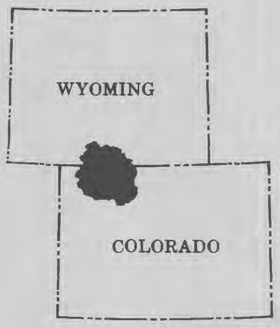
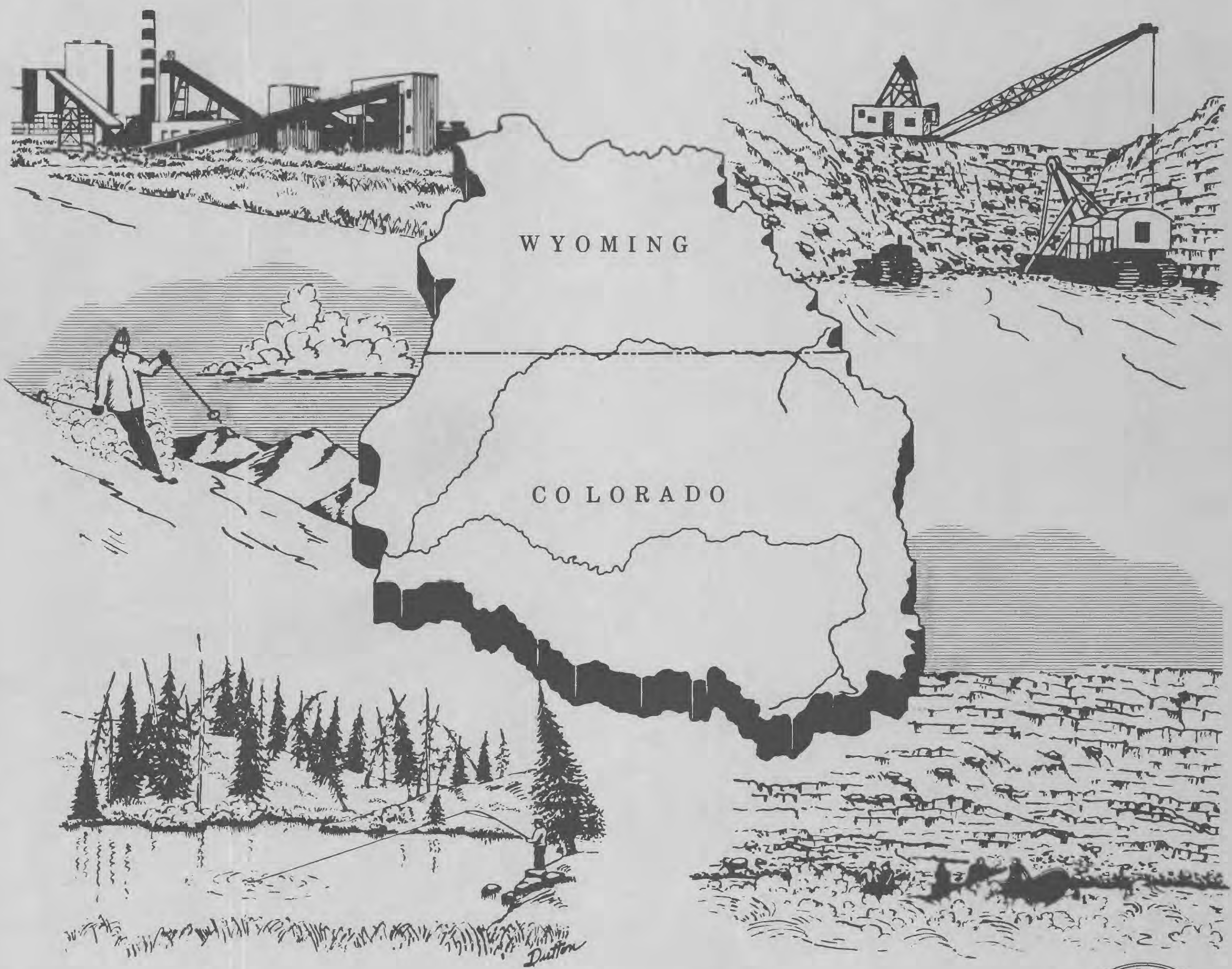


UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

RESERVOIR DEVELOPMENT IMPACTS ON SURFACE-WATER QUANTITY AND QUALITY IN THE YAMPA RIVER BASIN, COLORADO AND WYOMING



WATER-RESOURCES INVESTIGATIONS REPORT 81-30

RESERVOIR-DEVELOPMENT IMPACTS ON SURFACE-WATER QUANTITY AND QUALITY

IN THE YAMPA RIVER BASIN, COLORADO AND WYOMING

By D. Briane Adams, Daniel P. Bauer,

Robert H. Dale, and Timothy Doak Steele

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 81-30

Lakewood, Colorado
1983

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

Colorado District Chief
U.S. Geological Survey
Box 25046, MS 415
Denver Federal Center
Lakewood, CO 80225

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CONVERSION FACTORS

Factors for converting inch-pound units to metric (SI, International System) units are listed below. In the text, the metric equivalents are shown only to the number of significant figures consistent with the values for the inch-pound units.

Multiply inch-pound unit	*By*	*To obtain metric unit*
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
acre-feet per month	1,234	cubic meters per month
million acre-feet	1,234	cubic hectometers (hm^3)
acre	0.4047	hectare (ha)
inch	25.4	millimeter (mm)
ton (short)	0.9072	metric ton (t)

National Geodetic Vertical Datum of 1929: A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

RESERVOIR-DEVELOPMENT IMPACTS ON SURFACE-WATER QUANTITY AND QUALITY IN THE YAMPA RIVER BASIN, COLORADO AND WYOMING

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ABSTRACT

The Yampa River basin in northwestern Colorado and south-central Wyoming is an area in which development of the coal resources and associated economy is accelerating. This development includes increased use of the water resources of the area, which will have a direct impact on the quantity and quality of the water resources.

Current (1979) regulation of the basin's surface water by reservoirs is minimal. As part of 18 surface-water projects, 35 major reservoirs have been proposed with a combined total storage of 2.18 million acre-feet (2,688 cubic hectometers), which is 41 percent greater than the mean annual outflow from the basin.

Three computer models were used to demonstrate a method of evaluating future impacts of reservoir development in the Yampa River basin. Four different reservoir configurations were used in the analysis in order to simulate the effects of different degrees of proposed reservoir development.

A multireservoir-flow model included both within-basin and transmountain diversions. Simulations indicated that in many instances the proposed diversion amounts would not be available for either type of diversion. For example, a proposed industrial diversion of 130 cubic feet per second (3.64 cubic meters per second) from the proposed Blacktail Reservoir would not be possible from 85 to 93 percent of the time. A corresponding frequency analysis of various reservoir-storage levels indicated that most reservoirs would be operating with small percentages of total capacities, and, in most instances, with less than 20 percent of conservation-pool volumes.

Simulations using a dissolved-solids model indicated that extensive reservoir development could increase average annual concentrations at most locations. At Steamboat Springs, Colo., for example, most upstream water could be diverted, which could result in increased dissolved-solids concentrations during an average water year. Extensive reservoir development could reduce the larger May or June maximum mean monthly flows at Deerlodge Park, Colo., which is located downstream from the confluence of the Yampa and the Little Snake Rivers, from 460,000 to 250,000 acre-feet per month (567 to 308 cubic hectometers per month) and could increase the mean annual dissolved-solids concentrations by 60 percent.

Simulations using a single-reservoir model indicated that no significant water-temperature stratification would occur in most reservoirs because of limited reservoir storage. The model simulation also indicated that there could be a reduced range in water temperatures in most of the proposed reservoirs, such as the proposed Juniper Reservoir, where the inflow water temperature could range from 0°C to 26°C, while the unregulated outflow water temperature could range from 4°C to 18°C. In addition, the model simulations indicated that the range of specific-conductance values could be less in reservoir outflows than in reservoir inflows.

INTRODUCTION

The Yampa River basin in northwestern Colorado and south-central Wyoming (fig. 1) is being affected by accelerated rates of coal-resource and associated economic development, which will have a direct impact on the quantity and quality of the water resources of the basin. The projected water demands from this development will not only increase the water-supply requirements but redistribute the timing of demands from the traditional water-use patterns. Several potential impacts will result as a consequence of mining, processing, transport, and within-basin conversion of coal and the associated residential and commercial growth (Steele and others, 1979; Weatherford and Jacoby, 1975; Udis and Hess, 1976).

To meet these projected demands, considerable interest has been expressed and plans proposed for additional development of the surface waters of the Yampa River basin (fig. 1). Currently (1979), there is little regulation of streamflow by reservoirs in the basin. The main use of surface water during April, May, and June, when 60 to 70 percent of the annual stream runoff occurs, is for irrigation of hay meadows, grasslands, and grain fields. As part of 18 surface-water projects, 35 major reservoirs (larger than 2,000 acre-feet or 2.47 hm^3) have been proposed. The overall effect of these proposed reservoirs on the Upper Colorado River Basin is not known and will not be addressed in this report. Different Federal and State agencies, however, including the U.S. Bureau of Reclamation (1976; 1980), have written planning documents for the Upper Colorado River Basin, for which these report results may serve as useful input. The total proposed reservoir capacity in the Yampa River basin is about 2.18 million acre-feet (2,690 hm^3), which is 41 percent greater than the mean annual outflow from the basin. This contrasts to a current (1979) aggregate storage capacity of 54,000 acre-feet (66.6 hm^3) or approximately 2.5 percent of the total proposed reservoir capacity.

This report describes the results of an investigation in which three computer models were used to evaluate different levels of the proposed reservoir development. One model simulated streamflow conditions with alternative multireservoir configurations; a second model simulated the dissolved-solids concentrations at various locations in the basin; and a third model used streamflows and dissolved-solids concentrations to simulate the water-quality conditions within certain proposed reservoirs. This study was designed to demonstrate the application of computer-modeling techniques in evaluating impacts of proposed reservoirs. Hence, the configurations of proposed reservoirs considered in the analysis were not exhaustive; rather, reservoirs were selected to depict a range of potential locations and storage capacities. This is one of several investigations evaluating the

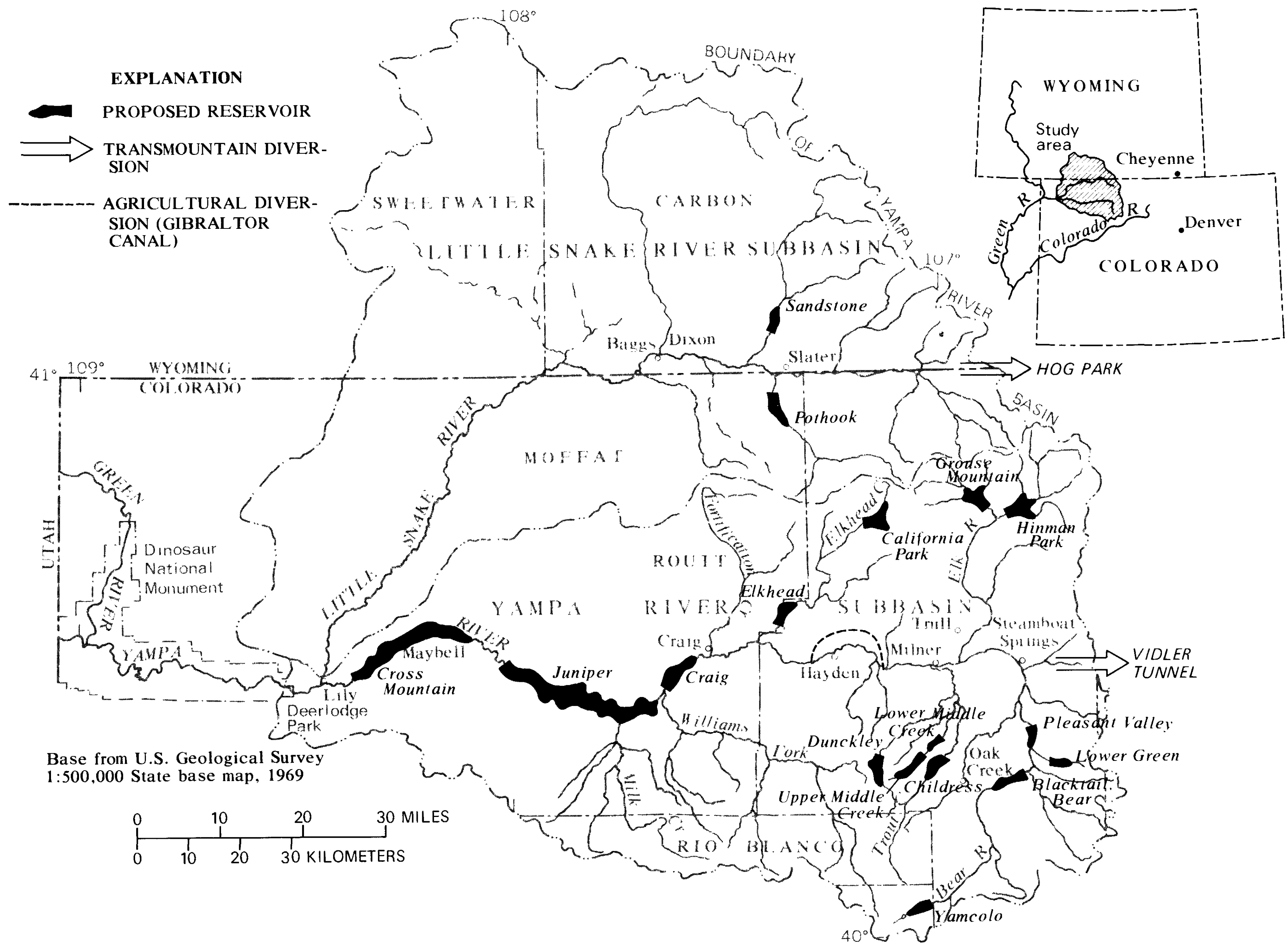


Figure 1.--The Yampa River basin, Colorado and Wyoming, showing location of selected major proposed reservoirs and transmountain diversions used in the multireservoir-modeling analyses.

projected impacts of coal-resource and associated economic development on the regional water resources of the Yampa River basin (Steele and others, 1976a; 1976b).

An extension of the multireservoir-flow model section of this report recently has been completed by Veenhuis and Hillier (1982). The extended work principally shows effects of additional variations of water use for the proposed agricultural and transmountain diversions with some reservoir configurations as given in this report. The Veenhuis and Hillier (1982) study, by simulating the different degrees of development, provides a greater range of alternatives for basin managers or planners to consider.

The techniques and procedures used in the model-analysis sections of this report are presented in considerable detail so that the applicability to other river basins can be determined. Results of this report, however, are summarized in less detail for the planner or decisionmaker in a Phase-II summary report (Steele and Hillier, 1981).

Appreciation is extended to the following individuals who contributed to the study: D. B. Tramberg, application and calibration of the dissolved-solids model developed by the U.S. Bureau of Reclamation; T. L. Washington, data coding; and S. M. Hofford, data processing and modeling application.

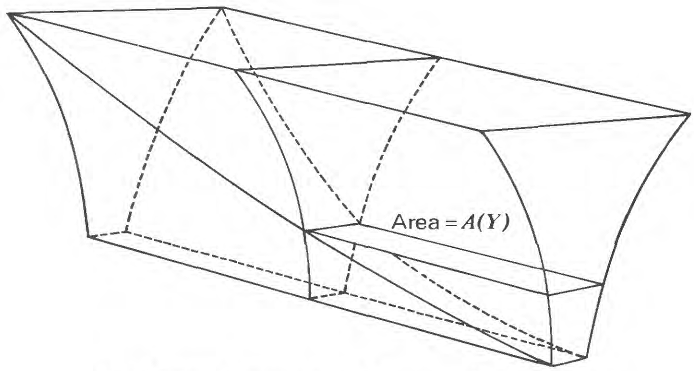
MODEL DESCRIPTIONS

The computer models used in this study were selected from several available operational models. Some of the guidelines of the model-selection procedure used for this study are defined by Jennings and others (1976). The choice of these three particular models is not an endorsement because other models also could have been used. The multireservoir-flow model chosen was the HEC-3 streamflow-routing model developed by the U.S. Army, Corps of Engineers (1968) and uses techniques discussed by Rutter and Engstrom (1964). The dissolved-solids model chosen was the NW01 river-salinity routing model developed by the U.S. Bureau of Reclamation (Ribbens, 1975). The single-reservoir model chosen was an adaptation (Adams, 1974) of the reservoir-stratification and concentration-prediction model developed at the Massachusetts Institute of Technology (Markofsky and Harleman, 1971).

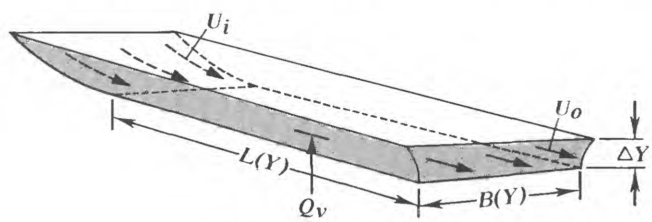
The multireservoir-flow model was developed to perform multipurpose, multireservoir routings of streamflow in a river basin. The Yampa River basin was depicted in the model by designating control points at reservoirs, diversions, return flows, and stream confluences. Monthly incremental runoff (runoff occurring between a control point and any control points immediately upstream) was specified for each control point. The total streamflow was then computed at each control point by summing the upstream incremental runoff values. Monthly diversions or return flows were specified for the appropriate control points. For each reservoir, monthly evaporation rates, outflow capacity, area-capacity curves, and the operating rules were specified. Operating rules were entered into the model by using six different storage levels. The reservoir releases were computed throughout the system to maintain all of the reservoirs within the same relative storage level each month. A control point was defined as having a flow shortage for any month that a diversion or reservoir release was reduced due to an operating rule, a minimum-flow requirement, or an insufficient quantity of water. Output from this model includes monthly and annual summaries of streamflow, reservoir conditions, and flow shortages.

The dissolved-solids model simulated monthly streamflow and both dissolved-solids concentrations and loads at specific locations in a river basin. The Yampa River basin was depicted in the model by designating control points at reservoirs, diversions, and streamflow-gaging stations. The flow-routing part of this model operates similarly to the multireservoir-flow model but is much more restricted in the size of the configuration that can be modeled. Data used in the model also are similar to those used in the multireservoir-flow model, except for the addition of dissolved-solids information. Output from this model includes simulated monthly and annual summaries of flow, dissolved-solids concentrations, and loads for each control-point location.

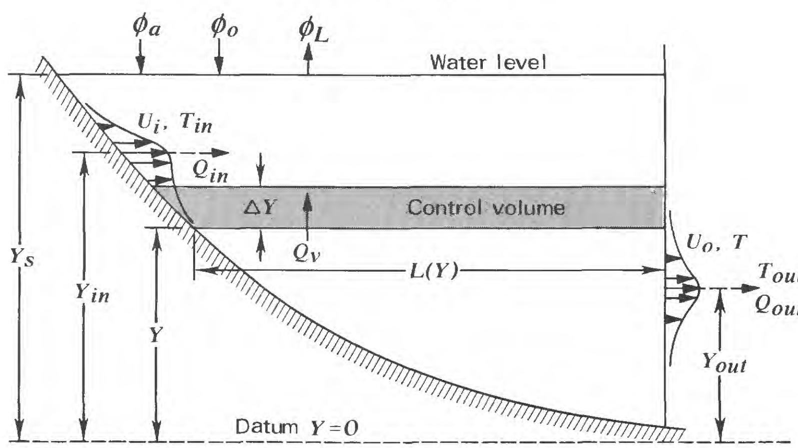
The single-reservoir model (Adams, 1974) was developed to simulate hydrologic conditions in deep reservoirs with horizontal isotherms in which temperature and selected water-quality variables are functions of depth and time. Flow patterns and the corresponding water quality within such reservoirs are affected not only by the location and quantity of inflows and outflows but also by the temperature gradients in a vertical column of water. Mathematically, this model is more complicated than the two models previously discussed. This model requires the simultaneous solution of the equations of state, motion, continuity, conservation of heat, and conservation of mass. Each reservoir is depicted in the model by a series of horizontal elements (fig. 2) which are identified by elevation, horizontal area, and thickness. The inflow and its dissolved-solids concentration must be distributed--based on the vertical-density profile--to each of the elements, and the quantity and location of all releases must be identified. Because water temperature is a driving force within the model, the temperature of the inflow also must be estimated. Finally, major factors that affect the water temperature at the reservoir surface must be entered into the model. Such factors include solar radiation, wind speed, relative humidity, and air temperature. Output from this model includes water-temperature and specific-conductance profiles within a given reservoir at selected time intervals and the water-temperature and dissolved-solids characteristics of reservoir releases.



a. Three dimensional view of a reservoir



b. Control volume



c. Section through part of a reservoir

EXPLANATION

U_i	INTERFACIAL VELOCITY	(L/T)
U_o	OUTFLOW VELOCITY	(L/T)
ΔY	INCREMENT OF CONTROL VOLUME	(L)
Q_v	VERTICAL FLOW RATE IN RESERVOIR	(L^3/T)
ϕ_a	ATMOSPHERIC RADIATION FLUX	*(Calories*$/L^3$*–T)*
ϕ_o	SOLAR RADIATION (Insolation)-HEAT FLUX	*(Calories*$/L^2$*–T)*
ϕ_L	HEAT FLUX FROM SURFACE HEAT LOSSES	*(Calories*$/L^2$*–T)*
Y_s	SURFACE ELEVATION	(L)
Y_{in}	ELEVATION OF INFLOW	(L)
Y	ELEVATION OF CONTROL VOLUME	(L)
Y_{out}	ELEVATION OF OUTFLOW	(L)
T	TEMPERATURE	$(^{\circ}C)$
T_{in}	INFLOW TEMPERATURE WITH ENTRANCE MIXING	$(^{\circ}C)$
T_{out}	OUTFLOW TEMPERATURE	$(^{\circ}C)$
Q_{in}	INFLOW RATE	(L^3/T)
Q_{out}	OUTFLOW RATE	(L^3/T)
A	HORIZONTAL CROSS-SECTIONAL AREA	(L^2)
B	RESERVOIR WIDTH	(L)
L	RESERVOIR LENGTH	(L)

Figure 2.--Control volume and schematization of the single-reservoir model (Adams, 1974).

DATA AVAILABILITY

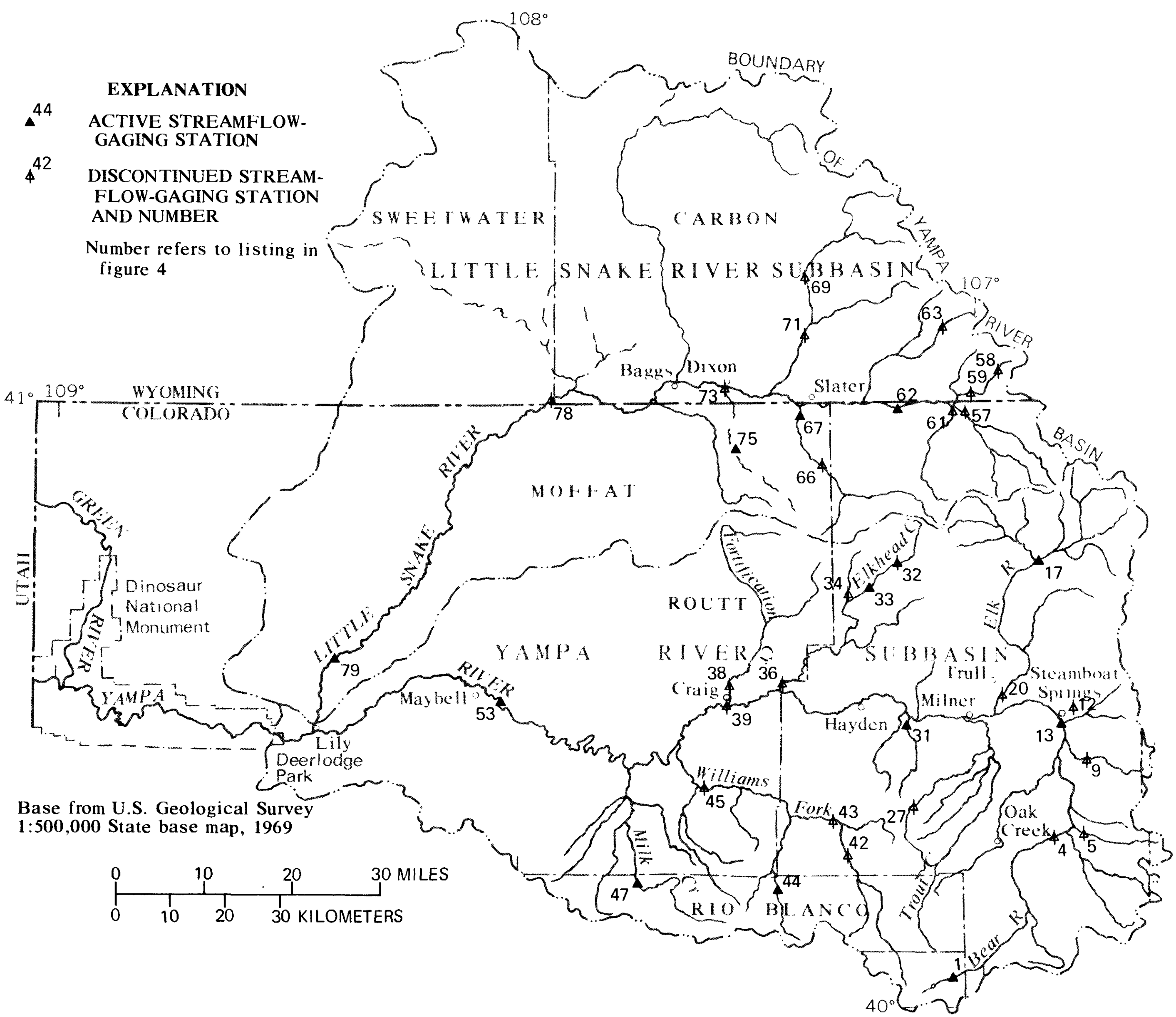
Streamflow Records

Daily streamflow records were available (either published or in computer files) for 79 streamflow-gaging stations in the basin for varying time periods during water years 1901-76 (Steele and others, 1979, table 6 and fig. 14). Records for 36 of the 79 streamflow-gaging stations within the Yampa River basin were used to compute monthly and annual summaries of flow conditions for use in the reservoir analysis. The location of these stations is shown in figure 3 with the same map-numbering scheme as used by Steele and others (1979), and the periods of available record for the stations are shown in figure 4. More than 777 years of daily records were available for these 36 stations.

A matrix of monthly and mean annual streamflows was developed for water years 1910-76 by using the existing station records. Approximately two-thirds of the data were computed by a "least-error," linear-regression technique based upon interstation correlation of streamflow discharge (A. W. Burns, U.S. Geological Survey, written commun., 1976). Either measured streamflow data or a combination of measured and synthesized streamflow data were used to determine what is termed in this report as "historic conditions" for the model-analysis period (water years 1927-76). No attempt was made to adjust the records of monthly streamflow data for changes in water use that occurred during water years 1910-76. Monthly and mean annual streamflow values were used in the study for the following purposes: (1) To determine inflows to individual proposed reservoirs, (2) to develop a mass-balance analysis for existing streamflow conditions at selected points in the basin, and (3) to serve as a reference base for describing hydrologic changes due to reservoir development.

Precipitation

Monthly precipitation data were available for 13 sites within the basin--2 sites near Dinosaur National Monument and 1 site near Rabbit Ears Pass (Colorado Water Conservation Board and U.S. Department of Agriculture, 1969). Because of longer record lengths and the proximity of the sites to the area of interest within the basin, data were used from only six of these sites (fig. 5). The sites included Steamboat Springs, Hayden, Columbine, Pyramid, and Craig, in Colorado; and Dixon in Wyoming (fig. 5). For each of these sites, varying amounts of monthly precipitation data were available. A complete data matrix of total monthly precipitation was needed for water years 1910-76. The same technique as noted for the streamflow data (A. W. Burns, U.S. Geological Survey, written commun., 1976) was used to provide missing precipitation data within the data matrix. The monthly precipitation values were used in the study to determine amounts of monthly rainfall on the surfaces of each of the proposed reservoirs used in the analysis. The completed monthly precipitation record for the nearest one of the six sites was directly applied to each proposed reservoir, as noted in table 1.



Base from U.S. Geological Survey 1:500,000 State base map, 1969

Figure 3.--Location of streamflow-gaging stations having records used in the multireservoir-modeling analyses (adopted from Steele and others, 1979).

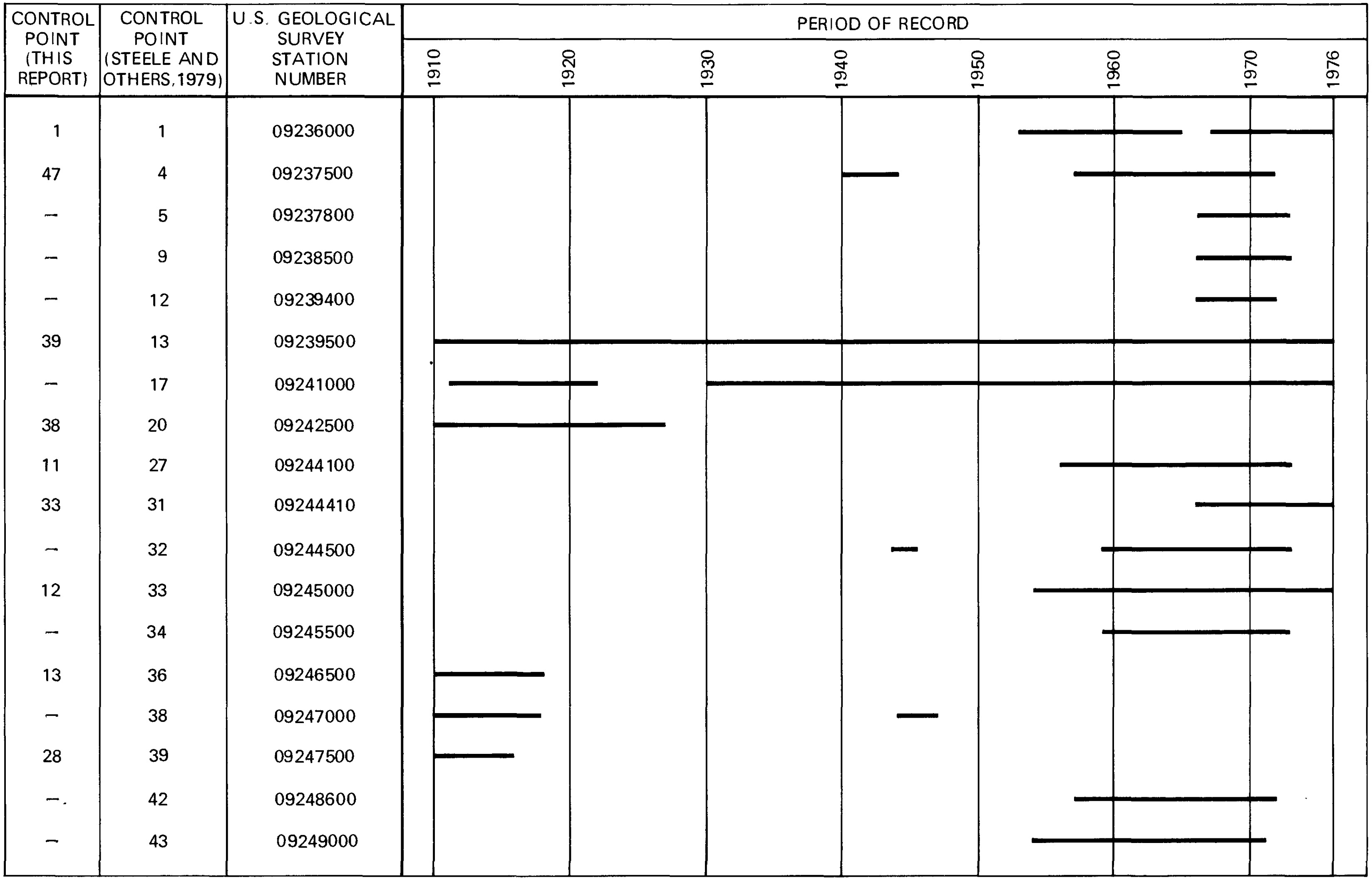


Figure 4.--Periods of record for streamflow data used in the multireservoir-modeling analyses.

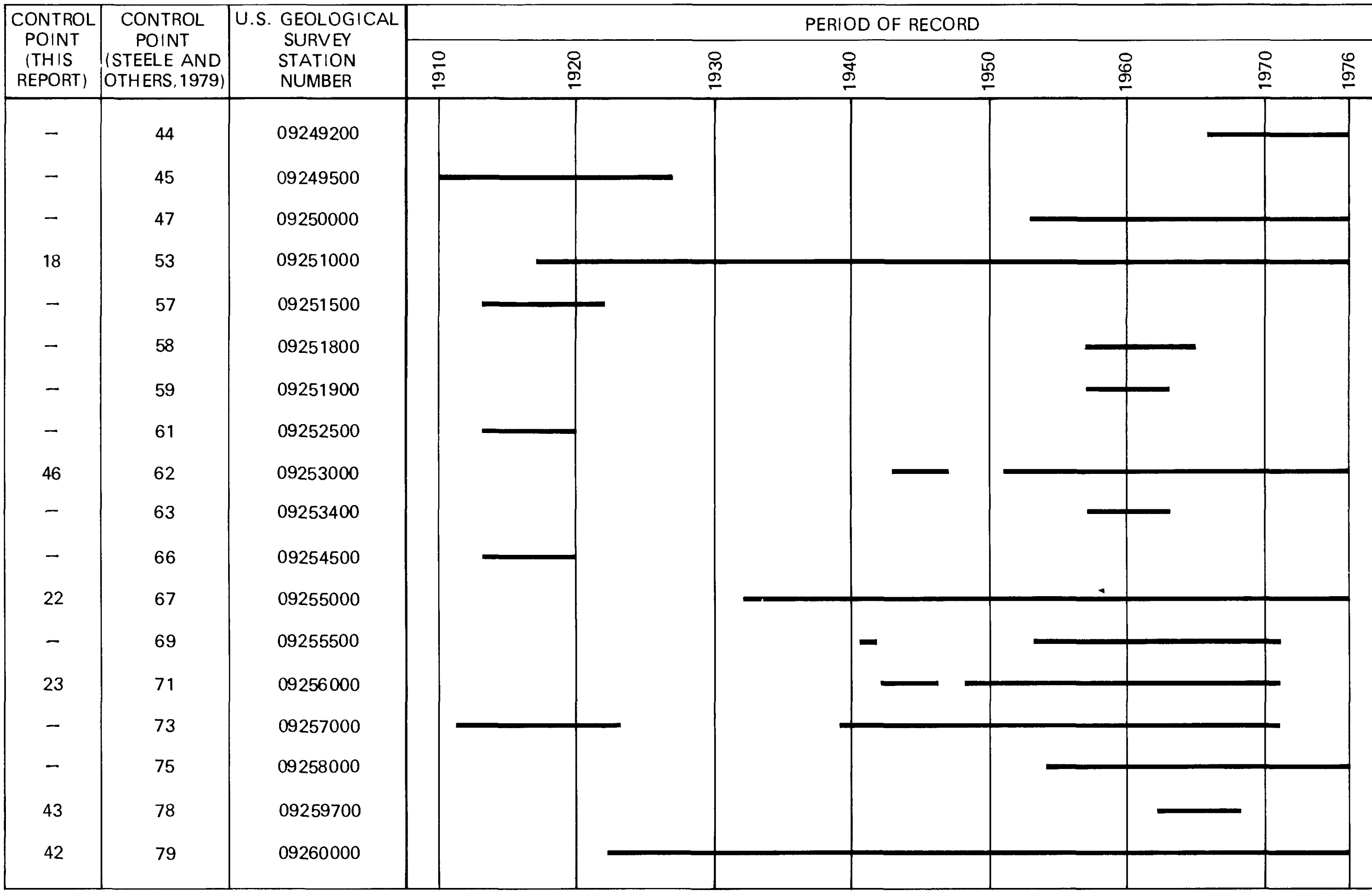
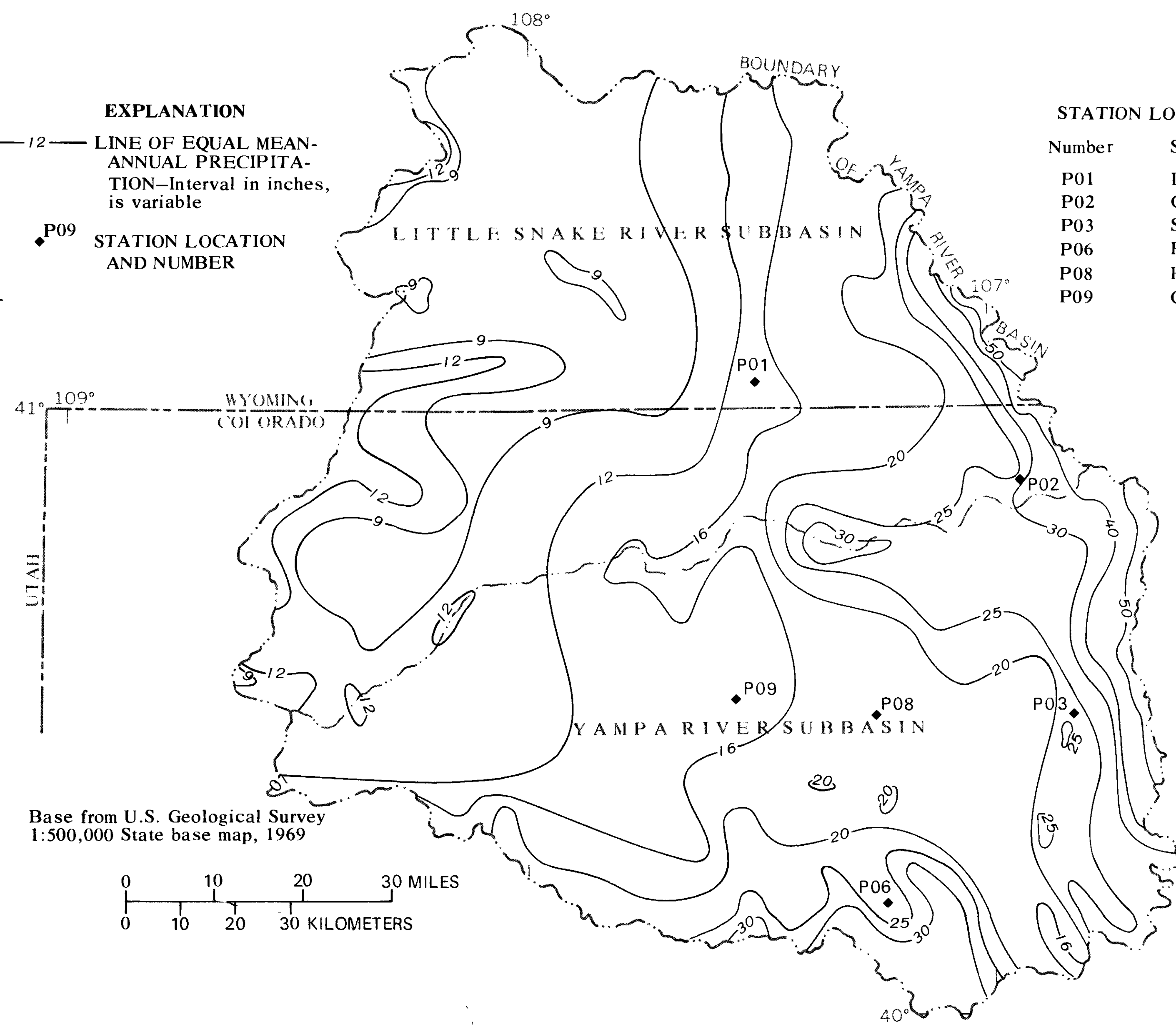


Figure 4.--Periods of record for streamflow data used in the multireservoir-modeling analyses--Continued.

EXPLANATION

—12— LINE OF EQUAL MEAN-ANNUAL PRECIPITATION—Interval in inches, is variable

◆P09 STATION LOCATION AND NUMBER



Base from U.S. Geological Survey
1:500,000 State base map, 1969

STATION LOCATIONS

Number	Station name
P01	Dixon
P02	Columbine
P03	Steamboat Springs
P06	Pyramid
P08	Hayden
P09	Craig

Figure 5.--Mean annual precipitation and location of climatological stations (Steele and others, 1979).

Table 1.--*Precipitation and evaporation data sites used for the proposed reservoir locations in the Yampa River basin*

[Ficke and others, 1976]

Middle control point	Proposed reservoir	Precipitation site	Reservoir near Denver, Colo.
1	Yamcolo--------------	Pyramid Lake-------	Elevenmile Canyon
2	Bear-----------------	Pyramid Lake-------	Elevenmile Canyon
3	Blacktail------------	Pyramid Lake-------	Elevenmile Canyon
4	Lower Green----------	Pyramid Lake-------	Elevenmile Canyon
5	Pleasant Valley------	Steamboat Springs--	Gross
7	Grouse Mountain------	Columbine----------	Elevenmile Canyon
8	Hinman Park----------	Columbine----------	Gross
9	Childress------------	Hayden-------------	Gross
10	Upper Middle Creek---	Hayden-------------	Gross
10	Lower Middle Creek---	Hayden-------------	Gross
11	Dunckley-------------	Hayden-------------	Gross
12	California Park------	Hayden-------------	Elevenmile Canyon
15	Craig----------------	Craig--------------	Ralston
18	Juniper--------------	Craig--------------	Ralston
19	Cross Mountain-------	Craig--------------	Ralston
22	Pot Hook-------------	Dixon--------------	Ralston
23	Sandstone------------	Dixon--------------	Ralston

Evaporation

Few evaporation data were available for the Yampa River basin. Evaporation data have been collected only in special studies throughout the basin, and, as a result, the areal extent and amounts are limited (Stearns-Roger, Inc., 1973-76; G. H. Leavesley, U.S. Geological Survey, written commun., 1976). However, reservoir-evaporation data are available for seven existing reservoirs near Denver, Colo. (Ficke and others, 1976).

Monthly evaporation amounts determined at five of the seven reservoirs in the Denver area (Ficke and others, 1976) were used for the reservoir analyses in the Yampa River basin. The climate conditions for the five eastern-slope reservoirs are comparable with those experienced in the Yampa River basin. Evaporation data used for a proposed reservoir were selected from the data in table 2, based on comparable geometric characteristics between an existing and a proposed reservoir. The evaporation data were selected for each of the proposed reservoirs listed in table 1. In many instances, the evaporation amounts shown in table 2 for November, December, January, February, and March had to be estimated because data were not collected for these months at the reservoirs because of ice-cover effects (N. E. Spahr, U.S. Geological Survey, oral commun., 1977).

Table 2.--*Monthly evaporation rates assumed for the proposed reservoirs in the Yampa River basin*

[Modified from Ficke and others (1976); values for November through March are estimated]

Reservoir near Denver, Colo.	Elevation, in feet above sea level[1]	Monthly evaporation rate, in inches											
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Antero----	8,788	3.30	3.30	1.60	0	0	0	0	4.30	4.40	3.80	3.50	3.50
Dillon----	9,017	4.50	3.50	1.70	0	0	0	0	3.20	4.00	5.20	5.50	5.00
Elevenmile Canyon--	8,597	4.60	4.00	2.00	0	0	0	0	4.00	5.30	5.70	5.90	6.30
Gross-----	7,282	3.70	3.30	1.60	0	0	0	4.13	4.30	4.70	4.90	5.60	3.80
Ralston---	6,046	4.65	4.31	3.44	0	0	0	0	2.97	2.88	2.74	3.07	3.41

[1]National Geodetic Vertical Datum of 1929.

Air Temperature, Relative Humidity, Cloud Cover, Wind Velocity, and Radiation

Mean monthly values for air temperature, relative humidity, cloud cover, and wind velocity used in the single-reservoir model were obtained from a climatic atlas of the United States (National Oceanic and Atmospheric Administration, 1968). These monthly values then were interpolated to obtain daily values for the single-reservoir model by weighting the monthly change to the number of days for each month. Daily radiation was computed by a subroutine in the single-reservoir model that used data on air temperature, relative humidity, and cloud cover.

Water Temperature

Daily water temperatures collected since late 1950 were available for one streamflow-gaging station on the Yampa River (site 53, figs. 3 and 4) and one streamflow-gaging station on the Little Snake River (site 79, figs. 3 and 4) (Wentz and Steele, 1976). Daily water-temperature data were used only for site-specific estimates of inflow water temperature to individual reservoirs and not for the basinwide analyses. Intermittent water-temperature measurements (4 to 12 values per year) have been collected at the above 2 sites and at 32 additional streamflow-gaging stations throughout the basin; the majority of the temperature data has been collected since 1961 (Wentz and Steele, 1976). All data were analyzed using a harmonic-analysis technique (Steele, 1972; 1974) to characterize the annual variability of stream temperatures at these measurement sites (Wentz and Steele, 1980).

Harmonic coefficients obtained for individual sites may be regionalized as functions of selected basin characteristics using linear, bivariate-regression equations (Steele, 1976a; Lowham, 1978; Wentz and Steele, 1980). In this manner, information on stream-temperature characteristics in terms of ambient seasonal variability may be transferred to stream locations within the basin where few or no data are available. The harmonic and regional-regression analyses were used to estimate daily water temperatures of inflow to the proposed reservoirs considered in this study.

Specific Conductance

Daily records of specific conductance were available for two downstream streamflow-gaging stations: Yampa River near Maybell (site 53, fig. 3) and Little Snake River near Lily (site 79, fig. 3). Specific-conductance data were collected at selected sites as part of reconnaissance or quarterly sampling basinwide surveys made between August 1975 and September 1976 (Steele and others, 1976a; 1979; Wentz and Steele, 1976; 1980). Regionalized regression relationships based upon discharge were developed from measurements of specific conductance and were used to estimate monthly average concentrations of major solutes and issolved solids for the dissolved-solids model.

Surface-Water Diversions and Consumptive Uses

Water rights and surface-water diversions were inventoried under the auspices of the State Engineer's Offices of Colorado (Knudsen and Danielson, 1977) and Wyoming. That inventory and a related analysis (Gray and others, 1977; Udis and others, 1977) have indicated that more than 90 percent of water withdrawals and 96 percent of consumptive use of water in northwestern Colorado in 1976 could be attributed to agriculture--primarily for irrigation.

Numerous small irrigation diversions within the basin principally are used to deliver water to hay and wheat fields and to pastureland (Colorado Water Conservation Board and U.S. Department of Agriculture, 1969). The actual amounts of water diverted through these small diversions, although recorded by the State Engineer's Office during intermittent onsite visitations, are not accurately known. However, data for the Gibraltar Canal, a large diversion canal located on the Yampa River near Hayden, Colo. (fig. 1), were available and were included in the basinwide-reservoir analyses.

Two proposed transmountain diversion projects that are intended to divert water from the Yampa River basin to another area were included in the reservoir analyses (fig. 1). These proposed transmountain diversions are an expansion of the existing Hog Park project that diverts water from tributaries of the Little Snake River to the Cheyenne, Wyo., metropolitan area (Banner & Associates, Inc., 1976; U.S. Department of Agriculture, 1981) and the Vidler (Sheephorn) project for diverting water from tributaries of the Yampa River upstream from Steamboat Springs to the Denver, Colo., metropolitan area (Robert Moreland, Vidler Tunnel Corp., written commun., 1977).

Reservoir Geometry

Preliminary reservoir-geometry data for 17 major proposed reservoirs were obtained from Herbert Dishlip (U.S. Bureau of Reclamation, written commun., 1977). These reservoirs represent 97 percent of the proposed reservoir volume in the basin (18 projects, 35 reservoirs). The primary data obtained included water-surface elevation versus surface area and storage capacity. Preliminary estimates of the active storage volumes of each reservoir also were obtained from Herbert Dishlip (U.S. Bureau of Reclamation, written commun., 1977). Storage volumes are determined by computing the differences between the volumes of the conservation pool (usable part of the reservoir storage) and dead storage (nonusable reservoir storage below outlets). Data for outlet elevations generally were not available, so estimates were made from dead-storage or conservation-pool elevations. No data were available for the amount of active reservoir storage to be allotted to given downstream needs.

Reservoir Configurations

Seventeen proposed reservoirs involving 10 projects were considered for the study analysis and are listed in table 3; their locations are shown in figure 1. The four alternative configurations or options of reservoir development considered in this study are also summarized in table 3.

Some of the larger proposed reservoir complexes considered in this study include: (1) Juniper-Cross Mountain project (Colorado River Water Conservation District, 1975); (2) Oak Creek Water and Power Project (Oak Creek Power Co., 1976), which includes the proposed reservoirs, Blacktail, Lower Green Creek, Lower Middle Creek, Upper Middle Creek, and Childress; (3) Savery-Pot Hook project (U.S. Department of the Interior, 1976), which includes the proposed Pot Hook and Sandstone Reservoirs (original Savery Reservoir location moved upstream to new Sandstone Reservoir location); and (4) Yamcolo project (Western Engineers, Inc., 1975). Numerous mineral resources exist at several of the proposed reservoir sites (Ward, 1977) and are being considered in the reservoir-construction proposals.

Table 3.--*Proposed reservoirs used in model analyses*

Proposed reservoir	Stream	Proposed storage capacity (acre-feet)	Option			
			1	2	3	4
Bear[1]-----------------	Yampa River----------	11,610	X	-	-	-
Cross Mountain[1]-------	Yampa River----------	142,000	X	X	X	-
Juniper[1]--------------	Yampa River----------	1,079,990	X	X	X	-
Yamcolo[1]--------------	Bear River-----------	9,000	X	X	X	X
Blacktail-------------	Yampa River----------	229,250	-	X	X	X
Childress-------------	Trout Creek----------	24,160	-	X	X	X
Lower Green Creek-----	Green Creek----------	99,600	-	X	X	X
Lower Middle Creek----	Middle Creek---------	25,150	-	X	X	X
Upper Middle Creek----	Middle Creek---------	102,200	-	X	X	X
Pot Hook[1]-------------	Slater Fork----------	60,000	-	X	X	X
Sandstone[1]------------	Savery Creek---------	15,500	-	X	X	X
California Park[1]------	Elkhead Creek--------	36,540	-	-	X	X
Craig[1]----------------	Yampa River----------	44,490	-	-	X	X
Dunckley[1]-------------	Fish Creek-----------	57,090	-	-	X	X
Grouse Mountain-------	Willow Creek---------	79,260	-	-	X	X
Hinman Park-----------	Elk River------------	44,040	-	-	X	X
Pleasant Valley[1]------	Yampa River----------	43,220	-	-	X	X

[1]Proposed diversions for agricultural use.

The alternatives selected were not exhaustive; rather, they represented a range of possible configurations for reservoir development in the Yampa River basin on the basis of known proposed projects. Results of modeling these configurations are representative of a given range of flow and changes in dissolved-solids concentrations that could occur from the assumed surface-water development in the basin. Reservoir-development option 3 provides for the highest amount of water usage while option 4 excluded the large Juniper-Cross Mountain project and provides for the smallest water usage (table 2).

MULTIRESERVOIR-FLOW MODEL

A majority of the control-point locations are shown in figure 6, and all proposed reservoirs that were used in the multireservoir-flow model are shown in figure 1. The transmountain diversions also are shown in figure 1. The proposed Vidler transmountain diversion will obtain water from six tributaries of the Yampa River and from the Yampa River upstream from Steamboat Springs (table 4). The proposed addition to the existing Hog Park transmountain diversion will obtain water from tributaries of the Little Snake River. For the model analysis, control point 39 represents the entire Vidler transmountain diversion for the six upstream tributaries and Yampa River (table 4), and control point 46 represents the entire Hog Park transmountain diversion. Proposed annual diversions are 132,000 acre-feet (163 hm^3) for the Vidler project and 31,000 acre-feet (38.3 hm^3), which is an addition of 23,000 acre-feet (28.4 hm^3) to the present diversion of 8,000 acre-feet (9.9 hm^3) for the Hog Park project (Banner & Associates, Inc., 1976; U.S. Department of Agriculture, 1981). These proposed annual diversions were converted to monthly flows for use in the model (table 5). The distributions were assumed because of the relatively greater streamflows during the spring snowmelt period.

Table 4.--*Proposed sources of water for the Vidler transmountain diversion*

[Robert Moreland, Vidler Tunnel Corp., oral commun., 1977]

Stream	Maximum annual diversion (acre-feet)	Average flow rate (cubic feet per second)
Fish and Walton Creeks	28,000	39
Harrison Creek	3,500	5
Morrison Creek	29,000	40
Service Creek	26,000	36
Silver Creek	13,500	19
Yampa River	32,000	44
TOTAL	132,000	183

The proposed reservoirs in the basin have a number of different purposes (Steele and others, 1979). For many of the reservoirs, multiple uses are proposed with certain amounts of storage allotted for each use. For the multireservoir-modeling analysis, it was assumed that all usable storages (conservation pool to dead storages) would be available for use each year. For many of the reservoirs, the amount of water to be alloted for each water use could only be estimated. Approximate water uses for some of the proposed reservoirs are shown in table 6.

Table 5.--*Assumed monthly schedules for proposed transmountain diversions*

Proposed transmountain diversion	Control point	Assumed monthly diversions, in thousands of acre-feet												Annual diversion
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	
Vidler----	39	4.70	4.70	4.70	4.70	4.70	4.70	23.6	23.6	23.6	23.6	4.70	4.70	132.0
Hog Park--	46	0	0	0	0	0	0	7.75	7.75	7.75	7.75	0	0	31.0

Irrigation water was one of the larger proposed uses of the reservoir waters. The waters apportioned for irrigation uses were allotted during the growing season (April through October) as summarized in table 7, and a majority of the control-point diversions and their approximate locations are shown in figure 6. For each irrigation-diversion amount, 67 percent of the diverted water was assumed to be returned to the stream system at some point downstream, and 33 percent was assumed to be consumptively used by plants, evapotranspired, or lost by seepage into the ground (Colorado Water Conservation Board and U.S. Department of Agriculture, 1969). Because of the large number involved, most return-flow control points are not shown in figure 6.

Table 6.--*Selected proposed reservoir uses and approximate locations*

[Use: I, irrigation; P, power; R, recreation; D, domestic; M, municipal; N, industrial. Modified from Steele and others, 1979]

Proposed reservoir	Stream	Proposed uses	Location (township, range)
Bear	Yampa River	I	4N-84W
Cross Mountain	Yampa River	P,I,R	6N-98W
Juniper	Yampa River	P,I,R	6N-94W
Yamcolo	Bear River	I,N,D	1N-86W
Blacktail	Yampa River	P	4N-84W
Childress	Trout Creek	M,N,D	4N-86W
Lower Green Creek	Green Creek	P	4N-84W
Lower Middle Creek	Middle Creek	P,N	5N-86W
Upper Middle Creek	Middle Creek	P,N	5N-86W
Pot Hook	Slater Fork	I	12N-89W
Sandstone	Savery Creek	I	13N-89W
California Park	Elkhead Creek	I	9N-87W
Craig	Yampa River	N,D	6N-92W
Dunckley	Fish Creek	I,D	4N-87W
Grouse Mountain	Willow Creek	R,N	9N-85W
Hinman Park	Elk River	P,N	9N-84W
Pleasant Valley	Yampa River	R,I	5N-84W

A summary of assumed industrial and municipal diversions is given in table 8 and control-point locations are illustrated in figure 6. The net consumption of water used for municipal purposes was assumed to be one-third, whereas industrial users were assumed to consumptively use all water diverted. The amount of water required for wet-tower cooling systems in coal-fired electric-power generation plants was adapted from computations from Palmer and others (1977). The approximate water required for wet-tower cooling is 27,000 acre-feet (33.3 hm^3) for each 2,000 megawatts of electricity generated, or a constant flow rate of 37 ft^3/s (1.04 m^3/s) per 2,000 megawatts. The proposed Oak Creek electrical-generation

Table 7.--*Assumed monthly schedules for proposed and existing irrigation diversions*

Reservoir or diversion	Control point[1]	Assumed monthly diversions, in thousands of acre-feet											
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Yamcolo------	1	0.12	0	0	0	0	0	0.12	0.36	0.36	0.84	0.60	0.36
Bear---------	2	.30	0	0	0	0	0	.30	1.16	2.09	2.77	2.09	1.16
Pleasant Valley-----	5	.36	0	0	0	0	0	.36	1.33	2.36	3.20	2.36	1.33
Dunckley-----	11	1.30	0	0	0	0	0	1.30	5.40	9.10	12.30	9.10	5.40
California Park-------	12	1.02	0	0	0	0	0	1.02	4.22	7.36	9.80	7.36	4.22
Juniper------	18	33.0	0	0	0	0	0	33.0	130	230	310	230	130
Cross Mountain---	19	3.70	0	0	0	0	0	3.70	15.0	26.0	35.0	26.0	15.0
Pot Hook-----	22	.78	0	0	0	0	0	.78	3.08	5.59	7.19	5.59	3.08
Sandstone----	23	.45	0	0	0	0	0	.45	1.70	2.90	3.90	2.90	1.70
Craig Reservoir--	27	1.60	0	0	0	0	0	1.60	6.50	11.4	15.0	11.4	6.50
Gibraltar Canal[2]-----	33	1.80	0	0	0	0	0	1.80	7.30	12.7	16.6	12.7	7.30

[1]See figure 6.
[2]Existing.

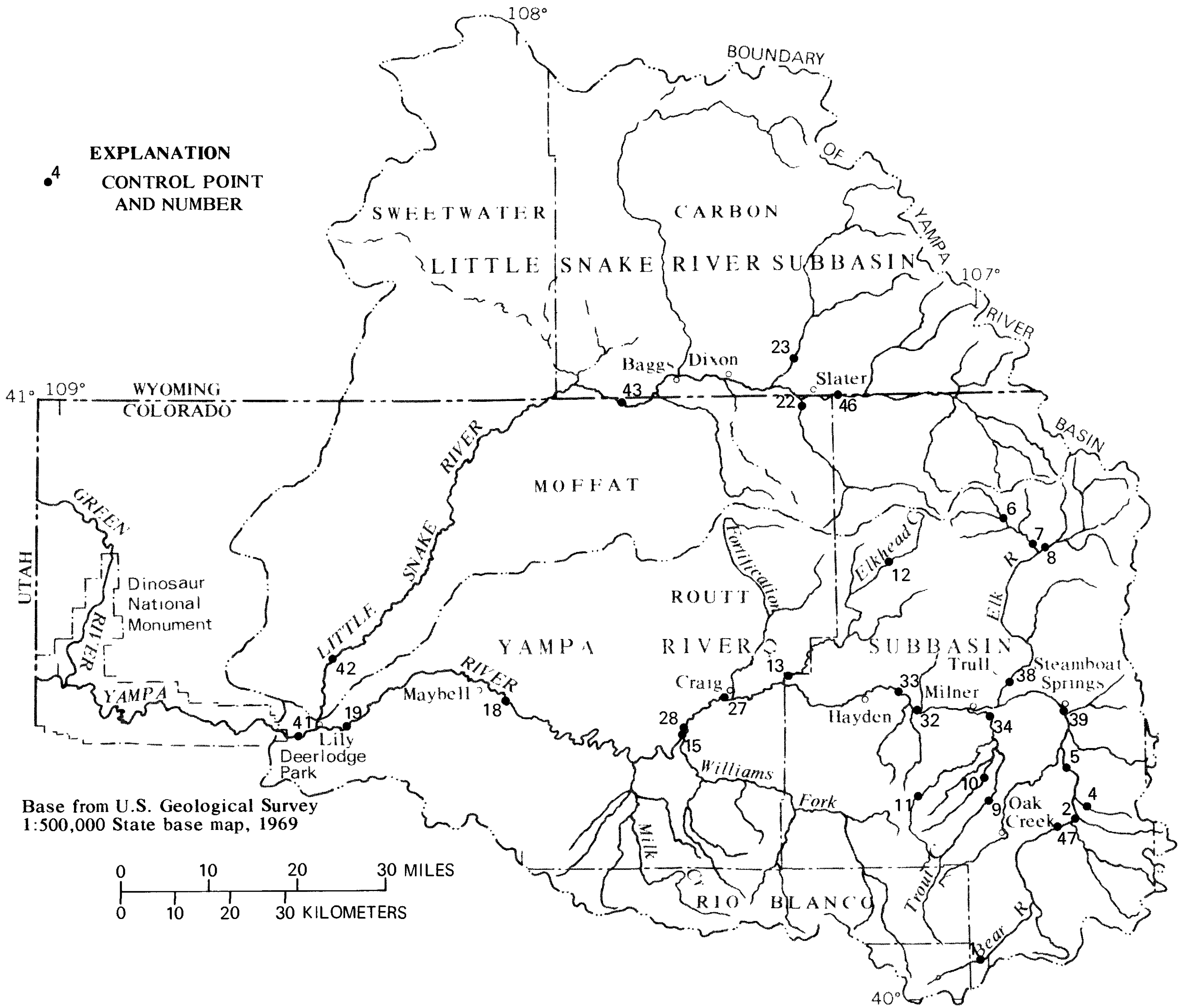


Figure 6.--Selected control points and locations used in the multireservoir-flow model.

complex, for example, will generate about 6,400 megawatts of electricity and, therefore, would require approximately 120 ft^3/s ($3.40\ m^3/s$) of cooling water. A constant flow rate of 130 ft^3/s ($3.68\ m^3/s$) was used in computing the monthly diversion of 7,850 acre-feet (9.69 hm^3) and is designated as the Blacktail Reservoir industrial diversion in table 8.

Table 8.--*Proposed and existing monthly diversions for industrial and municipal use*

[Water use: I, industrial; M, municipal]

Reservoir or diversion	Control point[1]	Water use	Monthly diversion (thousands of acre-feet)	Consumptive use (percent)	Remarks
Pleasant Valley Reservoir------	5	M	0.91	33	Steamboat Springs, Colo., area.
Dunckley Reservoir------	11	M	.60	33	Downstream area.
Elkhead Reservoir------	13	I,M	.66	100	Cooling water for electric-power generation plant and municipal use in Craig, Colo., area.
Yampa River downstream from Fortification Creek, near Craig, Colo.	28	I	.24	100	Cooling water for electric-power generation plant in Craig, Colo., area.
Hayden powerplant	33	I	.60	100	Cooling water for electric-power generation plant.
Blacktail Reservoir------	47	I	7.85	100	Cooling water for Oak Creek Power and Water Project.

[1]See figure 6.

Model Verification

Most digital-computer models, such as those used in this study, must be calibrated. This calibration procedure, as discussed by Hines and others (1975a, 1975b), is required to adjust certain model parameters so that the model results adequately represent actual conditions. As noted by Shearman (1976), the multi-reservoir-flow model is an accounting model and contains no model parameters that can be calibrated. However, the model can be verified if sufficient data are available. The model was verified previously using data for 1970-73 from the reservoir system in the Willamette River basin in Oregon (Shearman, 1976; Jennings and others, 1976). However, a similar verification of the model for conditions in the Yampa River basin could not be made because most of the reservoir system is not in existence.

To provide some means of testing the model as a predictive tool for the Yampa River basin, model simulations were made using historical streamflow data for 50 water years (1927-76). This period was chosen for two reasons: (1) The model is constrained by array sizes to a 50-year period; and (2) by starting with water year 1927, the model analysis included the droughts of the 1930's and the 1950's. For this analysis, comparisons between simulated historical and measured mean annual streamflow were made for streamflow-gaging stations at control point 39 (Yampa River at Steamboat Springs, Colo.) as shown in figure 7; control point 18 (Yampa River near Maybell, Colo.) as shown in figure 8; and control point 42 (Little Snake River near Lily, Colo.) as shown in figure 9. Approximate locations of the streamflow gages are shown in figure 6.

The comparison between simulated historical and measured annual-mean streamflow values indicates agreement within 5 percent for control points 39 (Yampa River at Steamboat Springs, Colo.) and for control point 42 (Little Snake River near Lily, Colo.) and agreement within 20 percent for control point 18 (Yampa River near Maybell, Colo.). The less accurate comparisons at the downstream control point of the Yampa River may be explained by the effects of numerous small irrigation diversions and tributaries that were not measured and could only be approximated in the multireservoir-flow model. In contrast, the Little Snake River has less irrigation and fewer unmeasured tributaries than the downstream Yampa River locations; the result is closer agreement between the simulated historical and measured streamflow values.

The unmeasured inflows and outflows were approximated within the multireservoir-simulation model by an additive "local-flow" computation procedure that involves starting at an upstream point and adding intervening flows in a downstream direction. These intervening flows, called local flows, were determined either directly by using existing streamflow records or were estimated by multiplying a nearby streamflow record by the ratio of the intervening drainage area and the drainage area upstream from the streamflow-gaging station. This assumes a direct correlation between the flows at the streamflow-gaging stations and the intervening flows. In some instances, the streamflow-gaging stations were located in or near the intervening area. Records for 22 of the 36 streamflow-gaging stations indicated in figures 3 and 4 were used in the local-flow computation.

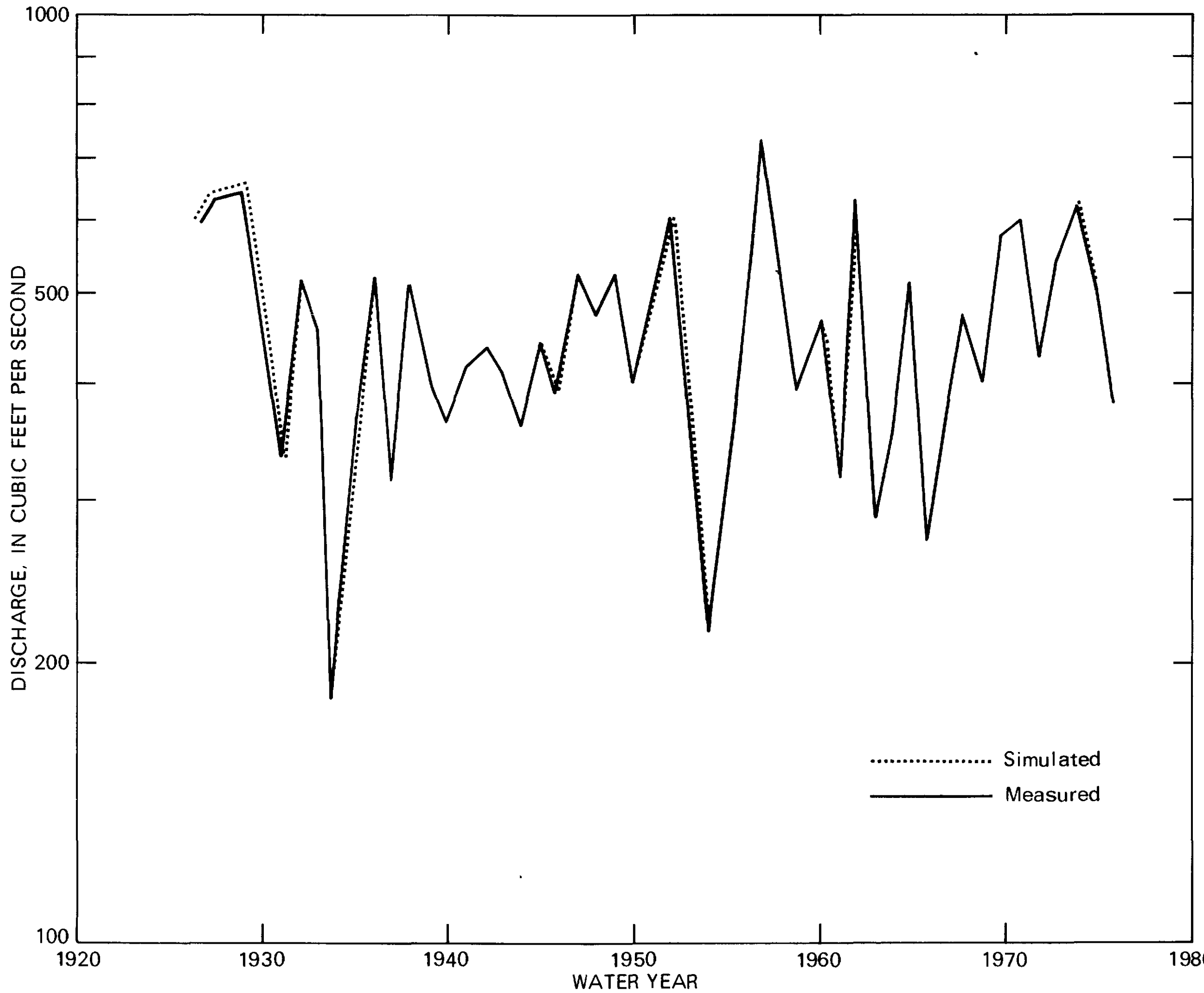


Figure 7.--Simulated historical and measured mean annual streamflow, water years 1927-76, at control point 39, Yampa River at Steamboat Springs, Colo.

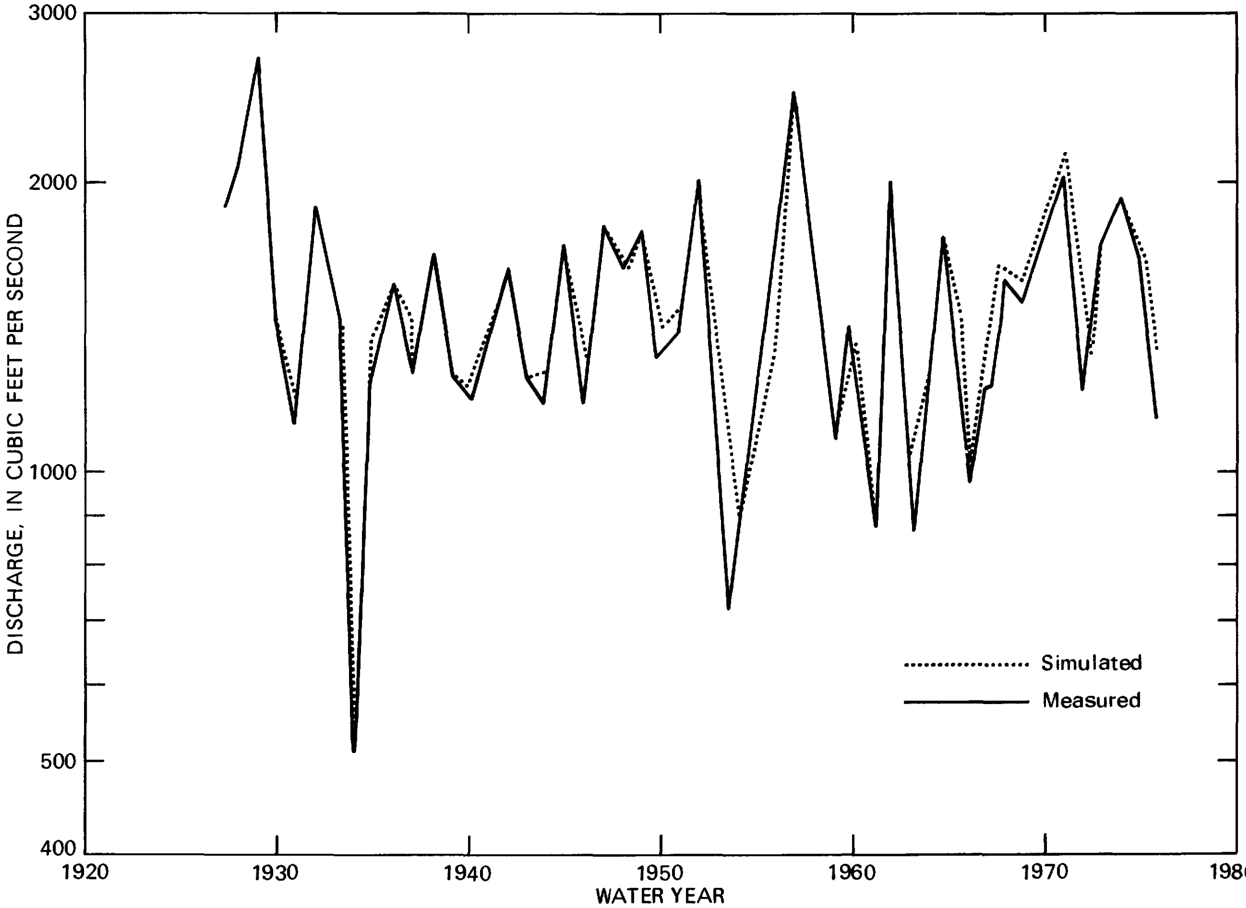


Figure 8.--Simulated historical and measured mean annual streamflow, water years 1927-76, at control point 18, Yampa River near Maybell, Colo.

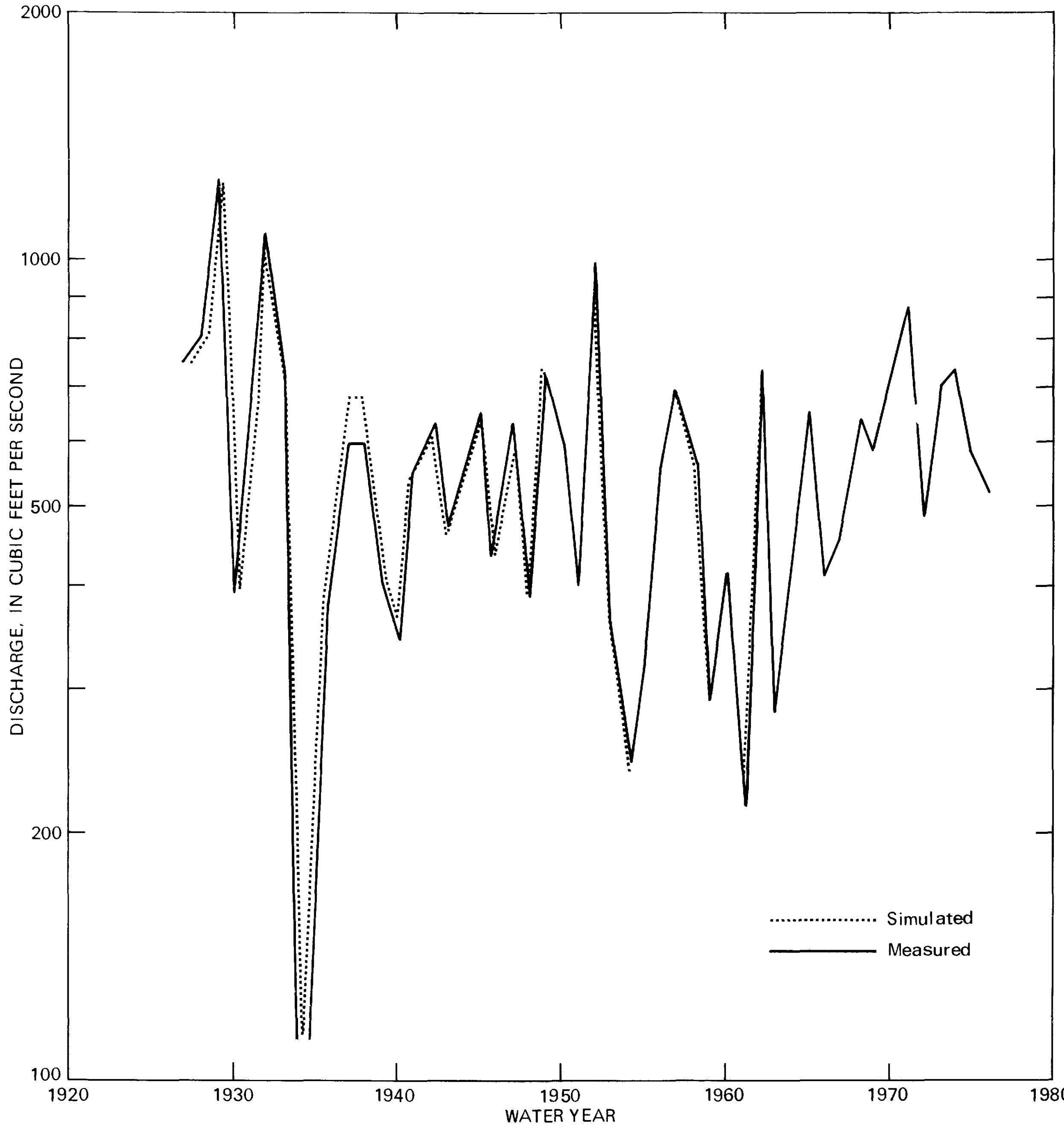


Figure 9.--Simulated historical and measured mean annual streamflow, water years 1927-76, at control point 42, Little Snake River near Lily, Colo.

Model Simulations

The four potential reservoir-development options studied using the multireservoir-flow model are described in table 3. Simulations for each potential reservoir-development option were made both with and without the proposed Vidler and Hog Park transmountain diversions. Also considered in the model simulations were historical conditions without any proposed transmountain diversions or reservoir development. Existing senior water rights (Knudsen and Danielson, 1977) in the basin were not included in these hypothetical analyses, although these will have considerable effect on the actual operation of the proposed reservoirs considered.

Simulated historical annual-mean streamflows that would have resulted from implementation of reservoir-development options 3 and 4 and observed historical conditions are presented in figures 10-17 for the following control points: Figures 10 and 11, control point 39 (Yampa River at Steamboat Springs, Colo.); figures 12 and 13, control point 28 (Yampa River at Craig, Colo.); figures 14 and 15, control point 18 (Yampa River near Maybell, Colo.); and figures 16 and 17, control point 42 (Little Snake River near Lily, Colo.). Reservoir-development option 3 was selected for illustrative purposes because it provides larger amounts of water consumption than reservoir-development options 1 and 2. Reservoir-development option 4 was selected because it provided for not only the smallest total storage volume (table 3) but also the greatest number of proposed reservoirs. The results shown in figures 10, 12, 14, and 16 represent streamflows with proposed diversions for irrigation, industrial, and municipal diversions but without proposed transmountain diversions. The results in figures 11, 13, 15, and 17 represent streamflows with all proposed diversions.

Although historical annual-mean streamflows are presented in figures 10 through 17, data for historical mean monthly streamflows also are available; the monthly data were not presented because of the large volume--600 monthly values for each reservoir-development option. The largest differences between historical and simulated historical streamflows for the various reservoir-development options would occur along the Yampa River (figs. 10 through 15) because of the larger number of reservoirs proposed for this part of the Yampa River basin.

The simulation results shown in figures 14 and 15 for control point 18 (Yampa River near Maybell, Colo.) include the large diversion requirements from the proposed Juniper Reservoir for reservoir-development option 3. The results for historical conditions and reservoir-development option 4 did not include diversions from the proposed Juniper Reservoir, which explains why these results plot significantly higher than the simulation option for configuration 3. The simulation results shown in figures 17 and 18 for control point 42 (Little Snake River near Lily, Colo.) indicate little variation between the various reservoir-development options. The Little Snake River subbasin includes only two proposed reservoirs (Sandstone and Pot Hook) and the proposed Hog Park transmountain diversion with the proposed annual diversion of 31,000 acre-feet (38.3 hm^3). The effects of the proposed Vidler transmountain diversion would be most pronounced at control point 39 (Yampa River at Steamboat Springs, Colo.) where mean annual streamflow would have been less than 10 ft^3/s (0.28 m^3/s) during several years (fig. 11). The effects of the proposed Vidler transmountain diversion would decrease at downstream control points along the Yampa River (figs. 13 and 15). The effects of the proposed Hog Park transmountain diversion would be minor at control point 42 (Little Snake River near Lily, Colo.) (fig. 17).

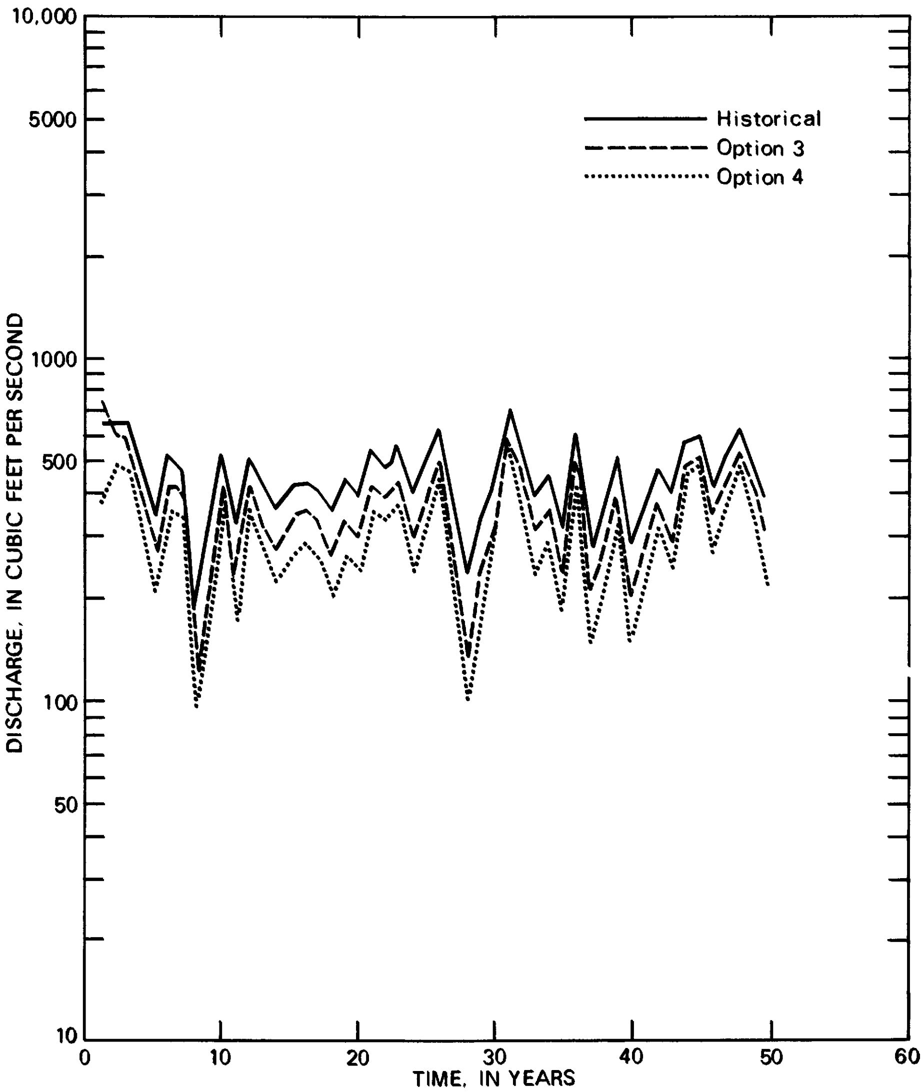


Figure 10.--Simulated historical mean annual streamflows for reservoir-development options 3 and 4 and historical conditions at control point 39, Yampa River at Steamboat Springs, Colo., with proposed irrigation, industrial, and municipal diversions but without proposed transmountain diversions.

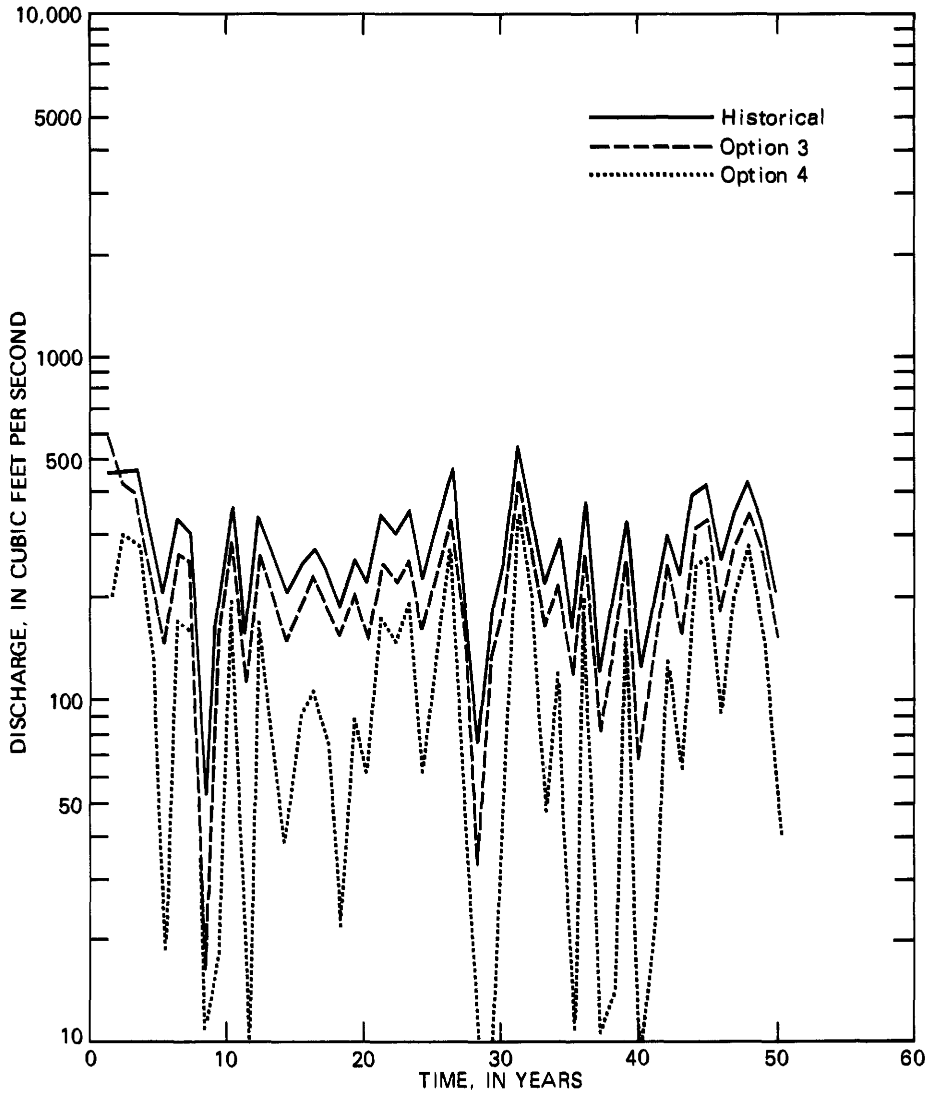


Figure 11. -- Simulated historical mean annual streamflows for reservoir-development options 3 and 4 and historical conditions at control point 39, Yampa River at Steamboat Springs, Colo., with all proposed diversions.

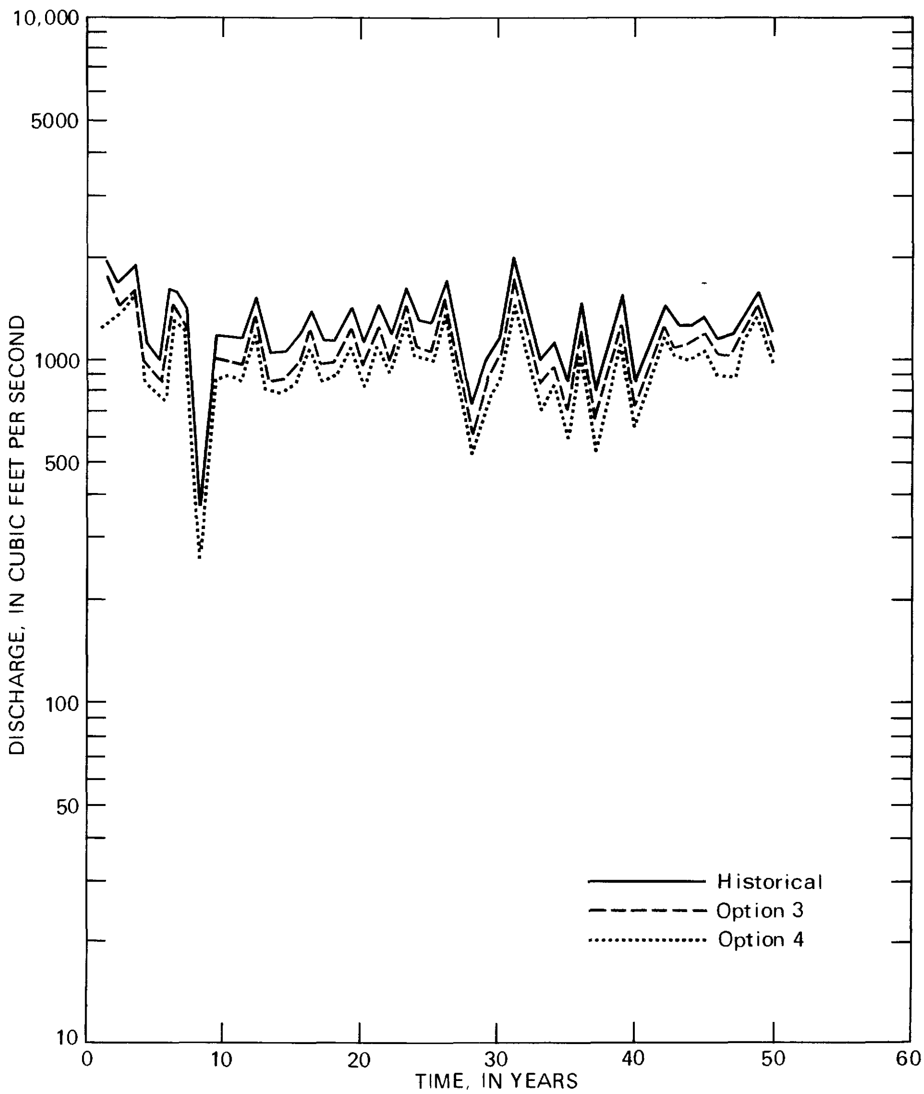


Figure 12.--Simulated historical mean annual streamflows for reservoir-development options 3 and 4 and historical conditions at control point 28, Yampa River at Craig, Colo., with proposed irrigation, industrial, and municipal diversions but without proposed trans-mountain diversions.

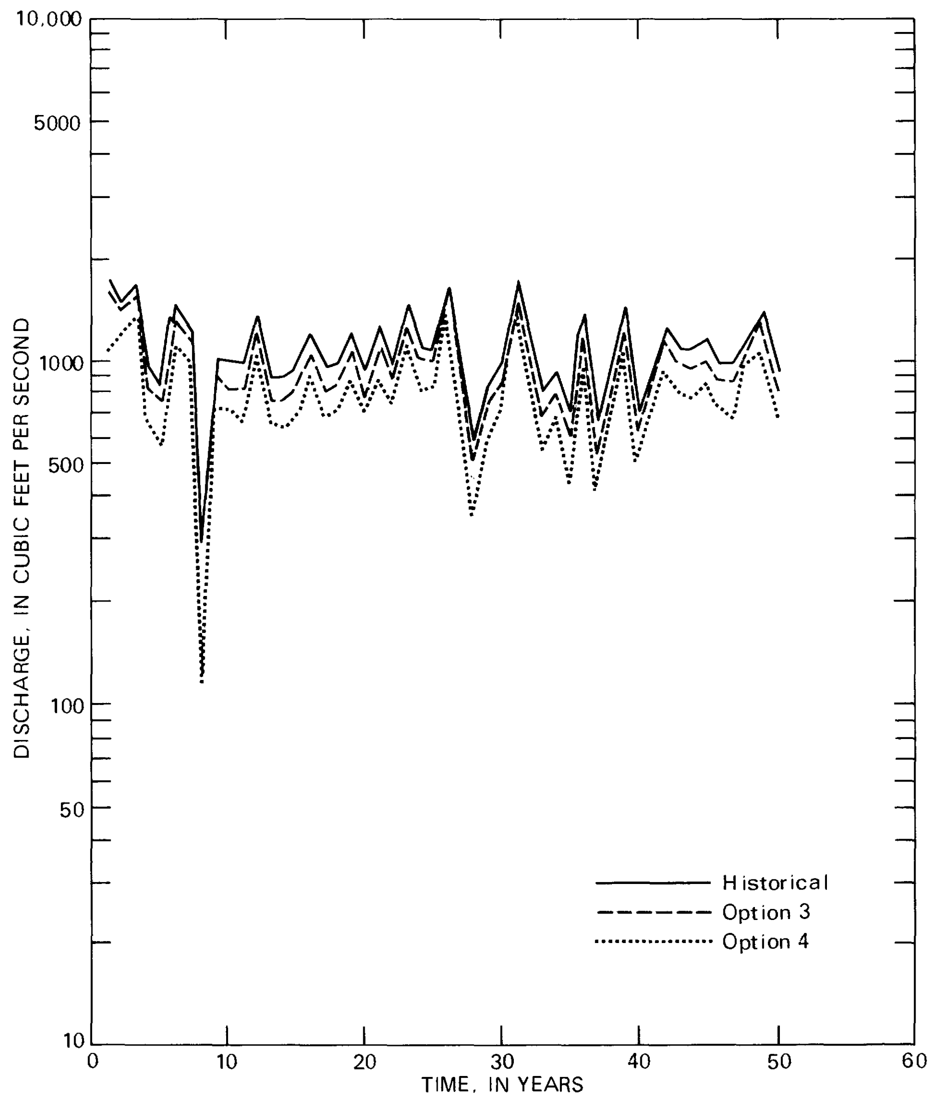


Figure 13.--Simulated historical mean annual streamflows for reservoir-development options 3 and 4 and historical conditions at control point 28, Yampa River at Craig, Colo., with all proposed diversions.

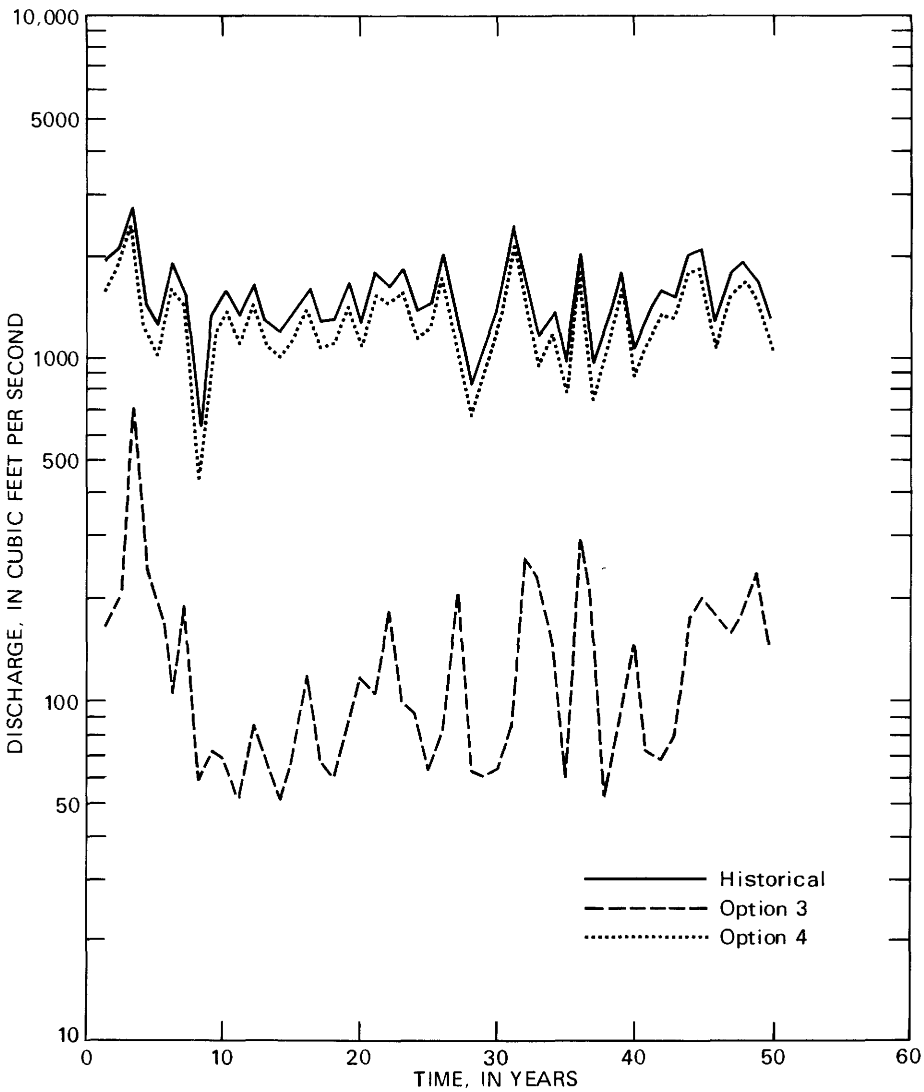


Figure 14.--Simulated historical mean annual streamflows for reservoir-development options 3 and 4 and historical conditions at control point 18, Yampa River near Maybell, Colo., with proposed irrigation, industrial, and municipal diversions but without proposed transmountain diversions.

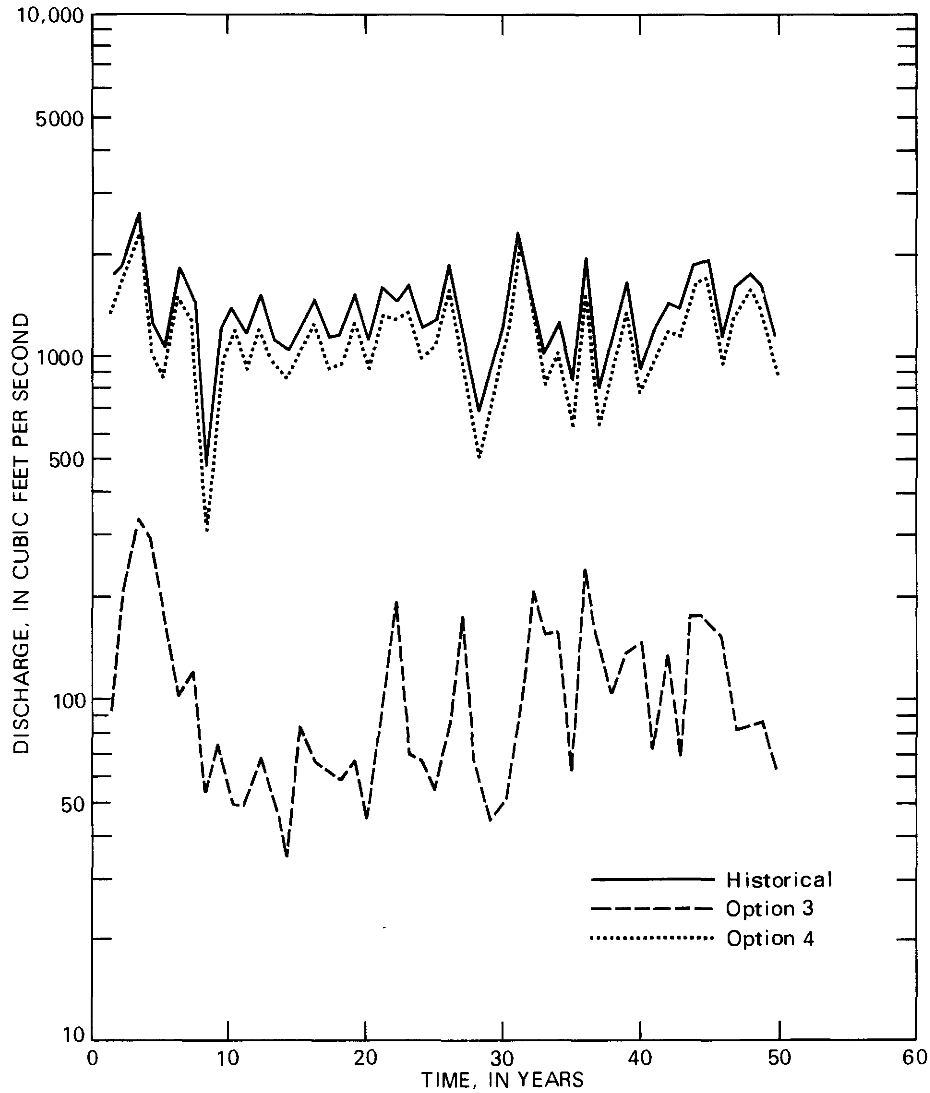


Figure 15.--Simulated historical mean annual streamflows for reservoir-development options 3 and 4 and historical conditions at control point 18, Yampa River near Maybell, Colo., with all proposed diversions.

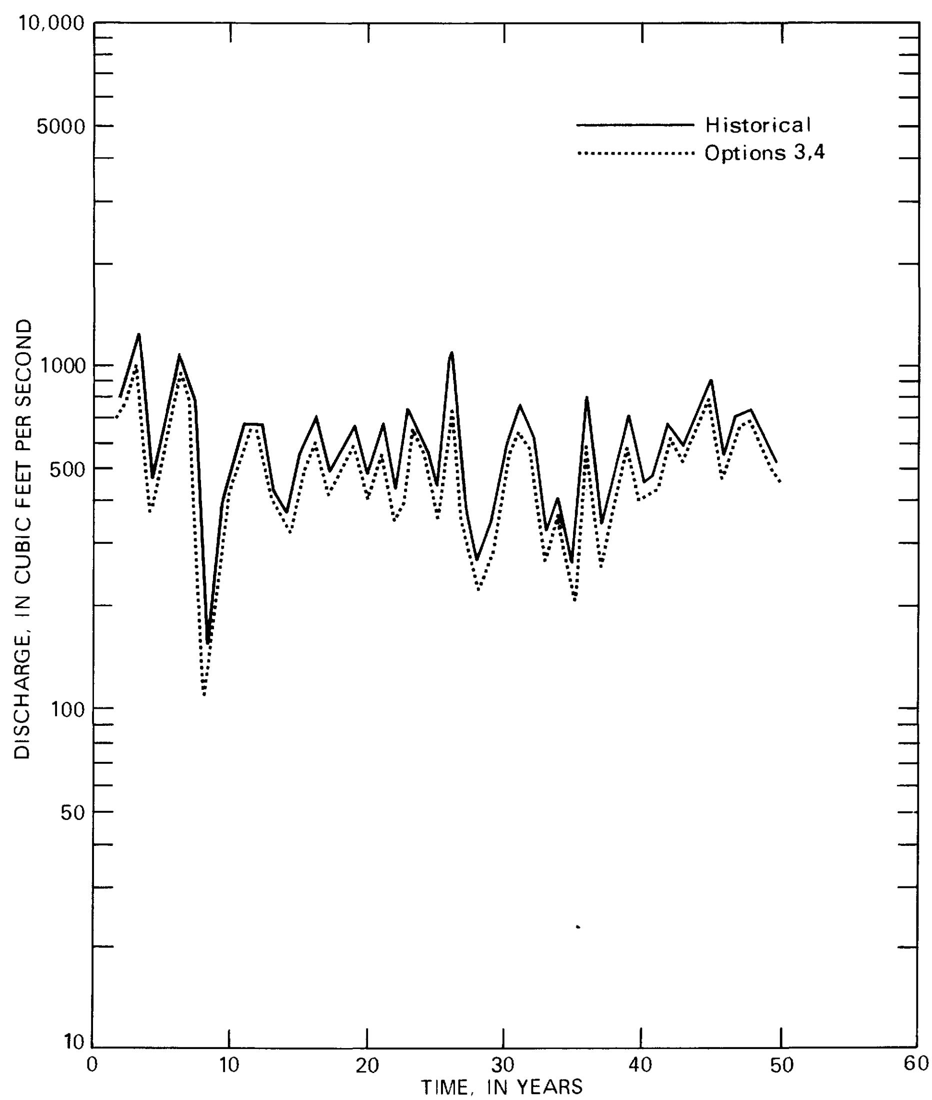


Figure 16.--Simulated historical mean annual streamflows for reservoir-development options 3 and 4 and historical conditions at control point 42, Little Snake River near Lily, Colo., with proposed irrigation, industrial, and municipal diversions but without proposed transmountain diversions.

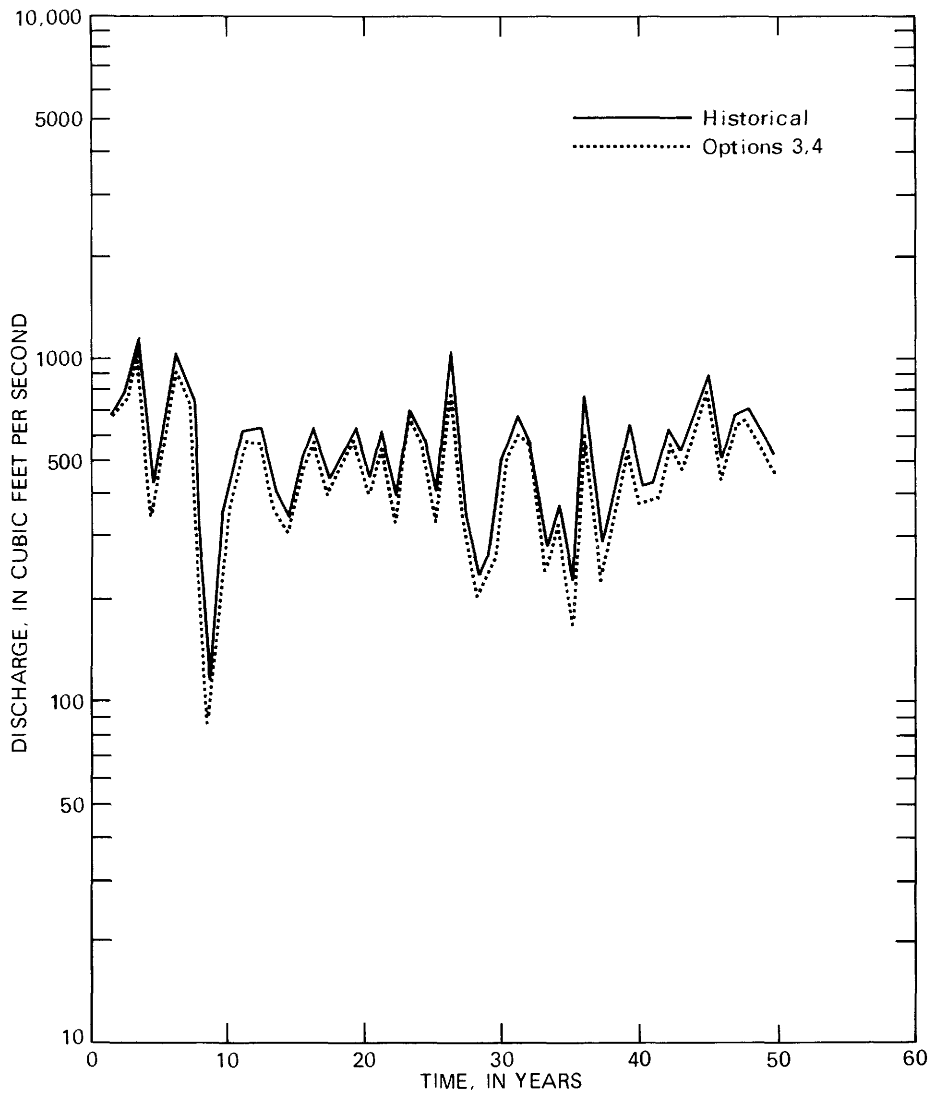


Figure 17.--Simulated historical mean annual streamflows for reservoir-development options 3 and 4 and historical conditions at control point 42, Little Snake River near Lily, Colo., with all proposed diversions.

In many instances, desired amounts for transmountain diversions historically would not be available--especially for the Vidler transmountain diversion, where only a fraction or none of the water desired would be available. Some of the potential diversion shortages are summarized in table 9. A shortage is defined as any model-computed value being less than the desired diversion requirement. These shortages are based on the diversion schedules shown in table 5. Most shortages associated with the Vidler transmountain diversion could occur with reservoir-development options 2, 3, and 4 (table 3), where shortages could occur during 417 to 460 of 600 months or 70 to 77 percent of the time (table 9). Options 2, 3, and 4 include the large Oak Creek Power and Water complex with significant diversions of water from the upper Yampa River basin into the Trout Creek subbasin. This diverted water, therefore, might not be available for the downstream Vidler transmountain diversion. Shortages associated with the Hog Park transmountain diversion could be the same for all reservoir-development options. Shortages could occur during 39 of 200 months or about 20 percent of the time (table 9).

Table 9.--*Summary of monthly shortages that could result from proposed transmountain diversions*

Model option	Number of months shortage could occur	Percentage of months shortage could occur	Maximum monthly shortage	
			(cubic feet per second)	(thousands of acre-feet)
Vidler transmountain diversion (12-month diversion schedule)--control point 39 (Yampa River at Steamboat Springs, Colo.)				
Historical conditions--	92	15	344	20.8
1------------------	252	42	358	21.6
2------------------	460	77	376	22.7
3------------------	417	70	391	23.6
4------------------	454	76	391	23.6
Hog Park transmountain diversion (4-month diversion schedule)--control point 46 (Little Snake River near Slater, Wyo.)				
Historical conditions--	39	20	124	7.49
1------------------	39	20	124	7.49
2------------------	39	20	124	7.49
3------------------	39	20	124	7.49
4------------------	39	20	124	7.49

A summary of selected monthly within-basin diversion shortages for irrigation, industrial, and municipal uses (tables 7 and 8) at selected locations in the basin is presented in table 10. The summary includes only those reservoir-development options for which each reservoir or canal was assumed to be operating. This method of analysis was selected because irrigation, industrial, or municipal diversions generally would be obtained from a specific reservoir or canal. As was noted earlier, these diversion amounts were computed assuming the entire reservoir storage (conservation pool to dead storage) to be usable for irrigation each year. In cases of multiple-purpose reservoirs, part of the storage would be allotted to each use (for example, industrial or municipal). The Blacktail Reservoir diversion described in table 8 is part of the proposed Oak Creek Power and Water Project and has an assumed desired maximum diversion of 7,850 acre-feet (9.69 hm^3) per month. Water from this diversion would be routed into the Trout Creek subbasin (fig. 6) and used for hybrid wet-tower, evaporation-pond cooling for an electric-power generation plant (Oak Creek Power Co., 1976). The modeling results indicate that this diversion requirement could not be met in most cases.

There could be a wide range of monthly shortages for the control points listed in table 10. Irrigation and municipal diversions from the proposed Dunckley Reservoir (control point 11), located on Fish Creek, could have the largest percentage of shortages, with 94 percent for all options, and industrial diversions from the proposed Blacktail Reservoir (control point 47), located on the Yampa River, could have the second largest percentage of shortages. The proposed Juniper Reservoir (control point 18) could have the largest monthly shortage--304,000 acre-feet (375 hm^3) (table 10), and similarly could have the largest assumed proposed irrigation schedule (table 7), with a maximum proposed diversion of 310,000 acre-feet (383 hm^3) per month during July of each year. The only proposed reservoir which would have no monthly shortages would be Yamcolo Reservoir (control point 1) located on the Bear River. (The Yampa River is known as the Bear River above the town of Yampa. See fig. 1.)

Desired hypothetical streamflows based on approximate streamflows required for fish habitat were arbitrarily selected for many of the control points. Desired flows were used in the model to permit use of a flow requirement somewhat higher than an absolute minimum when upstream reservoir-storage levels are not critically low. A summary of monthly shortages in desired streamflows at selected control points is shown in table 11. The desired flow values listed for control points 30, 34, 41, and 42 (fig. 6) are hypothetical in nature, but were based upon knowledge of probable minimum streamflow requirements of selected streams. These flow values were chosen to point out some additional possible shortages for the different reservoir-configuration options. Approximate locations for each of these sites are shown in figure 6.

The desired flow of 750 ft^3/s (21.2 m^3/s) at control point 41 (table 11) was primarily selected based on a flow of 690 ft^3/s (19.5 m^3/s) required by the Colorado River Compact of 1948 at the upstream Yampa River near Maybell, Colo., location (control point 18) and the Little Snake River drainage input. The Colorado River Compact of 1948 specifies a flow of 500,000 scre-feet (615 hm^3) per year for the Yampa River near Maybell, Colo., or approximately 690 ft^3/s (19.5 m^3/s). Some consideration of the desired flow for the location at Deerlodge Park, Colo., also was based on a proposed Wild and Scenic River designation within Dinosaur National Monument (H. J. Belisle, U.S. Bureau of Reclamation, written commun., 1976; U.S. Department of the Interior, 1979a, 1979b).

Table 10.--*Summary of monthly shortages at selected control points for proposed within-basin irrigation, industrial, and municipal diversions*

Model option	Trans-mountain diversions included	Number of months shortage could occur (12-month diversion schedule)[1]	Percentage of months shortage could occur	Maximum monthly shortage (cubic feet per second)	Maximum monthly shortage (thousands of acre-feet)
Control point 1--Bear River at site of proposed Yamcolo Reservoir					
1	Yes	0	0	0	0
1	No	0	0	0	0
2	Yes	0	0	0	0
2	No	0	0	0	0
3	Yes	0	0	0	0
3	No	0	0	0	0
4	Yes	0	0	0	0
4	No	0	0	0	0
Control point 2--Yampa River at site of proposed Bear Reservoir					
1	Yes	9	2	21	------
1	No	5	1	19	------
Control point 5--Yampa River at site of proposed Pleasant Valley Reservoir					
3	Yes	305	51	55	3.32
3	No	248	41	55	3.32
4	Yes	0	0	0	0
4	No	0	0	0	0
Control point 11--Fish Creek at site of proposed Dunckley Reservoir					
3	Yes	565	94	210	12.7
3	No	565	94	210	12.7
4	Yes	565	94	210	12.7
4	No	565	94	210	12.7
Control point 12--Elkhead Creek at site of proposed California Park Reservoir					
3	Yes	221	37	160	9.66
3	No	221	37	160	9.66
4	Yes	212	35	160	9.66
4	No	212	35	160	9.66

Table 10.--*Summary of monthly shortages at selected control points for proposed within-basin irrigation, industrial, and municipal diversions*--Continued

Model option	Trans-mountain diversions included	Number of months shortage could occur (12-month diversion schedule)[1]	Percentage of months shortage could occur	Maximum monthly shortage (cubic feet per second)	Maximum monthly shortage (thousands of acre-feet)
Control point 18--Yampa River at site of proposed Juniper Reservoir					
1	Yes	145	24	5,032	304.0
1	No	113	19	5,032	304.0
2	Yes	139	23	5,032	304.0
2	No	110	18	5,032	304.0
3	Yes	151	25	5,032	304.0
3	No	118	20	5,032	304.0
Control point 19--Yampa River at site of proposed Cross Mountain Reservoir					
1	Yes	15	2	566	34.2
1	No	7	1	423	25.5
2	Yes	11	2	566	34.2
2	No	6	1	566	34.2
3	Yes	10	2	566	34.2
3	No	6	1	423	25.5
Control point 22--Slater Creek at site of proposed Pot Hook Reservoir					
2	Yes	11	2	116	7.00
2	No	7	1	105	6.34
3	Yes	13	2	116	7.00
3	No	9	2	116	14.7
4	Yes	56	9	116	7.00
4	No	54	9	116	7.00
Control point 27--Yampa River at site of headgate of proposed Craig Canal[2]					
3	Yes	207	34	241	14.5
3	No	148	25	241	14.5
4	Yes	207	35	697	42.1
4	No	155	26	306	18.5

Table 10.--*Summary of monthly shortages at selected control points for proposed within-basin irrigation, industrial, and municipal diversions*--Continued

Model option	Trans-mountain diversions included	Number of months shortage could occur (12-month diversion schedule)[1]	Percentage of months shortage could occur	Maximum monthly shortage (cubic feet per second)	Maximum monthly shortage (thousands of acre-feet)
Control point 33--Yampa River at headgate of Gibraltar Canal[2]					
Historical conditions	Yes	99	17	187	11.3
Historical conditions	No	40	7	182	11.0
1	Yes	167	28	266	16.1
1	No	52	9	234	14.1
2	Yes	172	29	266	16.1
2	No	96	16	251	15.2
3	Yes	166	28	259	15.6
3	No	83	14	259	15.6
4	Yes	178	30	617	37.2
4	No	95	16	226	13.6
Control point 47--Yampa River at site of proposed Blacktail Reservoir[2]					
2	Yes	541	90	130	7.85
2	No	536	89	130	7.85
3	Yes	556	93	130	7.85
3	No	546	91	130	7.85
4	Yes	510	85	130	7.85
4	No	510	85	130	7.85

[1]Year-round diversion schedule, which is based on 50-year simulation period or 600 month periods.

[2]Shortage summaries indicate total of desired flow and diversion.

Table 11.--*Summary of monthly shortages in desired streamflows at selected control points*

Model option	Trans-mountain diversions included	Number of months shortage could occur (12-month diversion schedule	Maximum monthly shortage (cubic feet per second)	Maximum monthly shortage (thousands of acre-feet)	Desired flow (cubic feet per second)
Control point 30--Yampa River downstream from Elkhead Creek, near Craig, Colo.					
Historical conditions	Yes	156	100	6.03	100
Historical conditions	No	59	88	5.31	100
1	Yes	215	100	6.03	100
1	No	74	95	5.74	100
2	Yes	229	100	6.03	100
2	No	136	100	6.03	100
3	Yes	248	100	6.03	100
3	No	135	100	6.03	100
4	Yes	350	100	6.03	100
4	No	179	100	6.03	100
Control point 34--Trout Creek near Milner, Colo.					
Historical conditions	Yes	30	10	0.60	10
Historical conditions	No	30	10	.60	10
1	Yes	30	10	.60	10
1	No	30	10	.60	10
2	Yes	91	10	.60	10
2	No	82	10	.60	10
3	Yes	110	10	.60	10
3	No	98	10	.60	10
4	Yes	109	10	.60	10
4	No	109	10	.60	10

Table 11.--*Summary of monthly shortages in desired streamflows at selected control points*--Continued

Model option	Trans-mountain diversions included	Number of months shortage could occur (12-month diversion schedule	Maximum monthly shortage (cubic feet per second)	Maximum monthly shortage (thousands of acre-feet)	Desired flow (cubic feet per second)
Control point 41--Yampa River downstream from confluence of Little Snake River, near Deerlodge Park, Colo.					
Historical conditions	Yes	357	736	44.4	750
Historical conditions	No	331	698	42.1	750
1	Yes	193	749	45.2	750
1	No	126	744	44.9	750
2	Yes	135	750	45.3	750
2	No	96	747	45.1	750
3	Yes	170	756	45.3	750
3	No	140	747	45.1	750
4	Yes	339	687	41.5	750
4	No	320	687	41.5	750
Control point 42--Little Snake River near Lily, Colo.					
Historical conditions	Yes	16	52	3.14	0
Historical conditions	No	0	0	0	0
2	Yes	1	4	.24	0
2	No	0	0	0	0
3	Yes	2	5	.30	0
3	No	1	5	.30	0
4	Yes	1	4	.24	0
4	No	0	0	0	0

Shortages at control point 41 (table 10) could occur during a minimum of 96 months (16 percent of the time) if reservoir-development option 2 were implemented without the proposed Vidler and Hog Park transmountain diversions. Shortages (table 11) could occur during a maximum of 357 months (60 percent of the time) if no additional reservoir development were to occur and only the proposed Vidler and Hog Park transmountain diversions were implemented.

The Yampa River main-stem sites respond in different ways, depending on their locations in the proposed reservoir system and other downstream and upstream demands. In general, all locations studied responded to increases in agricultural diversions, water-use allocation percentages, and transmountain diversions with reduction in streamflow. In some instances, streamflow in certain reaches could be increased by releases from upstream reservoirs resulting from downstream reservoir demands. The number of monthly shortages in desired streamflow at control point 41 illustrates this point with fewer shortages for reservoir-development options 1, 2, and 3 as compared to reservoir-development option 4 (table 9) with options 1, 2, and 3 including the large Juniper-Cross Mountain Reservoir complex (Colorado River Water Conservation District, 1975).

The desired streamflow at control point 30 (Yampa River downstream from Elkhead Creek, near Craig, Colo.) of 100 ft^3/s (2.83 m^3/s), which is about the same as streamflows during the summer, was selected because this streamflow probably would be sufficient to maintain existing (1979) fish habitat at the control point. Shortages (table 11) could occur during a minimum of 59 months (10 percent of the time) if historical conditions without the proposed Vidler transmountain diversion were maintained. Shortages (table 11) could occur during a maximum of 350 months (58 percent of the time) if reservoir-development option 4 and the proposed Vidler transmountain diversion were implemented.

The desired streamflow at control point 34 (Trout Creek upstream from confluence of Yampa River, near Milner, Colo.) of 10 ft^3/s (0.28 m^3/s), which is about the same as streamflow during the summer, was selected because this streamflow probably would be sufficient to maintain existing (1979) fish habitat at the control point. Shortages (table 11) could occur during a minimum of 30 months (5 percent of the time) if historical conditions were maintained. There could be no effects of the proposed Vidler transmountain diversion with historical conditions at this control point, and no proposed reservoirs upstream from the control point are included in reservoir-development option 1. Shortages (table 11) could occur during a maximum of 110 months (18 percent of the time) if reservoir-development option 3 and the proposed Vidler transmountain diversion were implemented.

Results of frequency analyses for various reservoir-storage levels at selected reservoir-control points throughout the basin are shown in figures 18 to 22, and control-point locations are shown in figure 6. Several reservoir-development options are included and the effects of proposed transmountain diversions, denoted as "diversion included" or "no diversion," also are shown. Six to eight frequency-analysis summaries for selected reservoir-development options and transmountain-diversion options are shown in each figure.

EXPLANATION

RESERVOIR LEVEL	PERCENT OF CONSERVATION POOL	RESERVOIR LEVEL	PERCENT OF CONSERVATION POOL
1	99-100	6	60-70
2	95-99	7	40-60
3	90-95	8	20-40
4	80-90	9	1-20
5	70-80	10	0-1

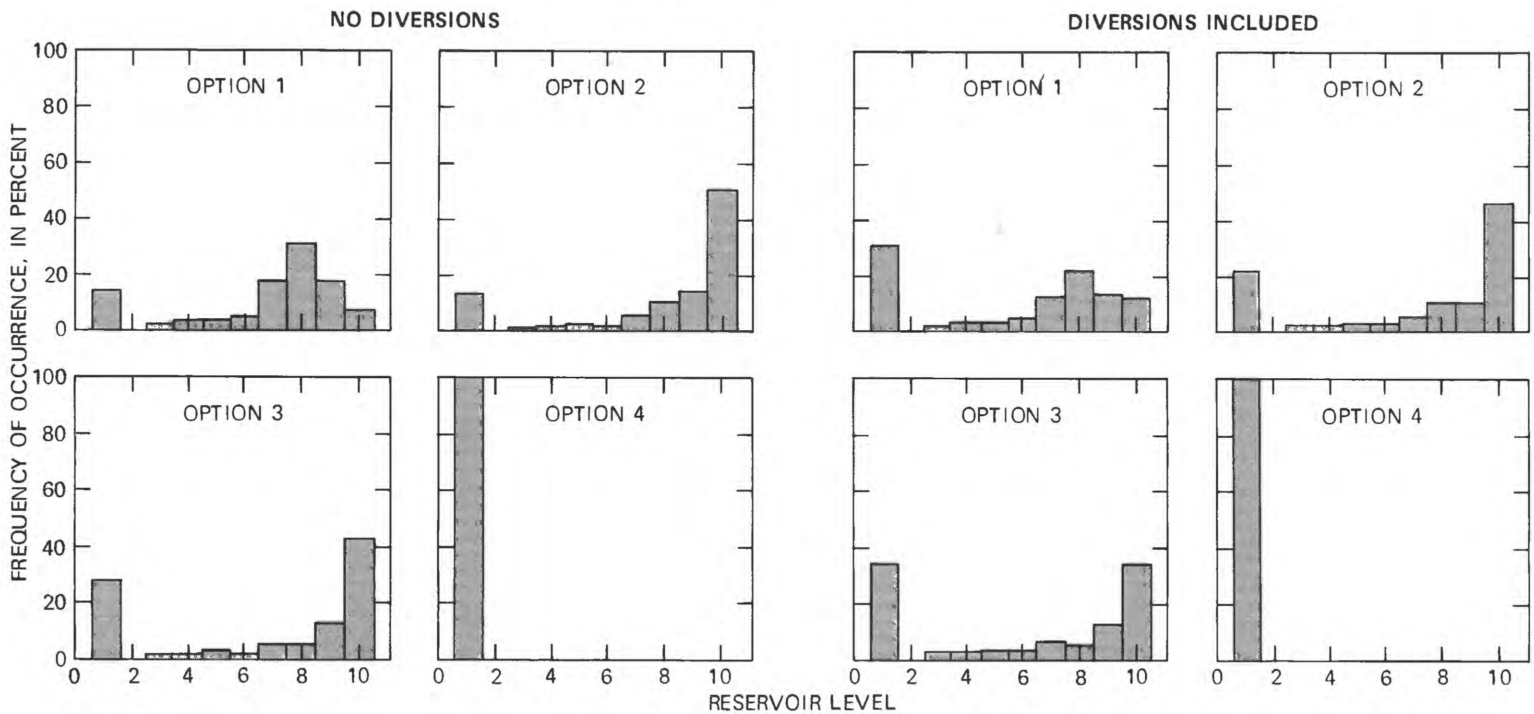


Figure 18.--Reservoir-storage frequency analysis at control point 1, Bear River at site of proposed Yamcolo Reservoir, reservoir-development options 1 through 4.

EXPLANATION

RESERVOIR LEVEL	PERCENT OF CONSERVATION POOL	RESERVOIR LEVEL	PERCENT OF CONSERVATION POOL
1	99-100	6	60-70
2	95-99	7	40-60
3	90-95	8	20-40
4	80-90	9	1-20
5	70-80	10	0-1

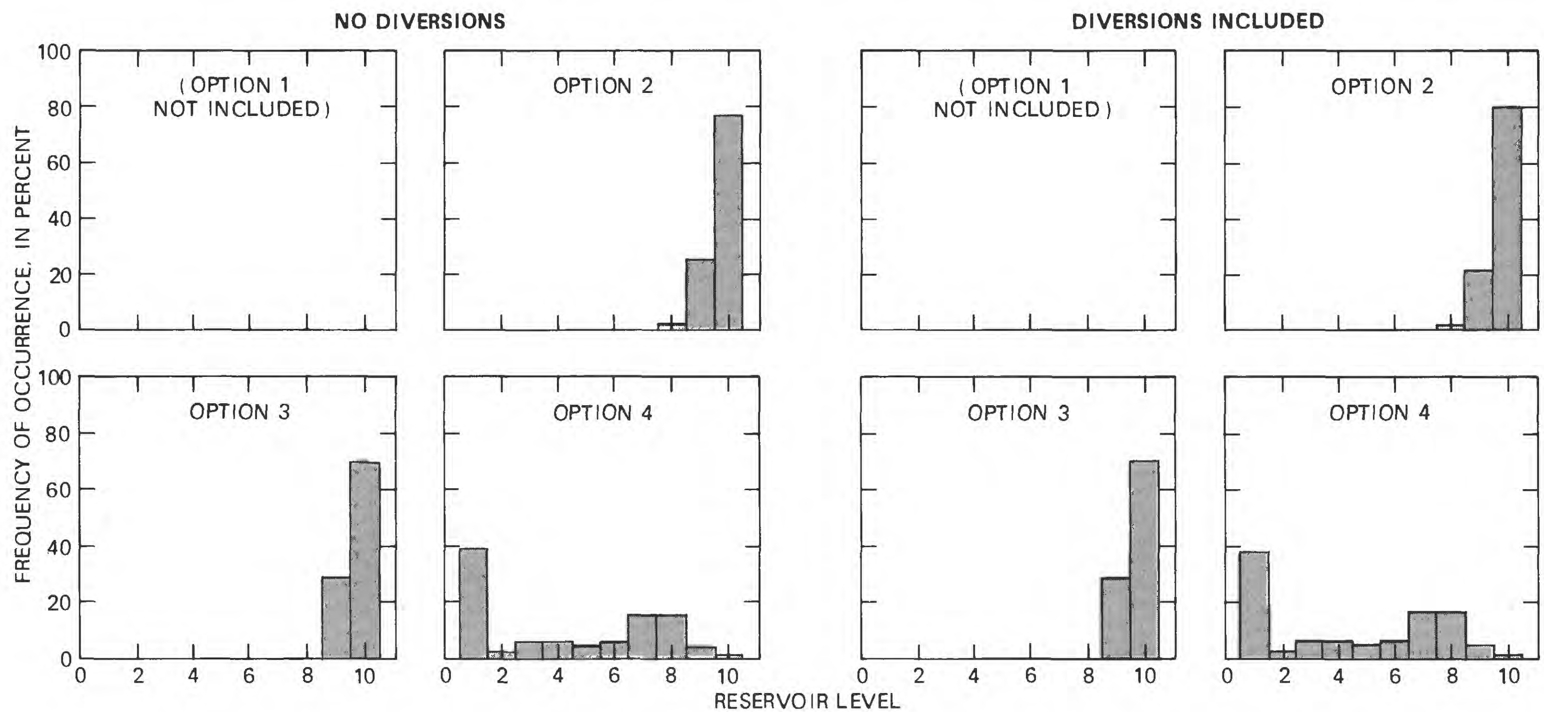


Figure 19. --Reservoir-storage frequency analysis at control point 10, Middle Creek at sites of proposed Upper Middle Creek and Lower Middle Creek Reservoirs, reservoir-development options 2 through 4.

EXPLANATION

RESERVOIR LEVEL	PERCENT OF CONSERVATION POOL	RESERVOIR LEVEL	PERCENT OF CONSERVATION POOL
1	99-100	6	60-70
2	95-99	7	40-60
3	90-95	8	20-40
4	80-90	9	1-20
5	70-80	10	0-1

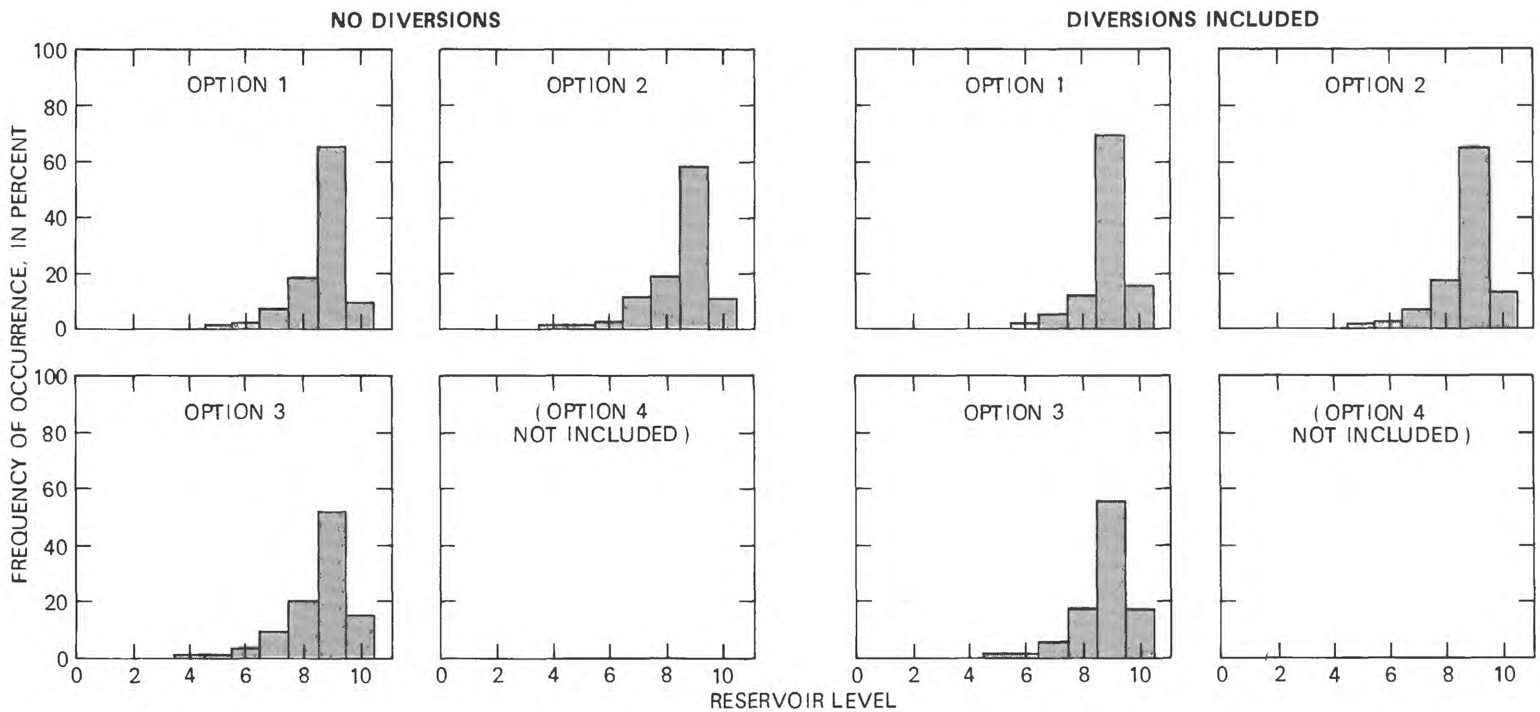


Figure 20. -- Reservoir-storage frequency analysis at control point 18, Yampa River at site of proposed Juniper Reservoir, reservoir-development options 1 through 3.

EXPLANATION

RESERVOIR LEVEL	PERCENT OF CONSERVATION POOL	RESERVOIR LEVEL	PERCENT OF CONSERVATION POOL
1	99-100	6	60-70
2	95-99	7	40-60
3	90-95	8	20-40
4	80-90	9	1-20
5	70-80	10	0-1

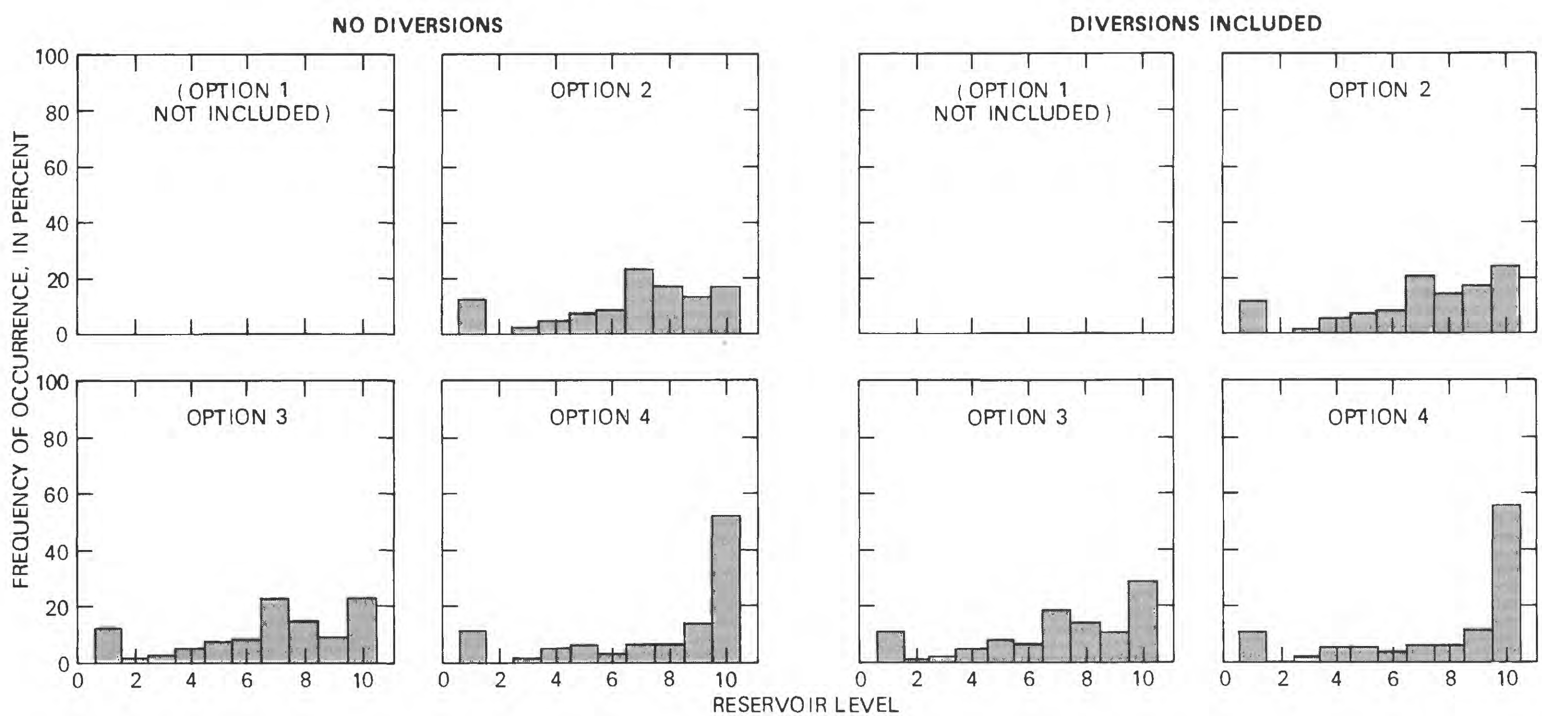


Figure 21.--Reservoir-storage frequency analysis at control point 22, Slater Creek at site of proposed Pot Hook Reservoir, reservoir-development options 2 through 4.

EXPLANATION

RESERVOIR LEVEL	PERCENT OF CONSERVATION POOL	RESERVOIR LEVEL	PERCENT OF CONSERVATION POOL
1	99-100	6	60-70
2	95-99	7	40-60
3	90-95	8	20-40
4	80-90	9	1-20
5	70-80	10	0-1

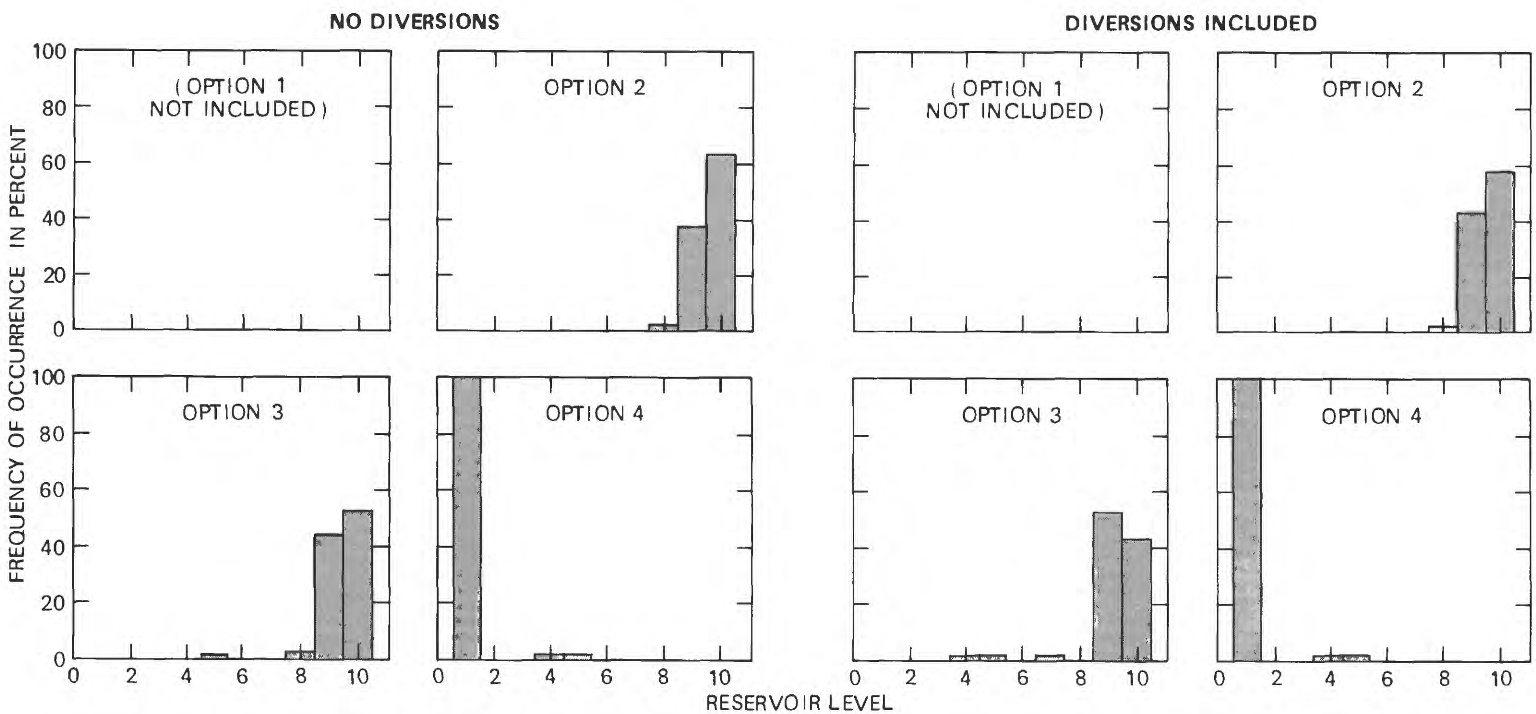


Figure 2[illegible].--Reservoir-storage frequency analysis at control point 47, Yampa River at site of proposed Blacktail Reservoir, reservoir-development options 2 through 4.

The results of the multireservoir-flow model give a frequency analysis for various reservoir-storage levels in a summary-class histogram for each reservoir. Reservoir storage is given in 10 separate categories as a percentage of the conservation-pool storage. An explanation of the category percentages of the active conservation pool is given in figures 18 to 22. The actual model results are on a monthly basis but only annual-mean frequency values are shown in figures 18 to 22.

The operation-storage patterns of the proposed Yamcolo Reservoir would be fairly consistent for reservoir-development and transmountain-diversion options 1 through 3 (fig. 18). A much larger difference could occur for reservoir-development option 4. This option does not include the large Juniper-Cross Mountain complex (Colorado River Water Conservation District, 1975) and consequently allows the Yamcolo Reservoir to maintain its approximate year-round full capacity (fig. 18). Reservoir-development options 2 and 3 involve the most extensive reservoir systems in the basin; consequently these options could have the largest requirements for the Yamcolo Reservoir resources. This seems to be substantiated by the greater frequency of occurrence of smaller reservoir volumes indicated for these options in figure 18.

The operation-storage patterns for the proposed combined Upper and Lower Middle Creek Reservoirs are shown in figure 19. These reservoirs, which would be part of the Oak Creek Power and Water Project (Oak Creek Power Co., 1976), would receive 130 ft^3/s (3.68 m^3/s) of diversion water, when available, from Blacktail Reservoir. For purposes of the multireservoir-simulation analysis, these two reservoirs were combined in the model to function as one reservoir. Their sole purposes would be to generate hydroelectric power and to supply cooling waters for a proposed 6,400-megawatt coal-fired electric-power generation plant (Oak Creek Power Co., 1976). Based on the operation-storage patterns (fig. 19) and the Blacktail Reservoir diversion shortages (table 10), the desired reservoir volumes would not be available most of the time except for reservoir-development option 4, which does not include the large downstream Juniper-Cross Mountain Reservoir complex (Colorado River Water Conservation District, 1975).

The operation-storage patterns for the proposed Juniper Reservoir that would be located on the Yampa River are shown in figure 20. Based on the analysis, this reservoir would be operated at a relatively small storage level, less than 20 percent conservation pool, for 60 percent or more of the total time (fig. 20), but because recreational aspects (Colorado River Water Conservation District, 1975) were not considered for this reservoir, the operation-storage patterns may be acceptable.

The operation-storage patterns for the proposed Pot Hook Reservoir are shown in figure 21. Similar results were obtained for the proposed Sandstone Reservoir. These reservoirs were designed to supply diversions for irrigation purposes (U.S. Department of the Interior, 1976). Both reservoirs would have fairly uniform operation-storage patterns for reservoir-development options 2, 3, and 4, with and without the proposed Hog Park transmountain diversion (fig. 21). The irrigation-diversion shortages for the Pot Hook Reservoir (table 10) and the transmountain-diversion shortages for the Hog Park diversion (Banner & Associates, Inc., 1976;

U.S. Department of Agriculture, 1981) (table 9) indicated minimal shortages less than 25 percent of the time). From these results and the operation-storage patterns in figure 21, it appears that impact on streamflow in the Little Snake River resulting from the proposed Hog Park transmountain diversion and the proposed Sandstone-Pot Hook Reservoirs could be minimal. However, further detailed analysis would be required to assess the extent to which existing senior water rights downstream might be affected.

The operation-storage patterns for the proposed Blacktail Reservoir, which is proposed as part of the Oak Creek Power and Water Project (Oak Creek Power Co., 1976), are shown in figure 22. The operation-storage patterns are almost identical for reservoir-development options 2 and 3. These results for options 2 and 3 show that the Blacktail Reservoir would be operating with less than 20 percent of the conservation pool and at least 40 percent of the time with less than 1 percent of the conservation pool. Similarly, under the less heavy reservoir-development option 4, indications are that the Blacktail Reservoir would maintain an approximately full level most of the time. The proposed industrial diversion of 130 ft^3/s (3.64 m^3/s) from this reservoir for options 2, 3, and 4 would be available less than 15 percent of the time (table 10). Within the multireservoir-flow model framework, a ranking system is assigned to each type of water demand. For the Yampa River basin study, the Blacktail Reservoir--78,500 acre-feet (96.9 hm^3) per year industrial diversion (table 8)--had a lower priority than the reservoir storage. This explains the approximately full reservoir volume for Blacktail Reservoir under option 4 (fig. 22) while only meeting the industrial diversion requirement less than 15 percent of the time (table 10).

DISSOLVED-SOLIDS MODEL

The Program NW01 dissolved-solids model (Ribbens, 1975) incorporates most of the features of the multireservoir-flow model, plus algorithms for simulation of monthly and annual dissolved-solids concentrations and loads. Because of the additional capability to simulate dissolved-solids concentrations and loads, the dissolved-solids model is scaled down, as compared to the multireservoir-flow model; for example, the dissolved-solids model can consider only a maximum of five reservoirs and a 19-year computation period. Consequently, the reservoir configurations used in the dissolved-solids model were different from those used in the multireservoir-flow model. The period 1951 to 1969, which includes the droughts of the 1950's, was selected and used for the dissolved-solids model analysis.

Model Adjustment

Monthly values of streamflow and specific conductance, which were collected during water years 1951-69 at the streamflow-gaging stations on the Yampa River near Maybell, Colo. (fig. 23, site 53), and on the Little Snake River near Lily, Colo. (fig. 23, site 79), were used to adjust the dissolved-solids model to historical conditions. The specific-conductance values were converted to dissolved-solids concentrations using regression functions developed from historical data at each streamflow-gaging station (Wentz and Steele, 1976; 1980; Gaydos, 1980).

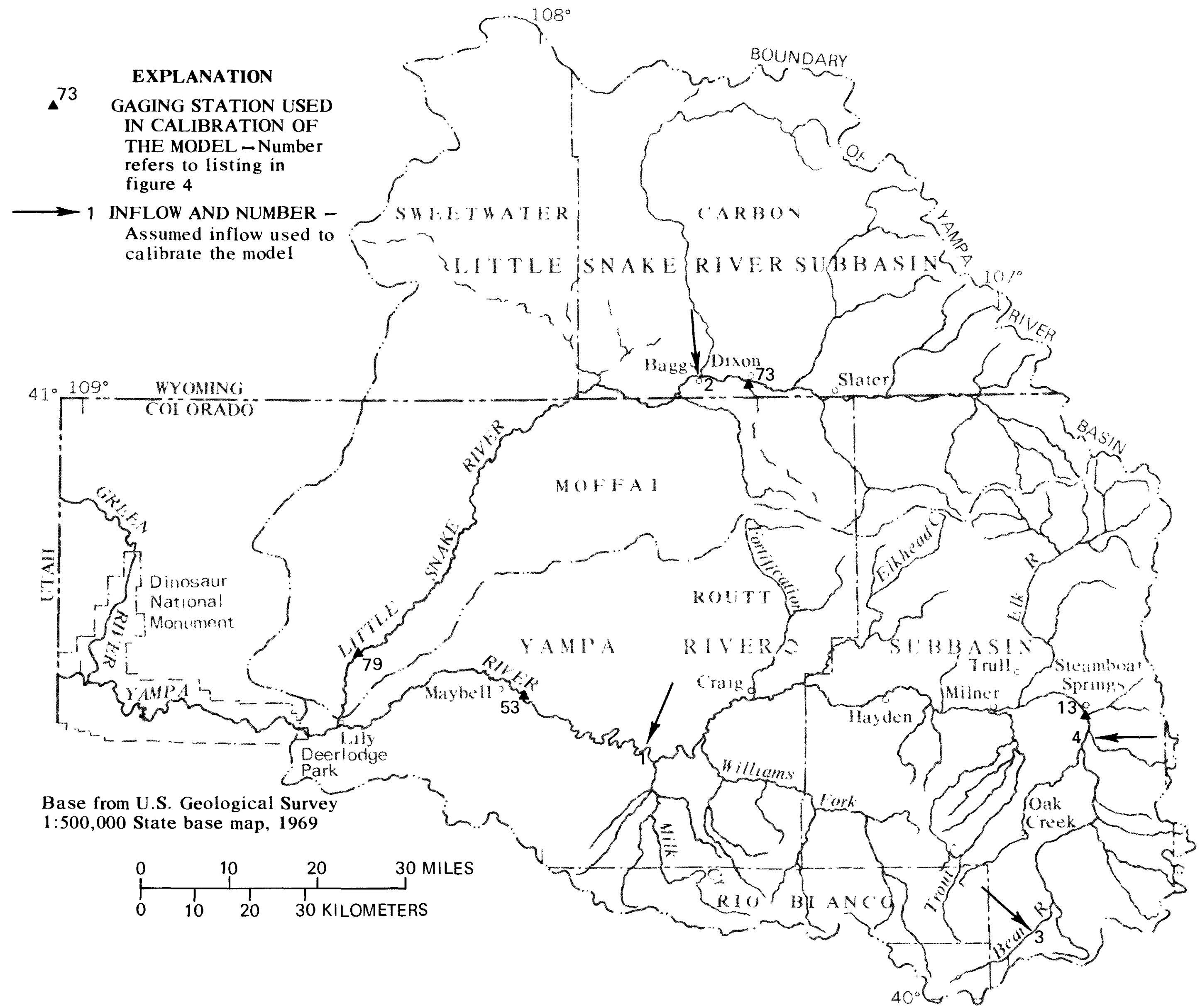


Figure 23.--Location of selected streamflow gages and inflows used in the calibration and extension of the dissolved-solids model.

The dissolved-solids model, which is similar to the multireservoir-flow model, is an accounting model and contains no model parameters. For this analysis, the dissolved-solids model-generated streamflow and dissolved-solids values at selected locations in the basin were initially adjusted to closely match the historical observed values for these locations. The model adjustment was a two-step procedure: (1) Historical streamflows and dissolved-solids concentrations were entered into the model to generate simulated streamflows and dissolved-solids loads; (2) the differences between the historical and simulated data then were examined, and the model output was adjusted (by modifying model inputs) until a reasonable match was achieved between historical and simulated data on a monthly basis for the 19 years of record. Appropriate ungaged streamflow and dissolved-solids values also were used for the ungaged areas between the observed streamflow-gaging locations. Details of the model adjustments are described more fully in subsequent sections of this report.

The measurement of the goodness-of-fit between the simulated and historical records was based on two criteria: (1) How well the mean monthly simulated values compared with the mean monthly historical values; and (2) how well the monthly mean simulated values compared with the monthly mean historical values. The goodness-of-fit of the individual values was based on the following:

$$S_i = \left(H_i - c_i\right) / H_i, \tag{1}$$

where: S_i=residual, as a decimal percentage of the historical value;

H_i=historical record of streamflow or dissolved-solids load;

C_i=simulated record of streamflow or dissolved-solids load; and

i=the ith value of the record.

The goodness-of-fit of the series is expressed as a decimal percentage of the total historical data points and residuals, computed by equation 1. The following adjustments were made to the model:

(1) Adjustment of the streamflow near Maybell, Colo.;
(2) Adjustment of the dissolved-solids load near Maybell, Colo.;
(3) Adjustment of the streamflow near Lily, Colo.; and
(4) Adjustment of the dissolved-solids load near Lily, Colo.

The adjustments are described in the following pages.

The dissolved-solids model was adjusted for only part of the Yampa River basin. The upstream control points used were the streamflow-gaging stations located at Steamboat Springs, Colo., on the Yampa River (fig. 23, site 13) and at Dixon, Wyo., on the Little Snake River (fig. 23, site 73). These streamflow-gaging stations were selected because they represented the farthest upstream points where a relationship could be developed between streamflow and dissolved-solids loads. Upstream from these two streamflow-gaging stations, the streams contain relatively small concentrations of dissolved solids. Also, the streams above these sites have not been sampled for dissolved solids on a regular basis.

Streamflow near Maybell, Colo.

Streamflow in the Yampa River near Maybell, Colo., was computed initially as the streamflow at Steamboat Springs, Colo., plus the inflow from major tributaries between the two streamflow-gaging stations. The major tributaries downstream from Steamboat Springs, Colo., are the Elk River, Trout Creek, Elkhead Creek, Fortification Creek, Williams Fork, and Milk Creek (fig. 23).

Monthly and annual discharge (Q) matrices developed by A. W. Burns (U.S. Geological Survey, written commun., 1976) synthesized tributary flows at streamflow-gaging stations rather than at the confluence of a tributary with the Yampa River. The monthly Q-matrix values were increased in value for Trout Creek, Milk Creek, and Williams Fork because the streamflow-gaging stations on these three streams are located upstream from their confluences with the Yampa River, and the total contributing drainage areas are not included in their streamflow records. The tributary gaged monthly discharges were multiplied by the ratio of the total contributing drainage area divided by the streamflow-gage drainage area.

A comparison test for water years 1951-69 made using the adjusted monthly Q-matrix values indicated that historical streamflows near Maybell, Colo., were consistently larger during April, smaller during May and June, and larger again during July, as compared to the simulated streamflows. These differences, which occurred during most years, are partially the result of snowmelt at low elevations during April and diversions for irrigation during May and June.

An assumed stream, Inflow 1 (fig. 23), was included as an additional tributary inflow in the model to account for much of the differences between historical and simulated streamflows during April through July. The low-elevation snowmelt was determined to be about three times the mean monthly flow of Fortification Creek during April, or 24,000 acre-feet (29.6 hm^3). Diversions for irrigation were estimated at 36,000 acre-feet (44.4 hm^3) during May and 4,500 acre-feet (5.5 hm^3) during June. The irrigation return flow was estimated to be 16,200 acre-feet (20.0 hm^3). However, the actual amounts of irrigation diversion or return flows in the vicinity of Craig, Colo., are not presently known so there is no practical way to check the validity of the generated values. The resulting simulated and historical flows are shown in figure 24.

Dissolved-Solids Load near Maybell, Colo.

The inflow of dissolved solids at the streamflow-gaging station at Steamboat Springs, Colo., and from the tributaries was based on a logarithmic correlation between specific conductance, as an index of the concentration of dissolved solids, and streamflow. This relationship, based on only a few samples collected upstream from Steamboat Springs, Colo., was used to generate a monthly concentration (C) matrix for all inflow points. In order to help balance the dissolved-solids loads for the location near Maybell, Colo., a constant dissolved-solids concentration of 200 mg/L (milligrams per liter) was assigned for Inflow 1. The 200-mg/L value used for Inflow 1, in the vicinity of Fortification Creek, appears reasonable because estimated dissolved-solids values from regression relationships (Gaydos, 1980) for the Yampa River both upstream and downstream of this inflow are approximately equal to 200 mg/L.

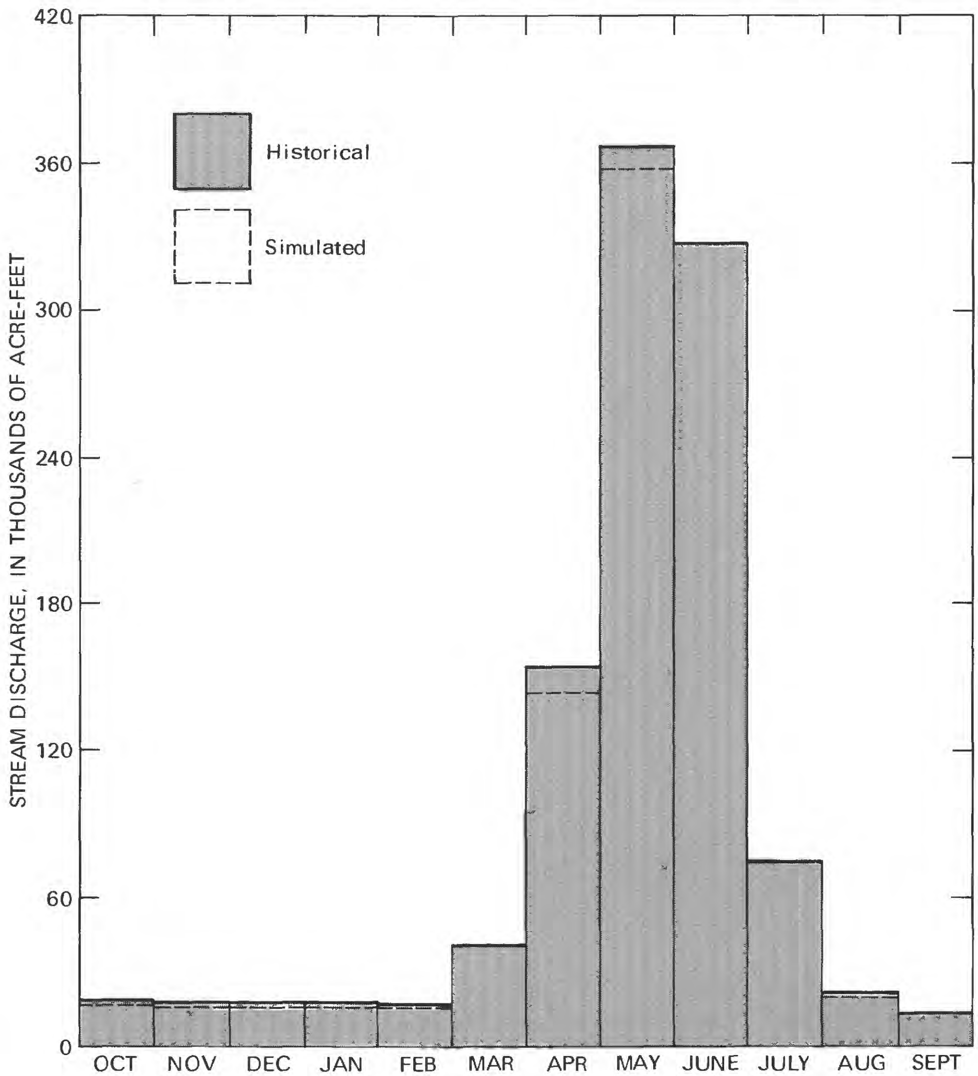


Figure 24.--Comparison, water years 1951-69, of simulated and historical streamflows, Yampa River near Maybell, Colo.

The C-matrix values and the constant value for Inflow 1 were used as input to the dissolved-solids model. With the exception of May and June, when streamflows are relatively large, the historical dissolved-solids load was more than 20 percent greater than the simulated dissolved-solids load. The dissolved-solids load values in the C matrix were adjusted on a month-by-month basis. Simulated and historical mean monthly dissolved-solids loads are compared in figure 25.

Streamflow near Lily, Colo.

Streamflow in the Little Snake River near Lily, Colo. (fig. 23, site 73), was considered to consist of the streamflow at Dixon, Wyo. (fig. 23, site 79), plus the inflow from a few ungaged ephemeral tributaries between the two streamflow-gaging stations. An adjustment test for water years 1951-69 indicated that historical streamflows near Lily, Colo., were consistently larger than the simulated streamflows during March and April and during July through October. These differences, which occurred during most years, are probably the result of unmeasured snowmelt runoff at low elevations for the stream reach from Dixon, Wyo., to Lily, Colo., during March and April and return flow of irrigation water during July through October.

An assumed stream, Inflow 2 (fig. 23), was included as an additional tributary inflow in the model to account for much of the differences between historical and simulated flows during March, April, and May, and during June, July, and August. The approximate mean monthly low-elevation snowmelt was determined to be 5,200 acre-feet (6.4 hm^3) for March, April, and May. The mean monthly irrigation return flow was estimated to be 1,000 acre-feet (1.2 hm^3) during June, July, and August. The resulting simulated and historical flows are shown in figure 26.

Dissolved-Solids Load near Lily, Colo.

There is a considerable difference between the dissolved-solids load of the Little Snake River at Dixon, Wyo., and the load near Lily, Colo. (fig. 27). The larger amounts of dissolved solids which occur during the months of March to July result because of flushing and leaching from larger streamflows with corresponding high dissolved-solids concentrations. In comparison, the amounts of dissolved-solids load during August and September (fig. 27) decrease principally because of large reductions in streamflow even though the dissolved-solids concentrations are generally higher than the preceding months. In order to help balance the dissolved-solids loads, dissolved-solids concentrations were assumed for Inflow 2 as follows: 700 mg/L during October through June; 400 mg/L during July to represent the relatively more diluted irrigation return flow; 1,000 mg/L during August; and 1,500 mg/L during September (fig. 27). The larger concentrations in the return-flow irrigation water during the August and September time period result principally because of smaller amounts of water available for irrigation purposes. The net result is larger consumptive losses for the available water with less water with much higher concentrations of dissolved solids being returned to the stream.

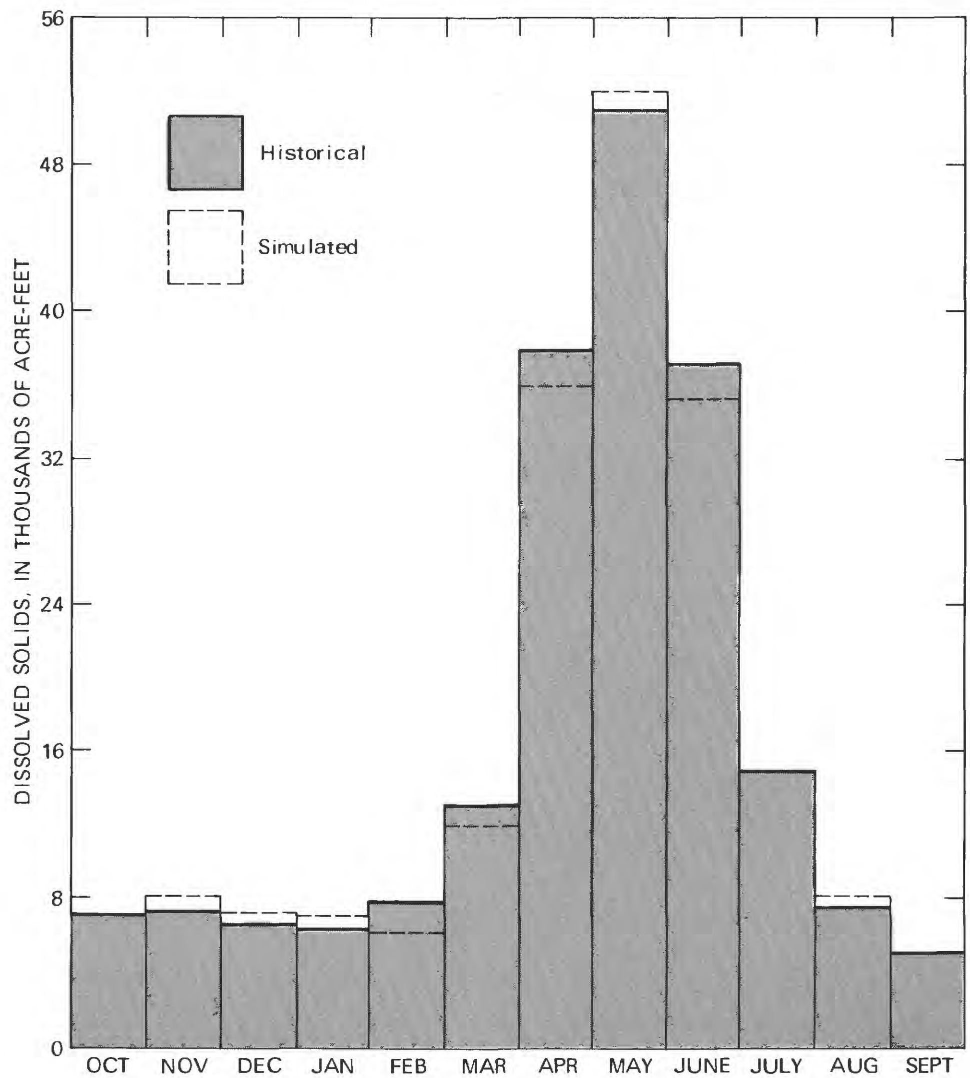


Figure 25.--Comparison, water years 1951-69, of simulated and historical mean monthly dissolved-solids loads, Yampa River near Maybell, Colo.

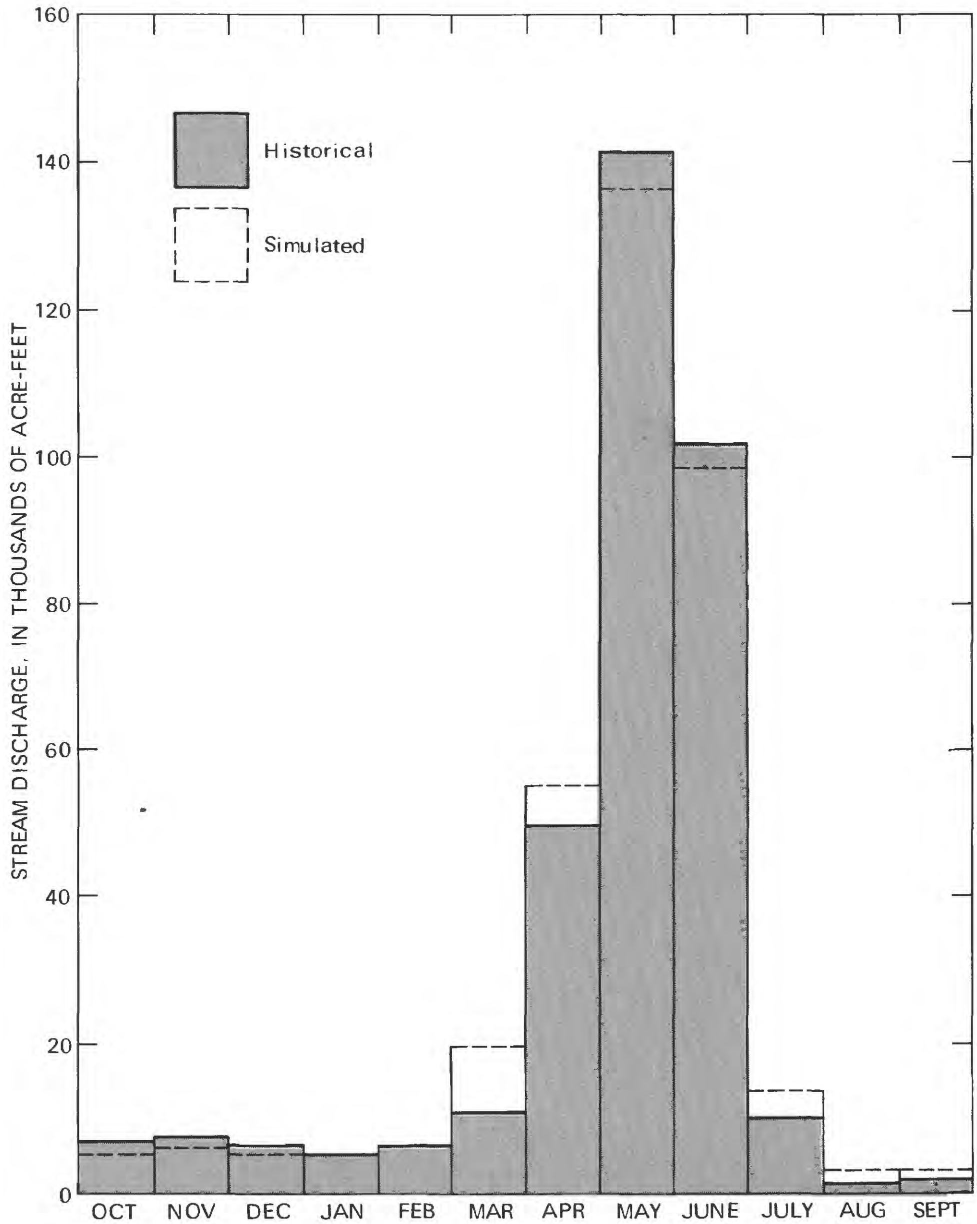


Figure 26.--Comparison, water years 1951-69, of simulated and historical streamflows, Little Snake River near Lily, Colo.

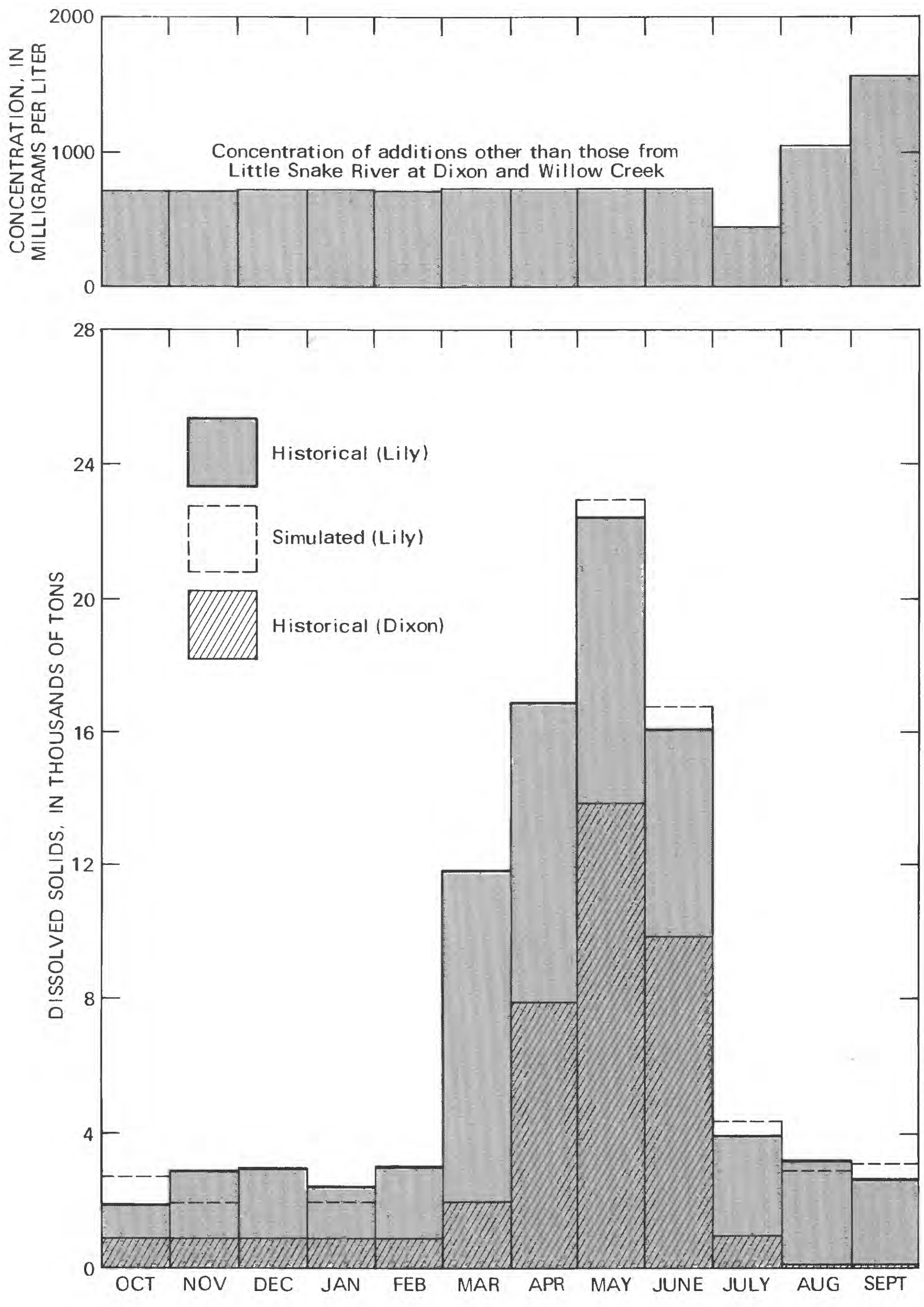


Figure 27.--Comparison, water years 1951-69, of simulated and historical mean monthly dissolved-solids loads, Little Snake River near Lily, Colo., for an upstream starting dissolved-solids load at Dixon, Wyo., and an assumed monthly dissolved-solids load added through inflow 2.

In addition to the dissolved-solids increases noted above, dissolved solids were added during the months of December to June to approximate the historical dissolved-solids load. Using this method of adjusting the dissolved-solids load, the mean monthly dissolved-solids load was simulated for the Little Snake River near Lily, Colo. (fig. 27).

Model Extension Upstream from Steamboat Springs, Colo.

Streamflow data were available for selected tributaries upstream from Steamboat Springs, Colo. These values were used to extend the dissolved-solids model in the Yampa River subbasin to a point on the Bear River just upstream from the proposed Yamcolo Reservoir (fig. 1). Inflows 3 and 4 (fig. 23) also were added to this upstream reach of the river to account for local tributary inflows.

Due to data deficiencies, there was no basis for distributing the dissolved-solids load of the various tributaries in the model extension. Therefore, the dissolved-solids concentrations for all tributaries used during the model adjustment also were used in the model extension.

Model Simulations

Configurations of proposed reservoirs studied using the dissolved-solids model were similar to reservoir-development options 1, 2, and 4 using the multireservoir-flow model. However, because only a maximum of five reservoirs could be included in the dissolved-solids model, the following modifications were made: (1) Reservoir-development option 3 was omitted; (2) various reservoirs were grouped for reservoir-development options 2 and 4, and the proposed Yamcolo and Dunckley Reservoirs were omitted from reservoir-development option 4; and (3) control points were renumbered. Because of modifications in the reservoir configurations, some results of the simulations of regulated streamflow using the dissolved-solids model were different from results for the corresponding historical simulations made using the multireservoir-flow model. The reservoir configurations and control points used in the dissolved-solids model simulations of regulated streamflow are shown in figure 28 and are described in table 12. The Vidler and Hog Park transmountain diversions, as described for the multireservoir-flow model (table 4), were not considered for the dissolved-solids model analysis. These diversions were not included because of model restrictions.

The assumed monthly schedules for proposed irrigation diversions and proposed annual diversions for industrial and municipal use adopted in the dissolved-solids model were the same as those developed in the multireservoir-flow model (table 7, irrigation, and table 8, industrial and municipal). The return flows for irrigation diversions, as described for the multireservoir-flow model, were assumed to amount to 67 percent of the water diverted. The return-flow amounts assumed for the various proposed reservoirs are shown in table 13. All dissolved solids diverted were assumed to be returned to the river; therefore, dissolved-solids concentrations were assumed to be greater in the return flows. The increment of increase in dissolved-solids load for each of the proposed diversions is shown in table 14. The largest incremental increase in dissolved-solids load would occur in the vicinity of the proposed Juniper and Cross Mountain Reservoirs.

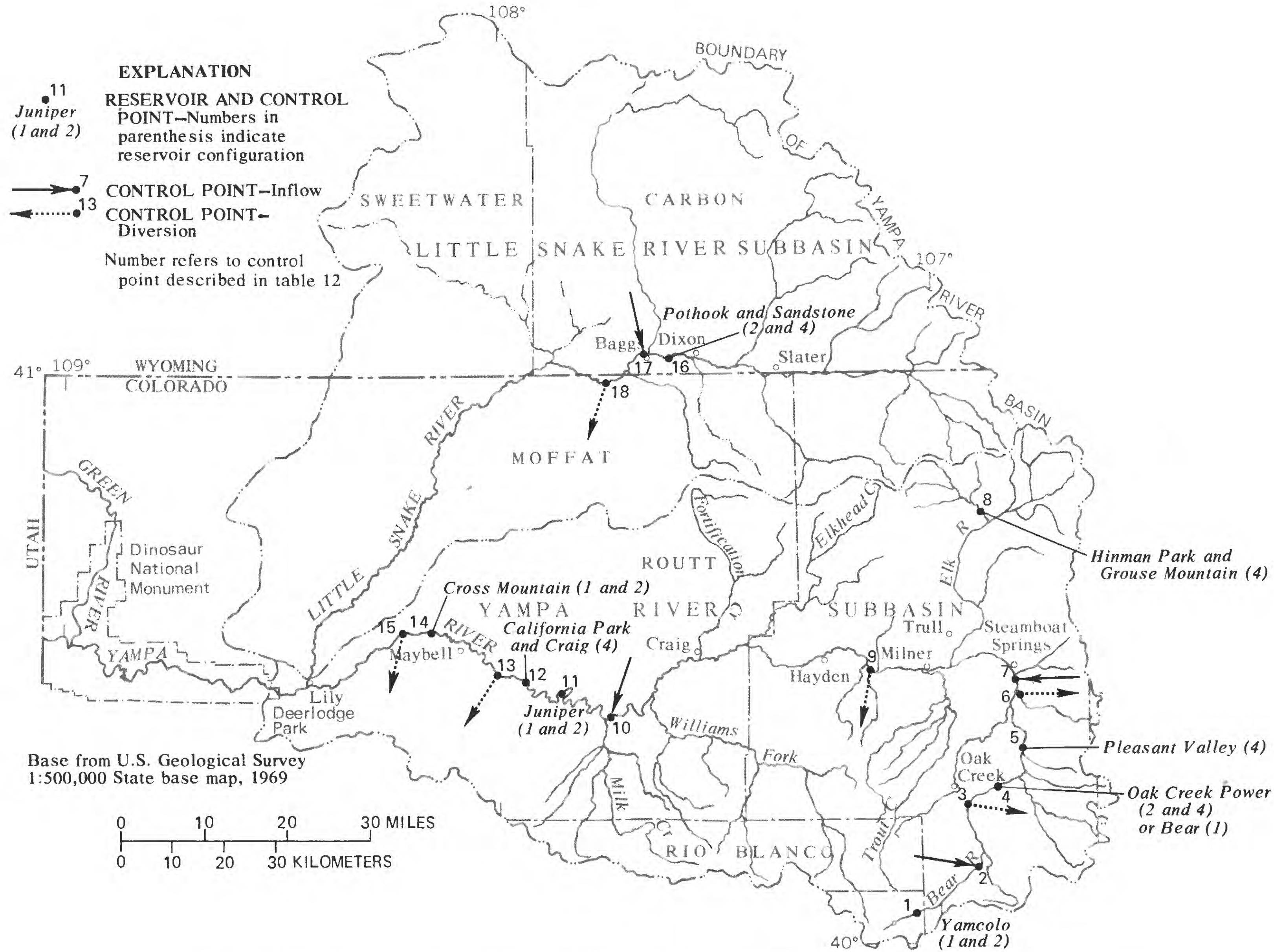


Figure 28.--Reservoir configurations and control points used in dissolved-solids model analysis.

Table 12.--*Description of control points and reservoir-development options in which control points were used, dissolved-solids model*

Control point[1]	Description	Reservoir-development option in which control point used		
		1	2	4
1	Bear River at site of proposed Yamcolo Reservoir	X	X	X
2	Bear River at site of assumed Inflow 4	X	X	X
3	Yampa River at site of assumed irrigation diversion from proposed Yamcolo Reservoir	X	X	X
4[2]	Yampa River at site of proposed Bear Reservoir	X	-	-
4[2]	Combination of: Yampa River at site of proposed Blacktail Reservoir, Trout Creek at site of proposed Childress Reservoir, Green Creek at site of proposed Lower Green Creek Reservoir, and Middle Creek at sites of proposed Upper Middle Creek and Lower Middle Creek Reservoirs	-	X	X
5	Yampa River at site of proposed Pleasant Valley Reservoir	-	-	X
6	Yampa River at site of assumed irrigation diversion from proposed Pleasant Valley Reservoir	-	-	X
7	Yampa River at site of assumed Inflow 3	X	X	X
8	Combination of: Elk River at site of proposed Hinman Park Reservoir and Willow Creek at site of proposed Grouse Mountain Reservoir	-	-	X
9	Site of assumed diversion for proposed powerplant	X	X	X
10	Yampa River at site of assumed Inflow 1	X	X	X
11	Yampa River at site of proposed Juniper Reservoir	X	X	-
12	Combination of: Yampa River at site of proposed Craig Reservoir and Elkhead Creek at site of proposed California Park Reservoir	-	-	X
13	Yampa River at site of assumed irrigation diversion from proposed Juniper, Craig, and California Park Reservoirs	X	X	X
14	Yampa River at site of proposed Cross Mountain Reservoir	X	X	-
15	Yampa River at site of assumed irrigation diversion from proposed Cross Mountain Reservoir	X	X	-
16	Combination of: Slater Fork at site of proposed Pot Hook Reservoir and Savery Creek at site of proposed Sandstone Reservoir	-	X	X
17	Little Snake River at site of assumed Inflow 2	-	X	-
18	Little Snake River at site of assumed irrigation diversion from proposed Pot Hook and Sandstone Reservoirs	-	X	X

[1]See figure 28 for location.

[2]Bear and Blacktail Reservoirs use the same control point for the dissolved-solids model.

Table 13.--*Assumed monthly return flows for irrigation diversions*

Proposed reservoir	Control point	Monthly return flows, in thousands of acre-feet											
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	May	June	July	August	Sept.
Yamcolo----------	1	0.08	0	0	0	0	0	0.08	0.24	0.40	0.56	0.40	0.24
Bear-------------	4	.20	0	0	0	0	0	.20	.77	1.39	1.85	1.39	.77
Pleasant Valley---	6	.24	0	0	0	0	0	.24	.89	1.57	2.13	1.57	.89
Juniper----------	11	22.00	0	0	0	0	0	22.00	86.7	153.0	207.0	153.0	86.7
California Park---	12	.68	0	0	0	0	0	.68	2.81	4.91	6.53	4.91	2.81
Craig------------	12	1.07	0	0	0	0	0	1.07	4.33	7.60	10.0	7.60	4.33
Cross Mountain----	14	2.47	0	0	0	0	0	2.47	10.0	17.3	23.3	17.3	10.0
Pot Hook----------	16	.52	0	0	0	0	0	.52	2.05	3.73	4.79	3.73	2.05
Sandstone---------	16	.30	0	0	0	0	0	.30	1.13	1.93	2.60	1.93	1.13

Table 14.--*Simulated monthly dissolved-solids loads in irrigation-return flows*

Proposed reservoir	Control point	Monthly dissolved-solids load, in thousands of tons											
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	May	June	July	August	Sept.
Yamcolo----------	1	0.01	0	0	0	0	0	0.01	0.03	0.05	0.07	0.05	0.03
Bear-------------	4	.02	0	0	0	0	0	.02	.09	.17	.28	.17	.09
Pleasant Valley---	6	.03	0	0	0	0	0	.03	.11	.19	.26	.19	.11
Juniper----------	11	3.90	0	0	0	0	0	3.90	15.3	27.1	36.5	27.1	15.3
California Park---	12	.07	0	0	0	0	0	.07	.29	.50	.67	.50	.29
Craig------------	12	.11	0	0	0	0	0	.11	.44	.77	1.00	.77	.44
Cross Mountain----	14	.44	0	0	0	0	0	.44	1.77	3.06	4.12	3.06	1.77
Pot Hook----------	16	.07	0	0	0	0	0	.07	.27	.48	.62	.48	.27
Sandstone---------	16	.04	0	0	0	0	0	.04	.15	.25	.34	.25	.15

Simulation results are presented in graphs showing mean monthly flows and mean monthly dissolved-solids concentrations for water years 1951-69 at selected locations in the Yampa River basin. Each graph compares historical conditions at a given site with simulated conditions that could result from regulation by a particular reservoir configuration considered in the analysis.

Between 100,000 and 114,000 acres (40,500 and 46,100 ha) of land are being irrigated in the Colorado part of the Yampa River basin, according to published estimates (U.S. Department of the Interior, 1976; Steele and others, 1979). Estimating the effects of irrigation on stream quality with additional reservoir construction is a difficult task (Slawson, 1972) because of the lack of detailed localized data. Therefore, the dissolved-solids model was calibrated using current estimates of irrigated acreage as a base. In the following model simulations, changes in dissolved solids related to irrigation are those that would result from irrigating additional lands.

Reservoir-Development Option 1

Reservoir-development option 1 for the dissolved-solids model, identical to option 1 used in the multireservoir-flow model, included the proposed Yamcolo and Bear Reservoirs located upstream from Steamboat Springs and the proposed Juniper and Cross Mountain Reservoirs located near Maybell (fig. 28). For this configuration, no reservoir development was assumed on the Little Snake River.

The proposed Yamcolo and Bear Reservoirs would be relatively small, having a combined storage capacity of slightly more than 20,000 acre-feet (24.7 hm^3). Much of this storage capacity was assumed to be used for the regulation of irrigation deliveries. Also, it was assumed that additional land would be irrigated. In the dissolved-solids model, the additional water for irrigation was removed from the streams at control points 3 and 6 (fig. 28), according to the distribution schedule developed for the multireservoir-flow model (table 7).

The proposed Yamcolo (Western Engineers, Inc., 1975) and Bear Reservoirs would have a relatively limited effect on seasonal patterns of streamflow and dissolved-solids concentrations of the Yampa River at Steamboat Springs (fig. 29), because the historical annual streamflow at Steamboat Springs is about 15 times the proposed combined storage capacity of the two reservoirs. The only notable regulation effects could be a small increase in dissolved solids during February through July. During several months the dissolved-solids historical concentrations are greater than the simulated regulated ones (fig. 29). This is explained partly by greater streamflow augmentation from the reservoirs during low-flow periods.

The proposed Juniper and Cross Mountain Reservoirs would be relatively large, having a combined storage capacity of more than 1,220,000 acre-feet (1,510 hm^3). These reservoirs were assumed to operate primarily for power generation and irrigation (Colorado River Water Conservation District, 1975). Because of the large amount of irrigation-diversion water assumed scheduled from these reservoirs (table 7), the majority of the power generation at these reservoirs was assumed to occur during the irrigation season. Thus, the irrigation diversions at control points 13 and 15 (fig. 28) were assumed to occur downstream from the reservoirs.

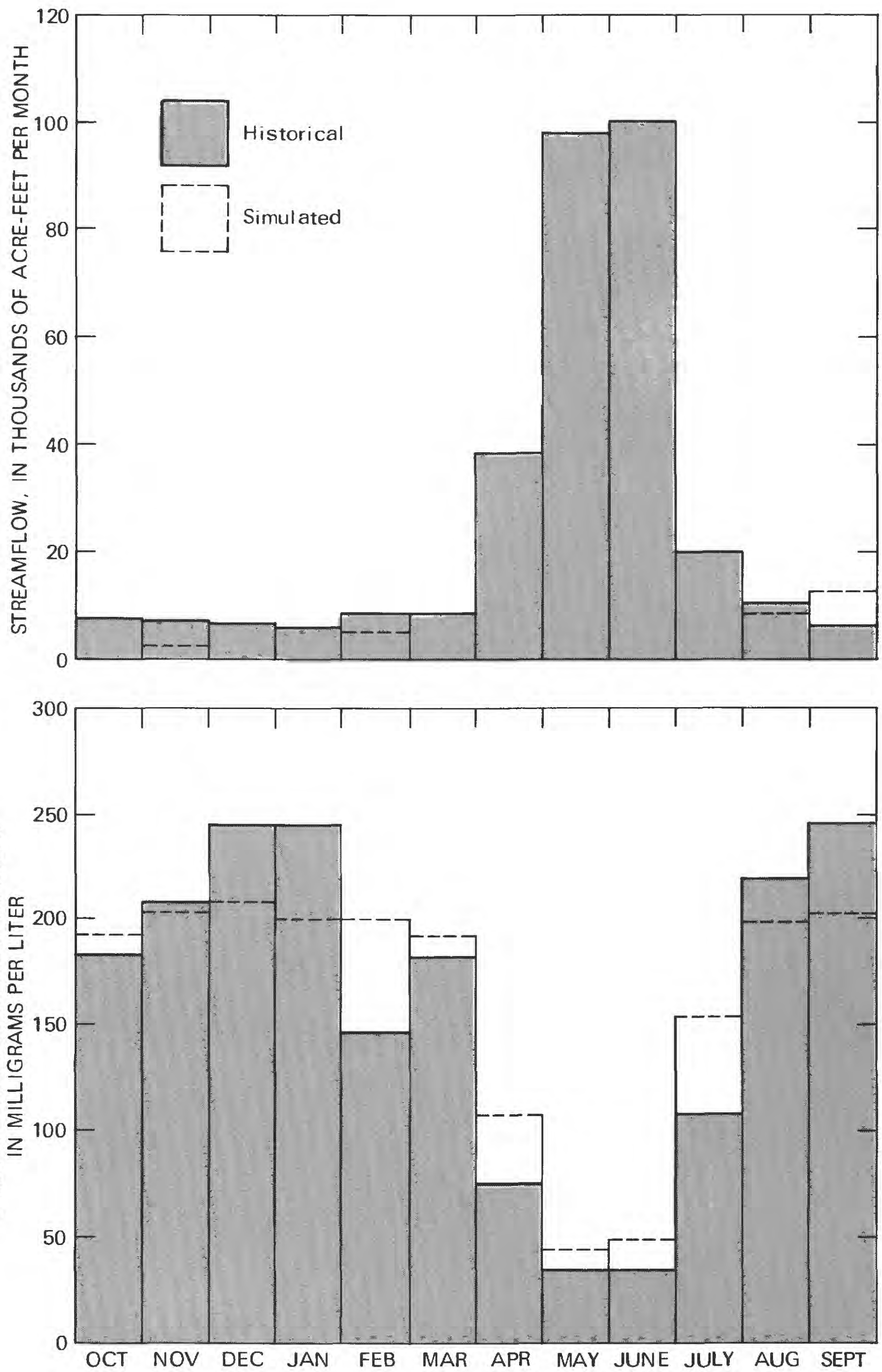


Figure 29.--Comparison of simulated regulated and historical mean monthly streamflow and dissolved-solids concentrations, reservoir-development option 1, water years 1951-69, Yampa River at Steamboat Springs, Colo.

The proposed Juniper and Cross Mountain Reservoirs could have a pronounced effect on downstream streamflows and dissolved-solids concentrations, because the historical annual streamflow of the Yampa River near Maybell is 94 percent of the combined storage capacities of the two reservoirs and also because the assumed proposed amounts of irrigation water are large (tables 7, 13, and 14). The historical streamflow downstream from Cross Mountain Reservoir is approximately twice the simulated regulated flow during April to August each year (fig. 30). This decrease in flow is largely the result of flow-volume losses from the upstream irrigation-return flows. Historical dissolved-solids concentrations downstream from the site of the proposed Cross Mountain Reservoir range between 150 and 940 mg/L, but with simulated regulation the annual variation of monthly concentrations would range between 320 and 640 mg/L (fig. 30). The results shown in figure 30 include the estimated effects of the dissolved-solids concentrations in the irrigation-return flows from the reservoir diversions.

Reservoir-Development Option 2

Reservoir-development option 2 for the dissolved-solids model was similar to option 2 for the multireservoir-flow model. A significant difference was that the proposed reservoirs for the Oak Creek Power and Water Project were combined into a single reservoir with a storage capacity equal to the combined capacities of the proposed project reservoirs. Also, the proposed Pot Hook and Sandstone Reservoirs were combined into a single reservoir with a storage capacity equal to the combined capacities of the two reservoirs.

The proposed Oak Creek Power and Water Project consists of five reservoirs, two principal diversions, and a coal-fired powerplant (Oak Creek Power Co., 1976). Plans include diverting water from Green Creek into the proposed Blacktail Reservoir on the Yampa River and then diverting nearly all the water flowing into Blacktail Reservoir to the Trout Creek subbasin where most of the diverted water would be used consumptively for evaporative-cooling water (table 8).

The net effect of the proposed Yamcolo Reservoir and the proposed reservoirs associated with the Oak Creek Power and Water Project would be to divert much of the water that normally would flow through Steamboat Springs, Colo., out of the upper Yampa River basin (fig. 31). For example, 80 to 100 percent of the water upstream of the Oak Creek power complex would be diverted into the Trout Creek subbasin for reservoir-development option 2. These diversions would result in an increase in dissolved-solids concentrations in the Yampa River at Steamboat Springs, Colo., during most months of the year (fig. 31).

For this simulation, the proposed Juniper and Cross Mountain Reservoirs were assumed to operate in the same manner as for reservoir-development option 1. The resulting flows and dissolved-solids concentrations for reservoir-development option 2 would be virtually the same for reservoir-development option 1 (fig. 30).

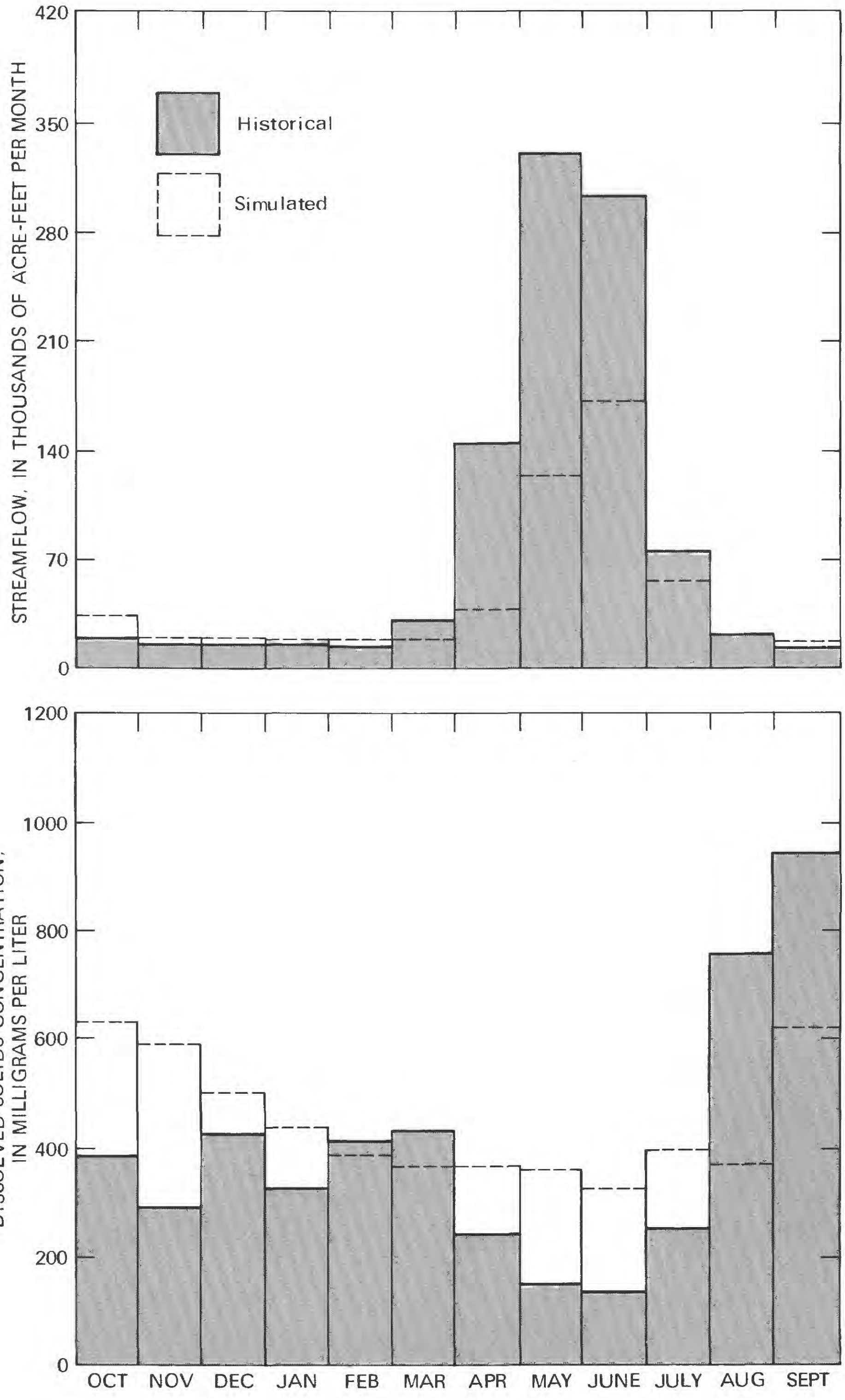


Figure 30.--Comparison of simulated regulated and historical mean monthly streamflow and dissolved-solids concentrations, reservoir-development option 1, water years 1951-69, Yampa River downstream from site of proposed Cross Mountain reservoir, Colo.

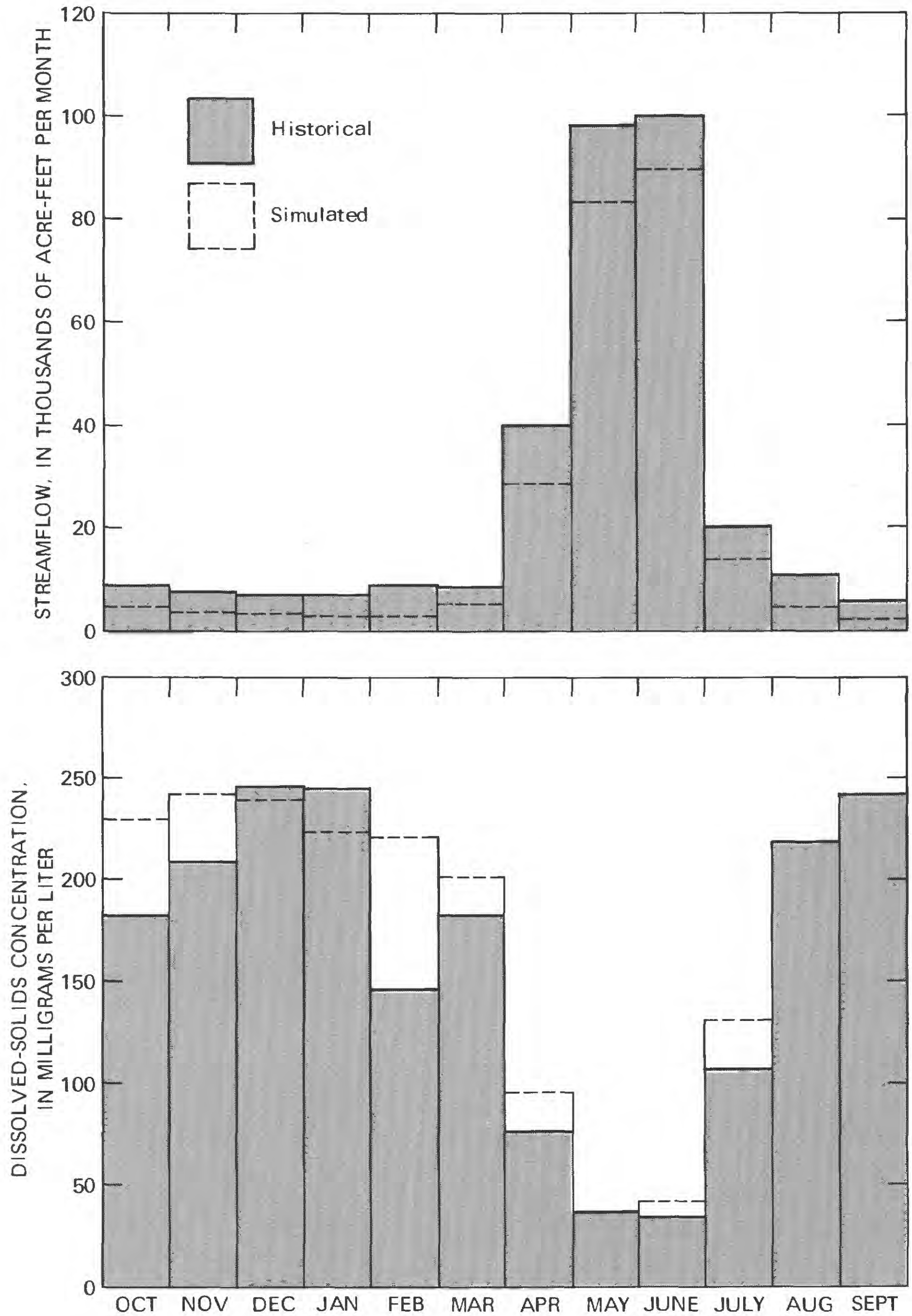


Figure 31.--Comparison of simulated regulated and historical mean monthly streamflow and dissolved-solids concentrations, reservoir-development option 2, water years 1951-69, Yampa River at Steamboat Springs, Colo.

The proposed Pot Hook and Sandstone Reservoirs would be located on tributaries of the Little Snake River and would have a combined storage capacity of about 40,000 acre-feet (49.3 hm^3) (U.S. Department of the Interior, 1976). These reservoirs were assumed to be operated primarily for irrigation. The irrigation diversion that could result from the construction of these two reservoirs was simulated at control point 18 in the dissolved-solids model. The proposed irrigation diversions are described in table 7, and the assumed return flows and computed dissolved-solids loads are described in tables 13 and 14.

Near Lily, Colo., simulated regulated streamflow in the Little Snake River could be similar, but slightly less than historical streamflows during most months (fig. 32). However, the dissolved-solids concentrations for the simulated regulated streamflow would be larger than for the historical streamflow throughout most of the year except during August and September. The estimated dissolved-solids concentrations during August and September would be less because of slightly larger simulated regulated streamflows (fig. 32) due to the upstream Sandstone-Pot Hook Reservoir complex.

At Deerlodge Park, Colo., downstream from the confluence of the Yampa and the Little Snake Rivers, streamflows and dissolved-solids concentrations could be as depicted in figure 33. Maximum monthly flows could be decreased from 460,000 acre-feet (568 hm^3) per month to 250,000 acre-feet (308 hm^3) per month. The increase in dissolved-solids concentrations could average 60 percent greater for the simulated regulated versus the historical streamflows, primarily because of the large reductions in streamflow (fig. 33). Due to the storage characteristics of the upstream reservoirs, the effect of the increased dissolved-solids concentrations would be exhibited throughout each year (fig. 33).

Reservoir-Development Option 4

The reservoirs used in development option 4 of the multireservoir-flow modeling analysis were the Yamcolo, the set of Oak Creek Water and Power Project and the Pleasant Valley, Hinman Park, Grouse Mountain, Dunckley, Craig, California Park, Sandstone, and Pot Hook Reservoirs (table 3). The proposed Pleasant Valley Reservoir would be an expansion of the existing Lake Catamount Reservoir (Woodward-Clyde Consultants, 1977). All reservoirs, with the exception of Yamcolo and Dunckley Reservoirs, were also used as part of the dissolved-solids model analysis. These reservoirs were excluded because of the maximum five-reservoir limitation of the model. Because of this constraint, the following reservoirs were combined for this configuration: Hinman Park and Grouse Mountain Reservoirs on the Elk River; Craig and California Park Reservoirs on the Yampa River; and Sandstone and Pot Hook Reservoirs on tributaries of the Little Snake River (fig. 28).

Irrigation diversions for this configuration are given in table 7; assumed return flows and dissolved-solids concentrations are given in tables 13 and 14. Sites of proposed irrigation diversions are shown in figure 28 as follows: Control point 6 for Pleasant Valley Reservoir, control point 18 for the combined Pot Hook and Sandstone Reservoirs, and control point 13 for California Park and Craig Reservoirs. The Hinman Park and Grouse Mountain Reservoirs within the Elk River drainage are not intended for irrigation purposes (Steele and others, 1979).

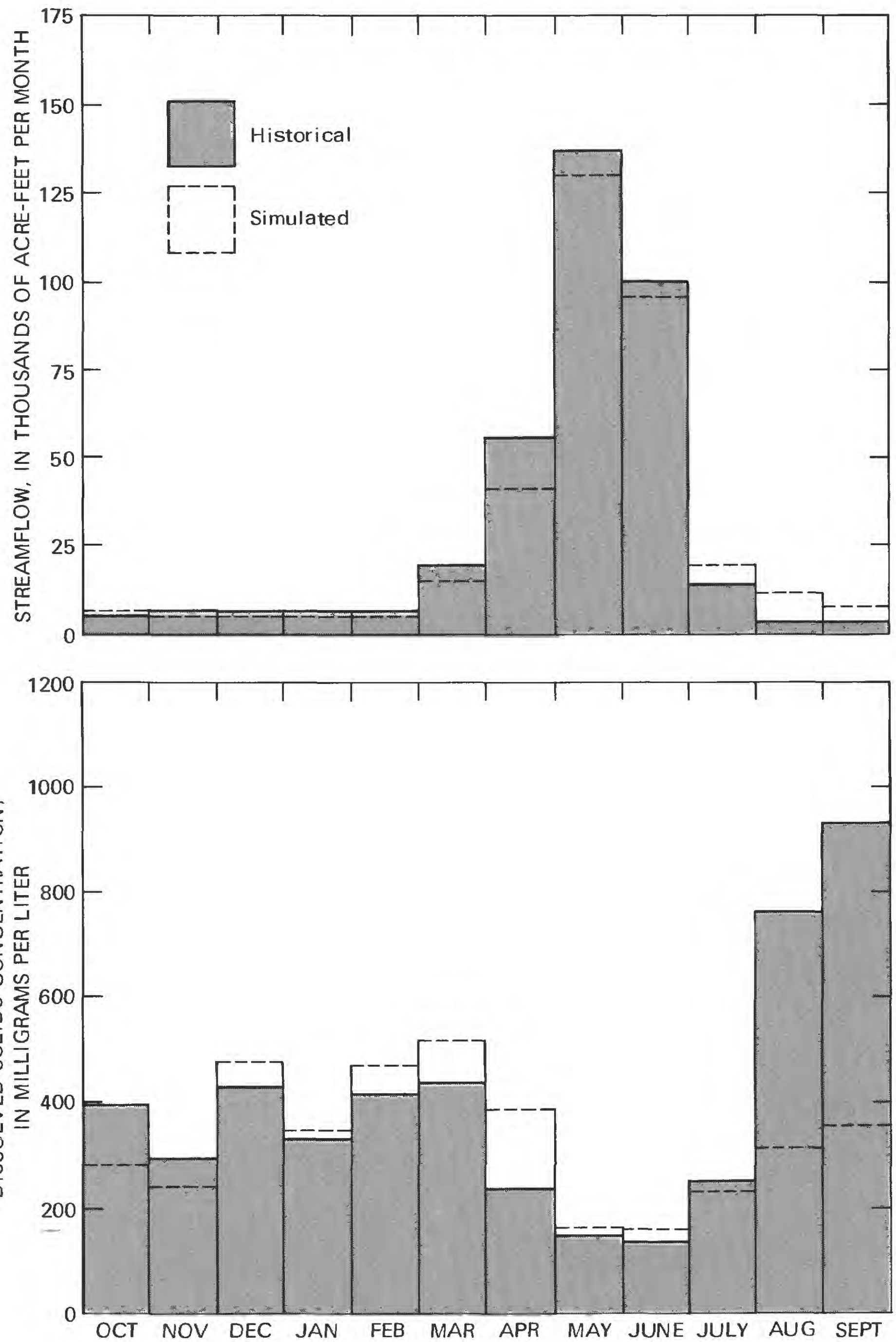


Figure 32.--Comparison of simulated regulated and historical mean monthly streamflow and dissolved-solids concentrations, reservoir-development option 2, water years 1951-69, Little Snake River near Lily, Colo.

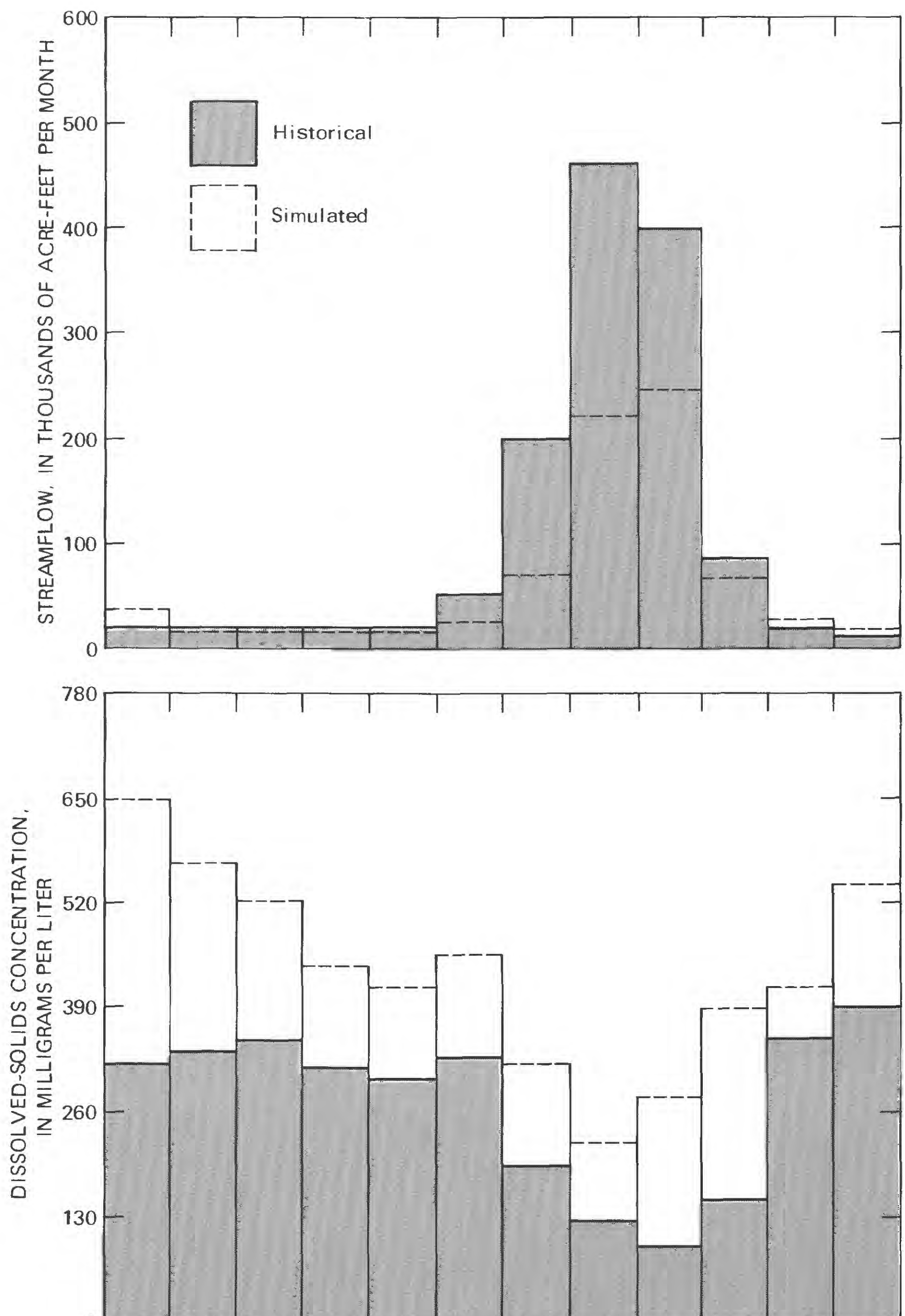


Figure 33.--Comparison of simulated regulated and historical mean monthly streamflow and dissolved-solids concentrations, reservoir-development option 2, water years 1951-69, Yampa River at Deerlodge Park, Colo.

The analysis of this reservoir configuration showed that the proposed Pleasant Valley Reservoir would not be compatible with diversions associated with the Oak Creek Water and Power Project. With these diversions, Service Creek would be virtually the only source of inflow to Pleasant Valley Reservoir. The mean annual streamflow of Service Creek is 23,000 acre-feet (28.4 hm^3) per year, which would make it unrealistic to effectively use the proposed total storage capacity of the Pleasant Valley Reservoir of 43,000 acre-feet (53.1 hm^3). The combined industrial diversions of the Oak Creek Water and Power Project and the irrigation diversions from Pleasant Valley Reservoir simulated for reservoir-development option 4 would further reduce streamflow at Steamboat Springs, Colo., by 3 percent annually and 21 percent during August and September, when compared with reservoir-development option 2 (figs. 31 and 34). Because of the small amounts of streamflow, the dissolved-solids concentrations would be significantly increased during August and September (figs. 31 and 34).

The composite effect on streamflow and dissolved-solids concentrations for the Yampa River near Maybell, Colo., location is shown in figure 35 and includes all the proposed reservoir effects in the Yampa River subbasin for the option-4 development. Because of smaller irrigation diversions from the proposed California Park and Craig Reservoirs, compared to the proposed Juniper and Cross Mountain Reservoirs (table 7), there would be 55 percent less dissolved-solids concentrations during most months in simulated regulated streamflows resulting from reservoir-development option 4, as compared to reservoir-development option 2 during most months (figs. 30 and 35). Dissolved-solids concentrations for simulated regulated streamflows would average 15 percent less than dissolved-solids concentrations for historical streamflows with reservoir-development option 4.

At Deerlodge Park, Colo., streamflows and dissolved-solids concentrations in the Yampa River resulting from reservoir-development option 4 also would be somewhat different from those resulting from option 2 (fig. 33). The dissolved-solids concentrations in simulated regulated streamflows generally would be less than dissolved-solids concentrations in historical streamflows during August through February (fig. 36).

SINGLE-RESERVOIR SIMULATION MODEL

The 10 proposed reservoirs used in the single-reservoir modeling analysis were the same as the proposed reservoirs used in reservoir-development option 2 for the multireservoir-flow model (table 3). Each of the 10 reservoirs analyzed with the single-reservoir simulation model, under an approximate full storage condition, can be considered as deep reservoirs with the possible development of horizontal isotherms. Reservoir-geometry data used in the single-reservoir simulation model are the same as used in the multireservoir-flow model. Climatic data used are from nearby stations and the Climatic Atlas of the United States (National Oceanic and Atmospheric Administration, 1968). Streamflows that would enter the reservoirs were the same as the streamflows computed using the multireservoir-flow model. The temperatures of the streamflows that would enter the reservoirs, except for the proposed Juniper and Cross Mountain Reservoirs, were computed using

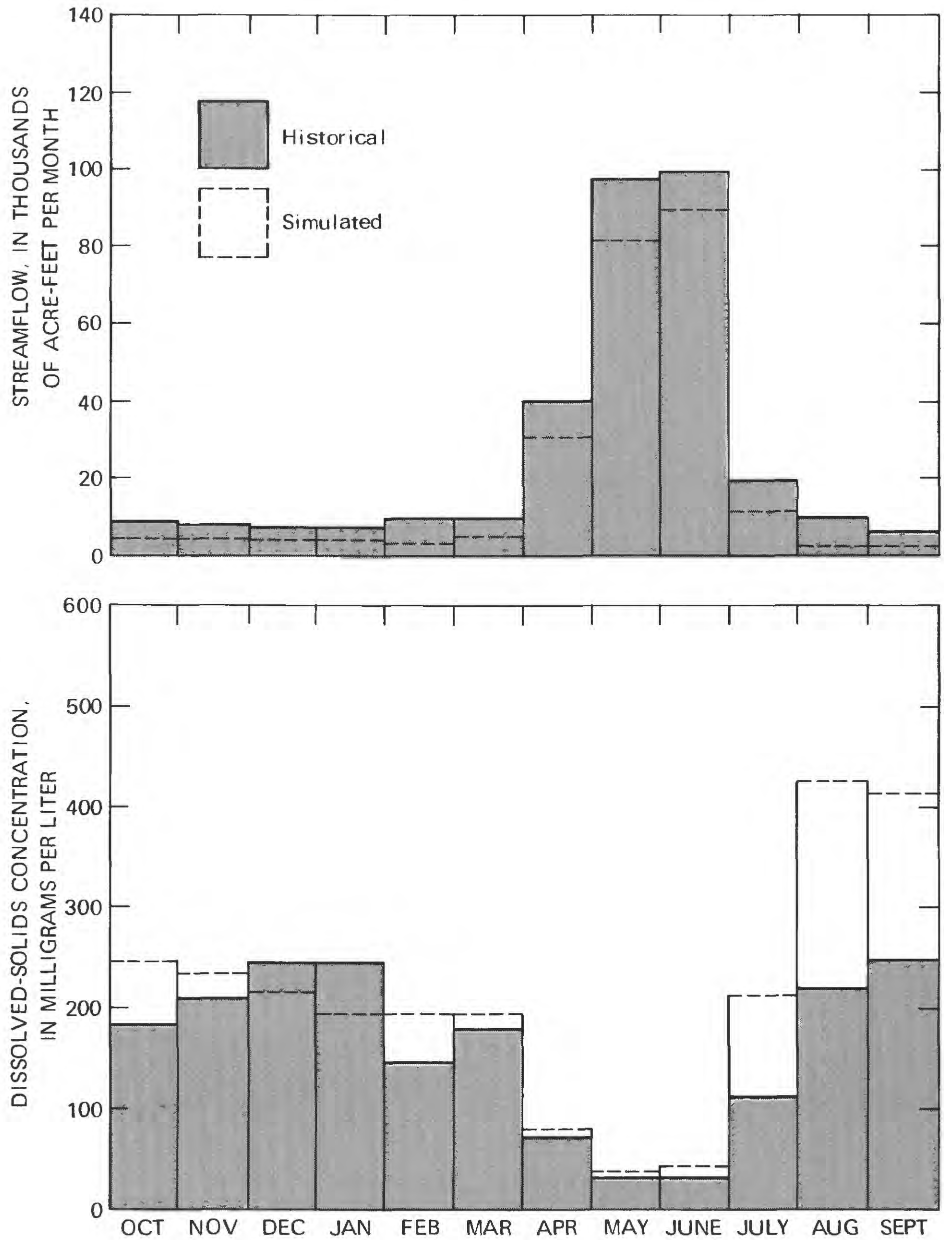


Figure 34.--Comparison of simulated regulated and historical mean monthly streamflow and dissolved-solids concentrations, reservoir-development option 4, water years 1951-69, Yampa River at Steamboat Springs, Colo.

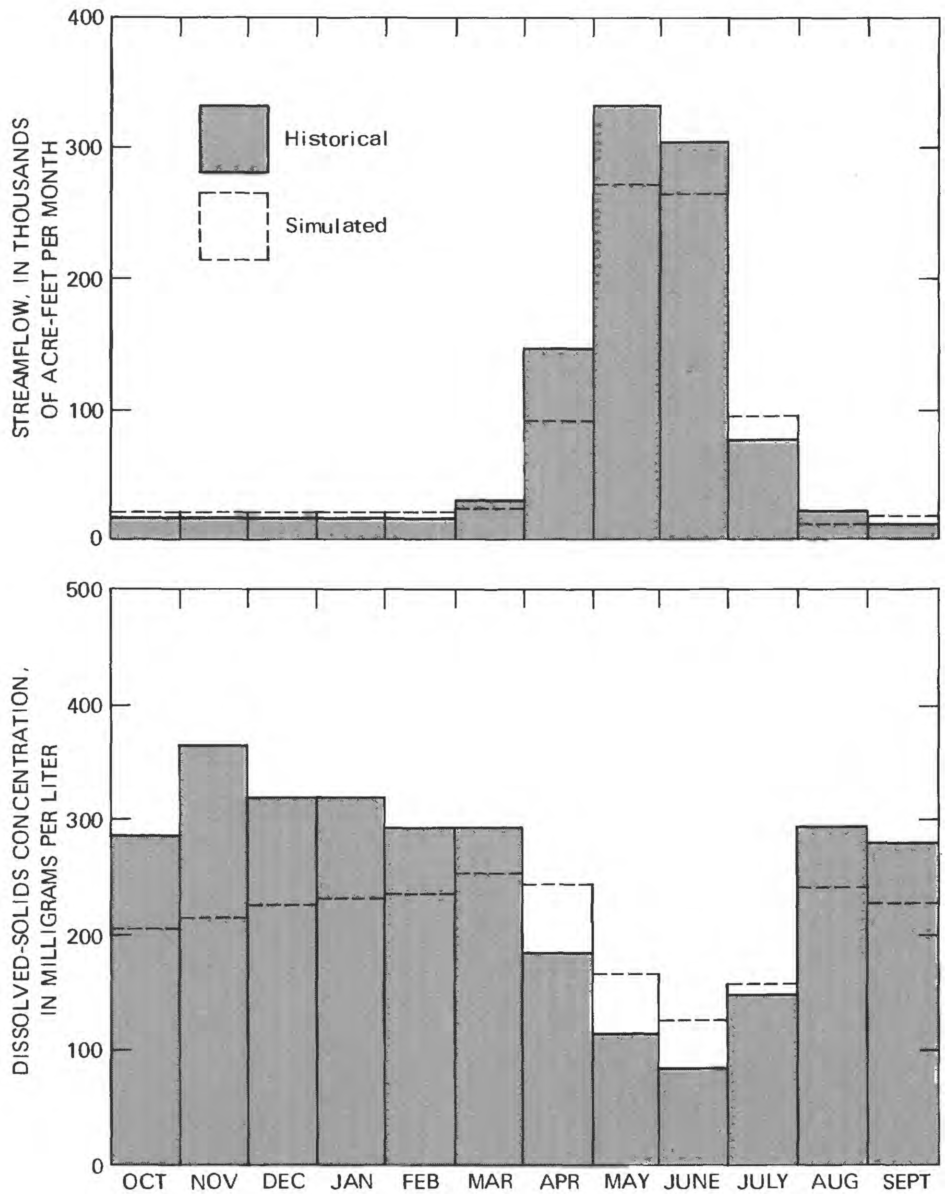


Figure 35.--Comparison of simulated regulated and historical mean monthly streamflow and dissolved-solids concentrations, reservoir-development option 4, water years 1951-69, Yampa River near Maybell, Colo.

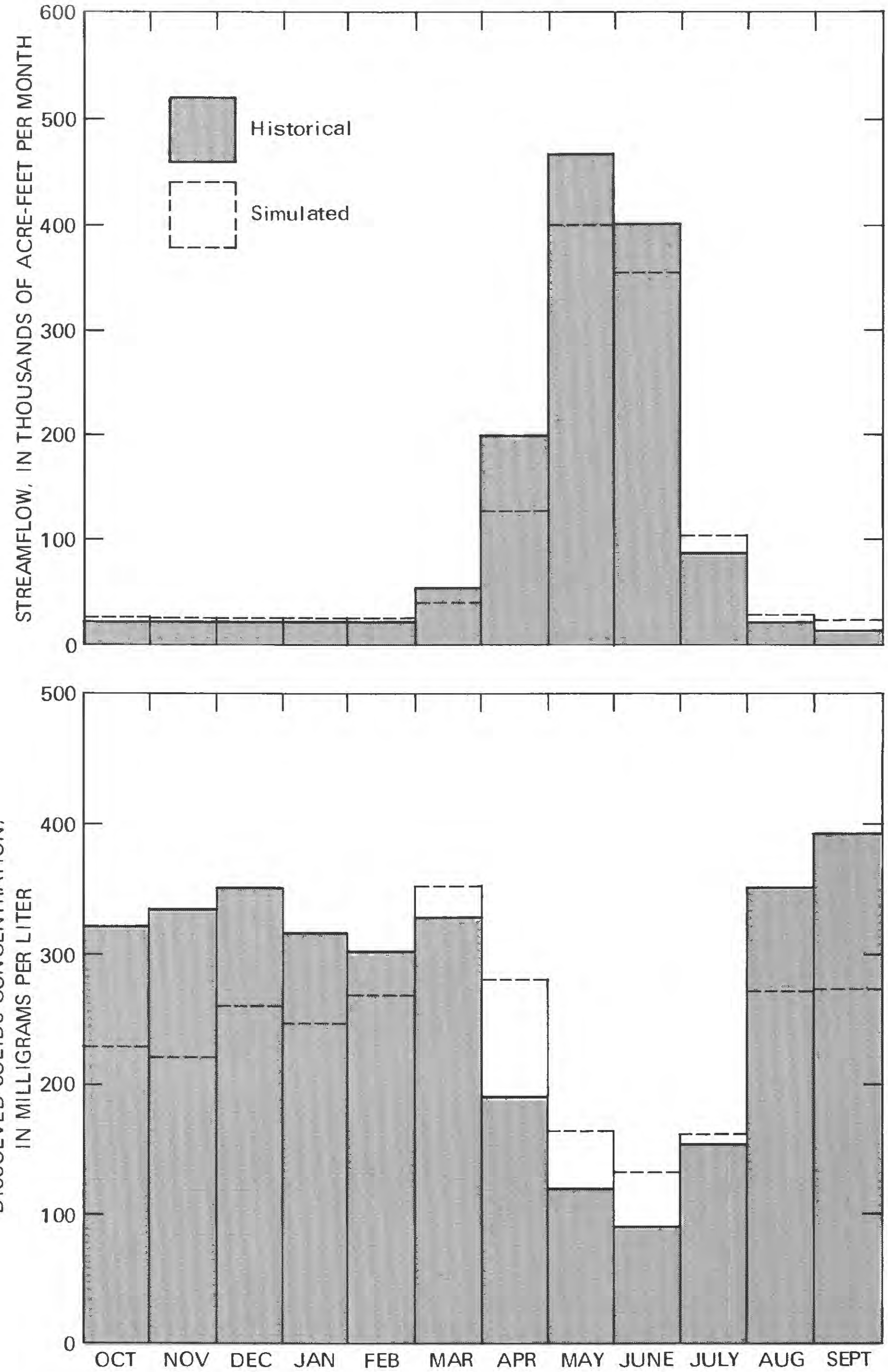


Figure 36.--Comparison of simulated regulated and historical mean monthly streamflow and dissolved-solids concentrations, reservoir-development option 4, water years 1951-69, Yampa River at Deerlodge Park, Colo.

a harmonic-analysis method described by Steele (1974). Temperatures of streamflows that would enter the proposed Juniper and Cross Mountain Reservoirs were from daily water temperatures measured at the streamflow-gaging station, Yampa River near Maybell, Colo.

Model Verification

The single-reservoir simulation model has been verified for the Flaming Gorge Reservoir (Adams, 1975), located on the Green River upstream from its confluence with the Yampa River, and for several other reservoirs. Flaming Gorge Reservoir has been the subject of many water-quality studies by the U.S. Geological Survey (Madison and Waddell, 1973; Bolke and Waddell, 1975; and Bolke, 1979) to determine the ambient water quality and seasonal cycles of the reservoir. Because none of the reservoirs being considered in this study has been constructed, verification was not possible.

Model Simulations

Simulations using the single-reservoir simulation model were made for 3 calendar years: 1966, representing less-than-normal streamflow conditions; 1968, representing normal streamflow conditions; and 1971, representing greater-than-normal streamflow conditions. The simulations were made for March through December when the reservoirs would be relatively ice free. Outflow temperatures were simulated for each reservoir as follows: (1) Outflow temperatures without streamflow regulation from upstream reservoirs; and (2) outflow temperatures with streamflow regulation by upstream reservoirs. Without streamflow regulation, inflow and outflow from each reservoir was assumed to be equal; the reservoir storage was assumed to be constant at full capacity. With streamflow regulation, inflow, outflow, and storage were assumed to vary. Outflow temperatures from deep thermally stratified reservoirs with low elevation discharge penstocks generally would not be less than 4°C (Celsius), the temperature of water at its maximum density. Results of the simulations are shown in figures 37 to 46, with "regulated outflow" denoting streamflow regulation by upstream reservoirs and "unregulated outflow" denoting no streamflow regulation by upstream reservoirs.

Outflow Water Temperatures Without Streamflow Regulation from Upstream Reservoirs

Generally, outflow water temperatures from reservoirs without streamflow regulation from upstream reservoirs (unregulated outflow) would be the warmest of the year in August-September. With the exception of the proposed Yamcolo (fig. 37), Cross Mountain (fig. 44), and Sandstone (fig. 46) Reservoirs, unregulated outflow temperatures generally would be cooler than inflow temperatures from April or May through September. Outflow temperatures at the proposed Yamcolo Reservoir (fig. 37) always would be warmer than inflow temperatures because of the cold inflow temperatures--the coldest of any reservoir--and the solar-heat collection characteristics of the reservoir. Because of the solar energy stored in the water, reservoir releases of outflow temperatures would be warmer than inflow temperatures.

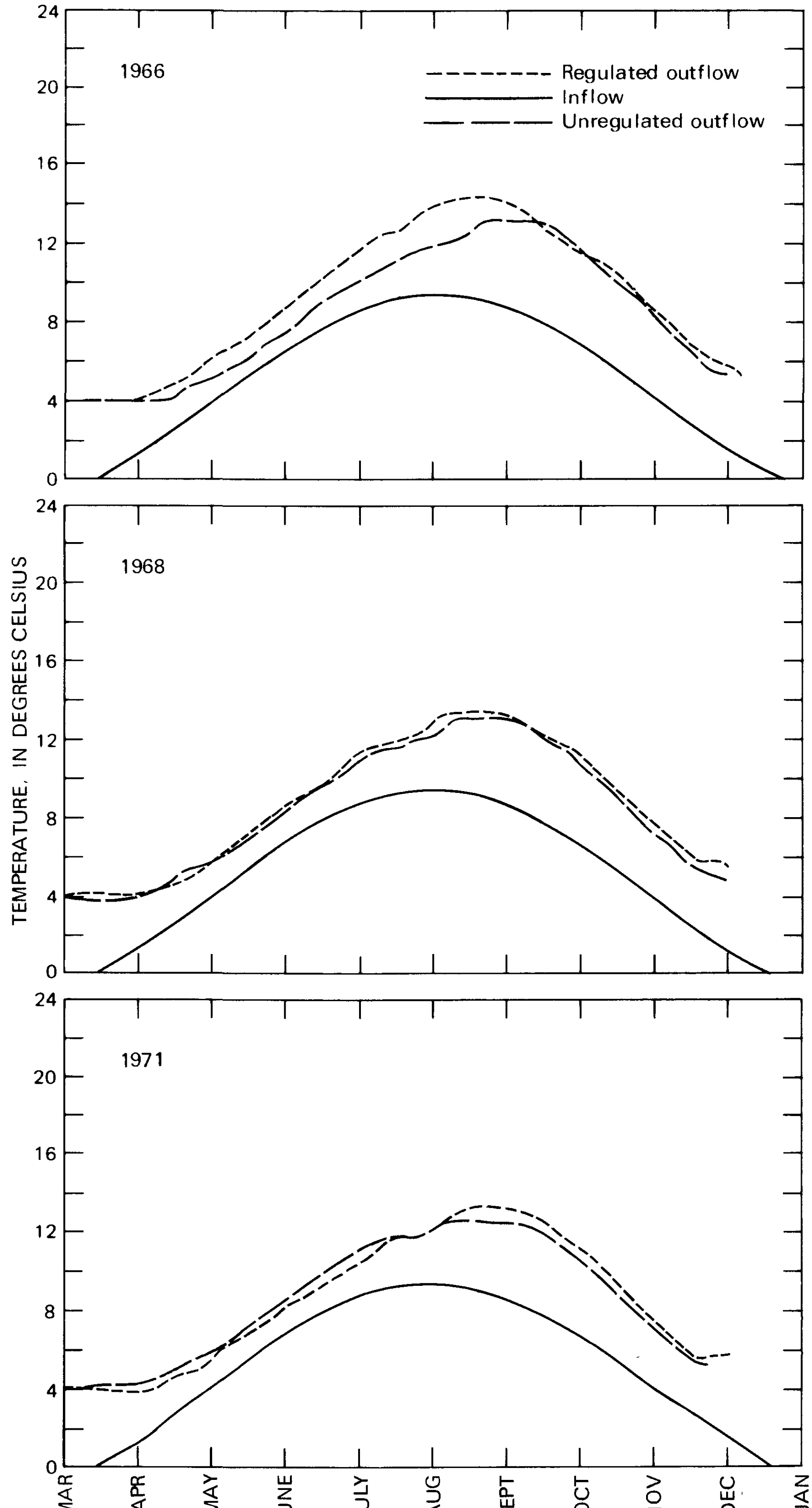


Figure 37.--Simulated temperatures of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Yamcolo Reservoir.

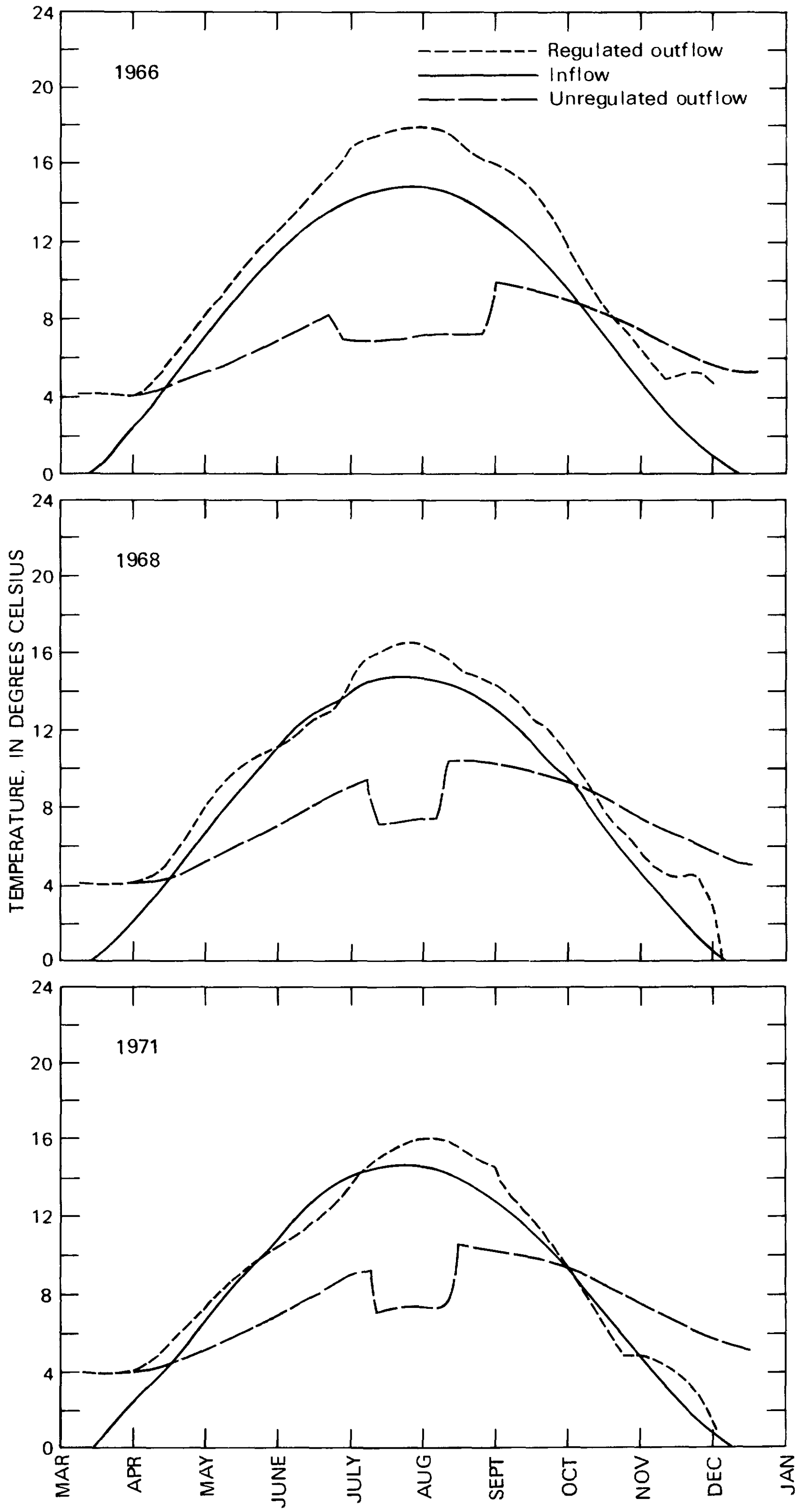


Figure 38.--Simulated temperatures of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Blacktail Reservoir.

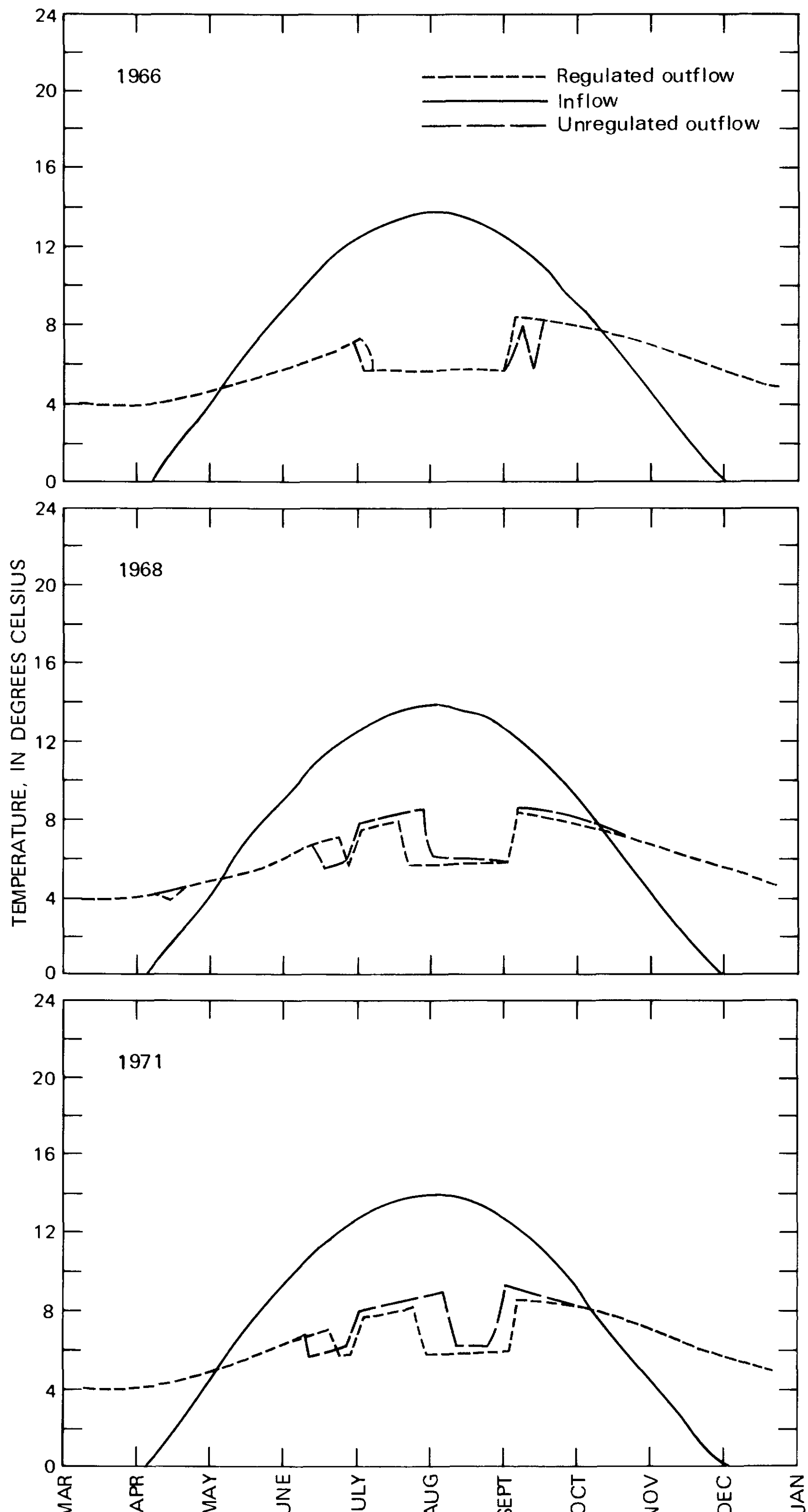


Figure 39.--Simulated temperatures of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Lower Green Creek Reservoir.

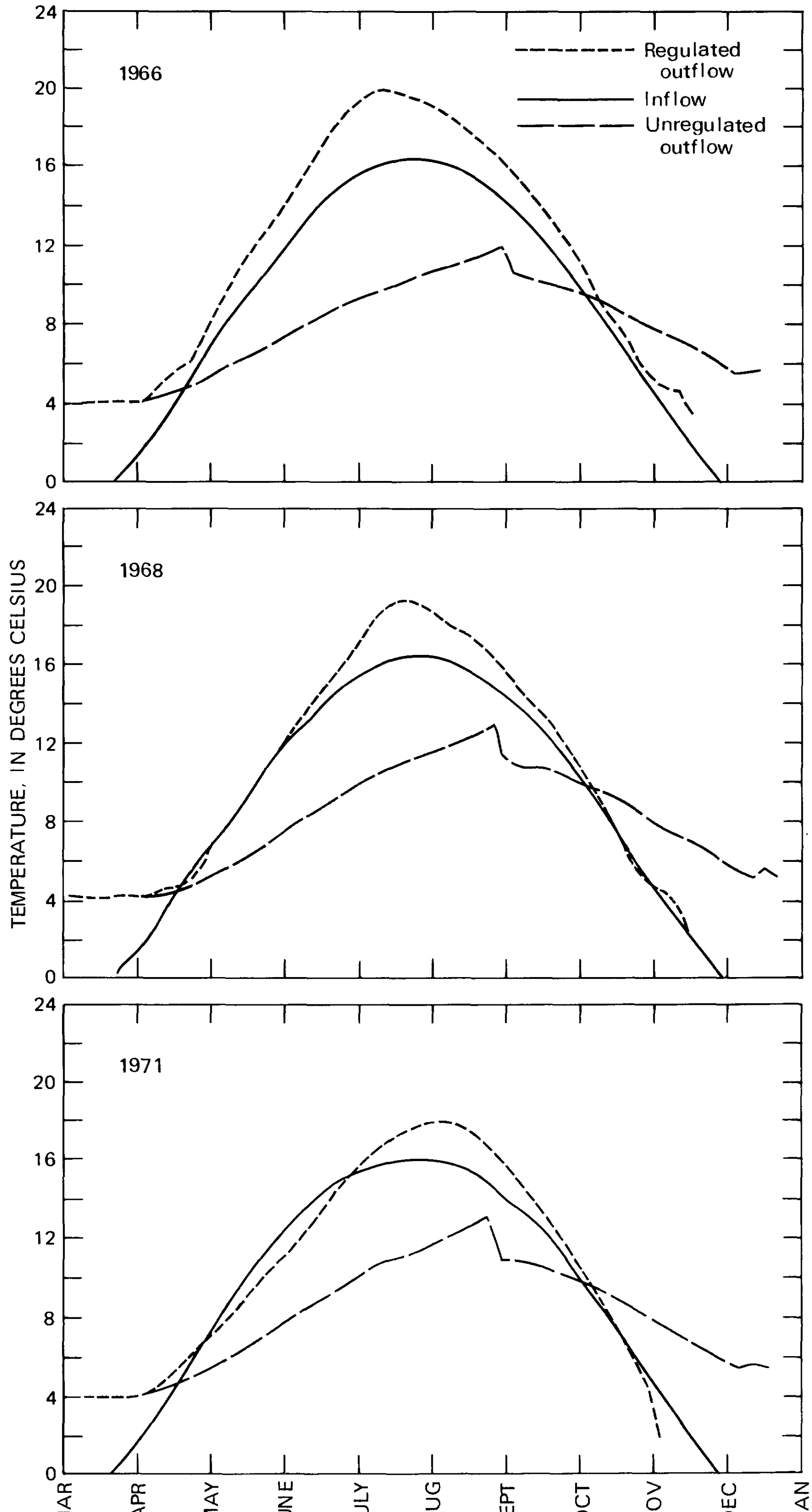


Figure 40. -- Simulated temperatures of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Childress Reservoir.

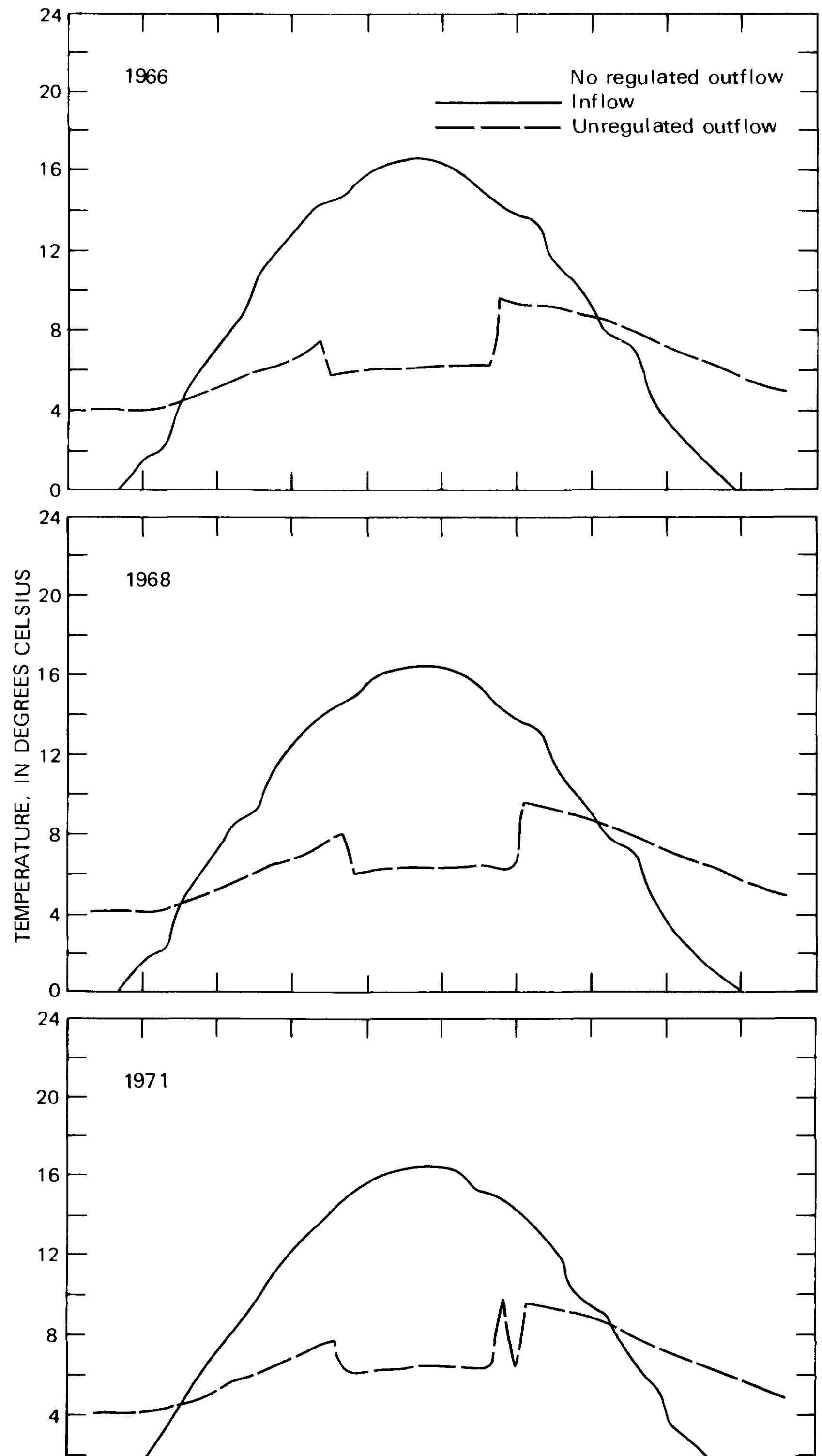


Figure 41.--Simulated temperatures of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Upper Middle Creek Reservoir.

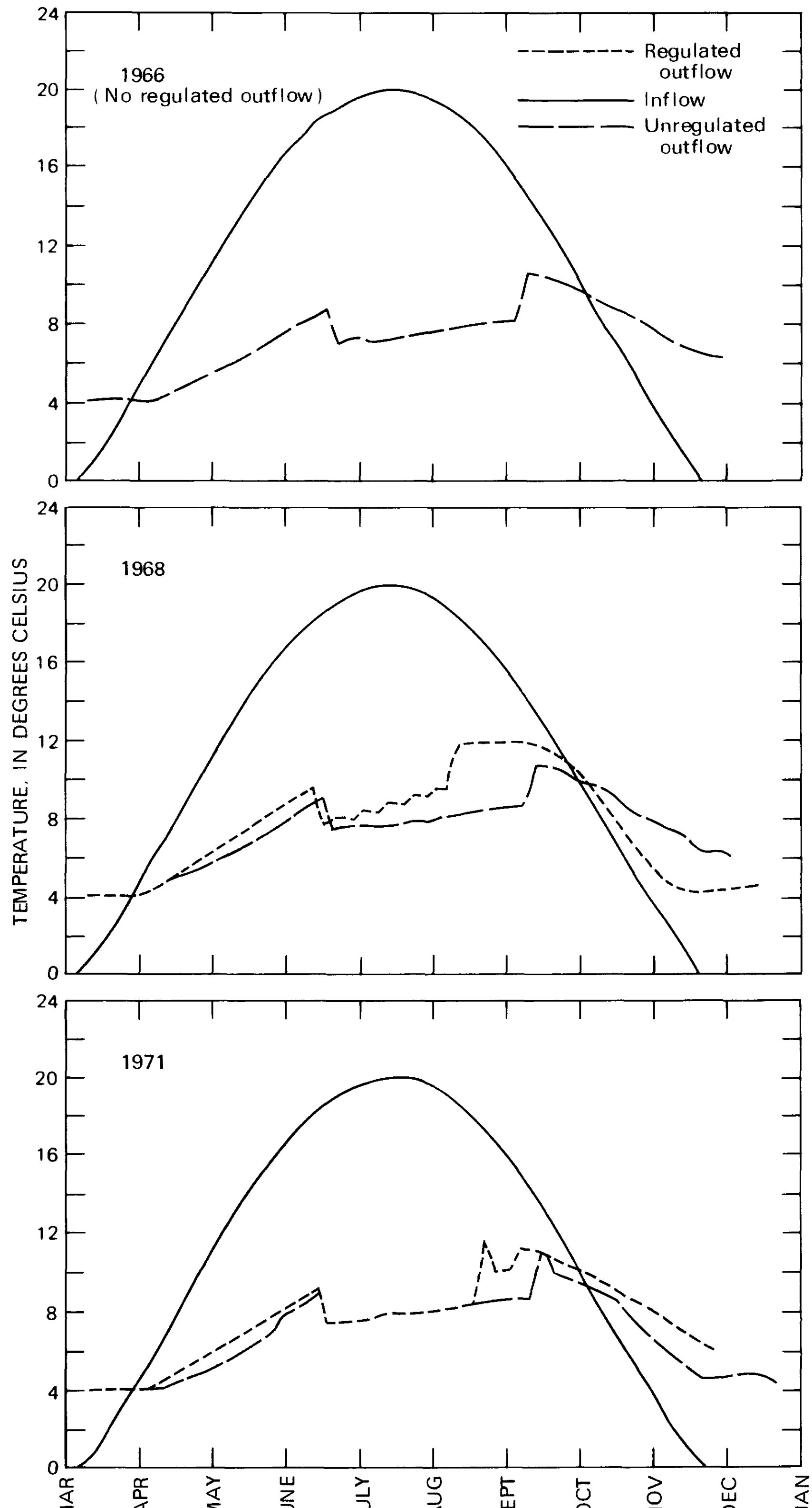


Figure 42. -- Simulated temperatures of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Lower Middle Creek Reservoir.

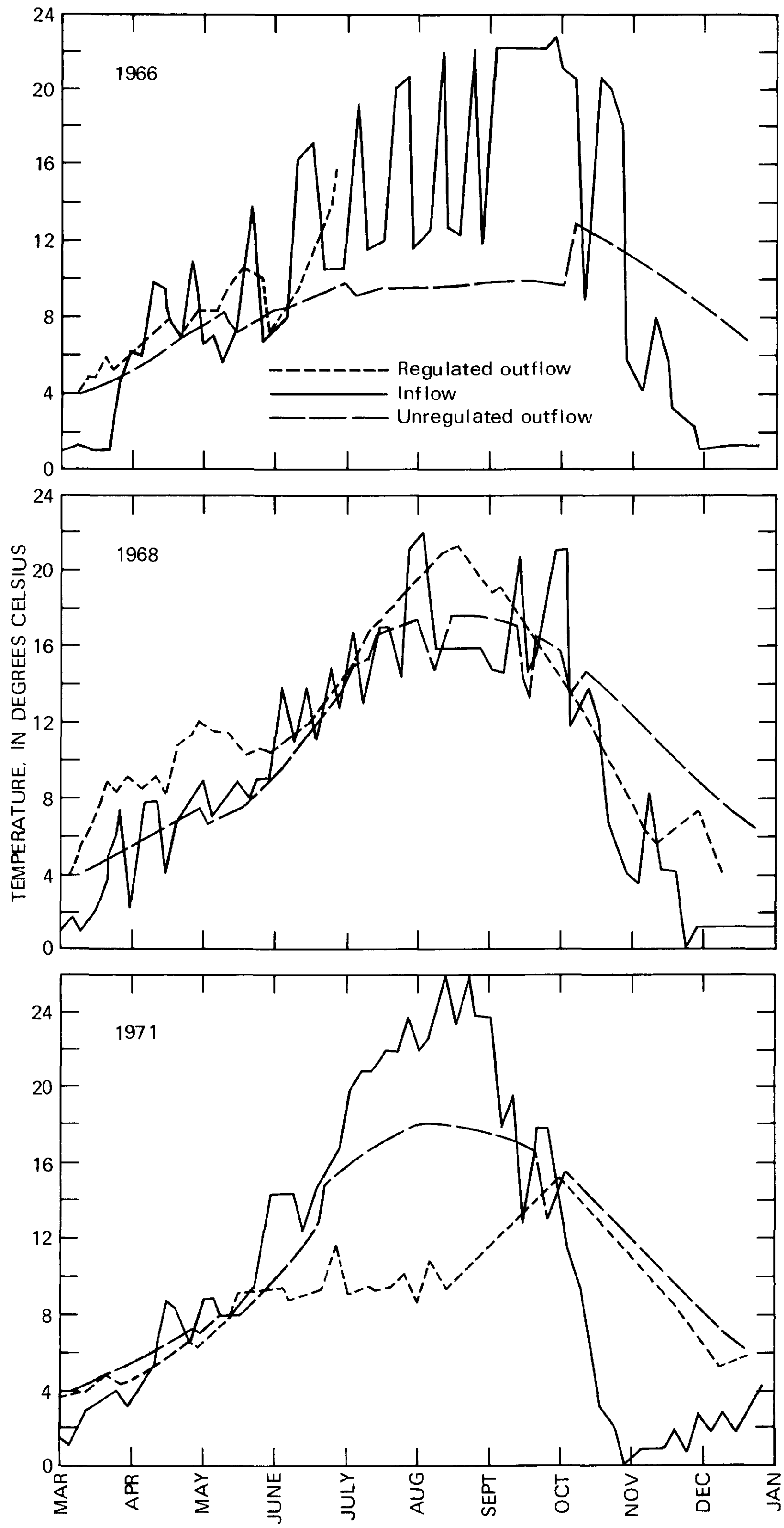


Figure 43. --Simulated temperatures of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Juniper Reservoir.

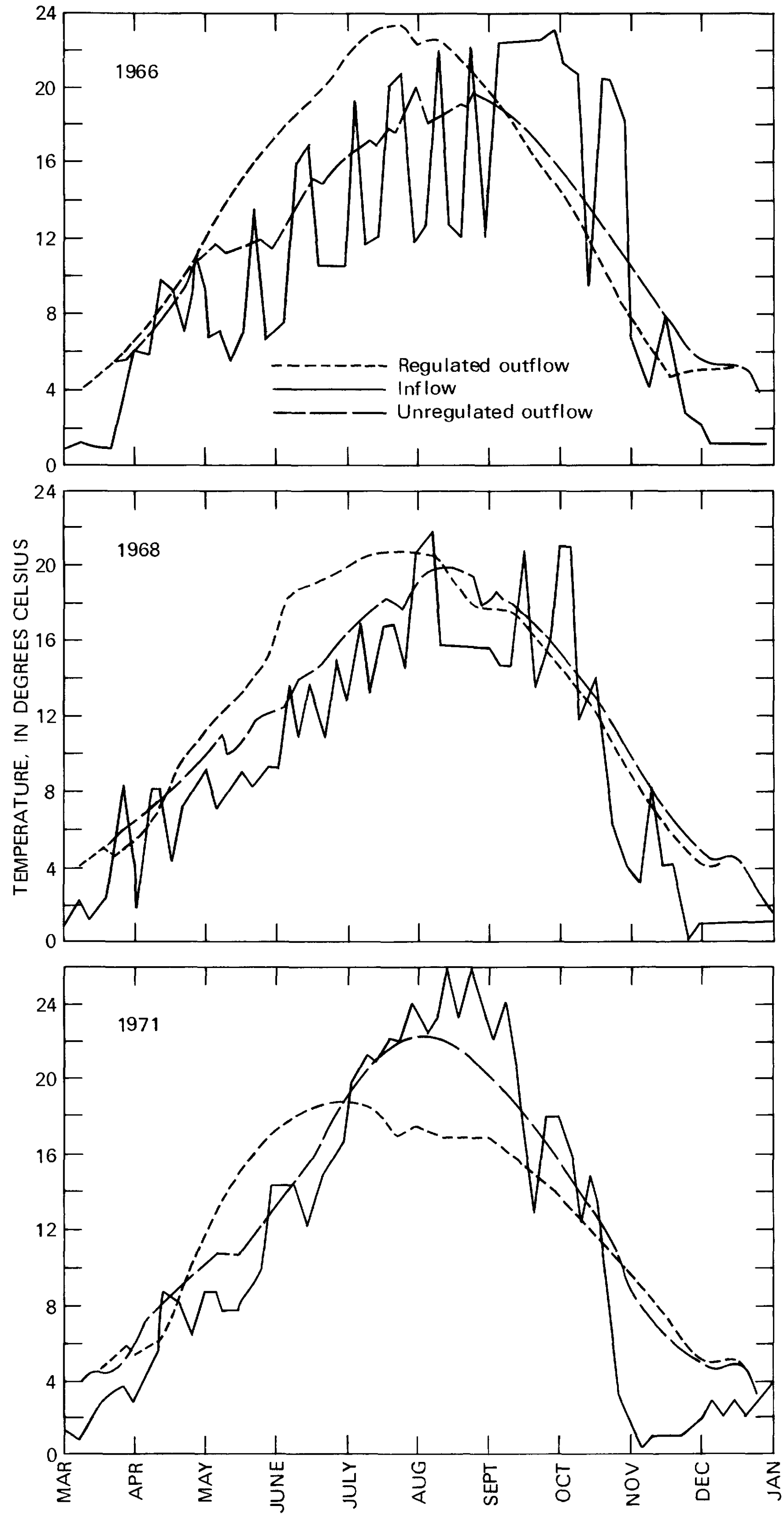


Figure 44.-- Simulated temperatures of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Cross Mountain Reservoir.

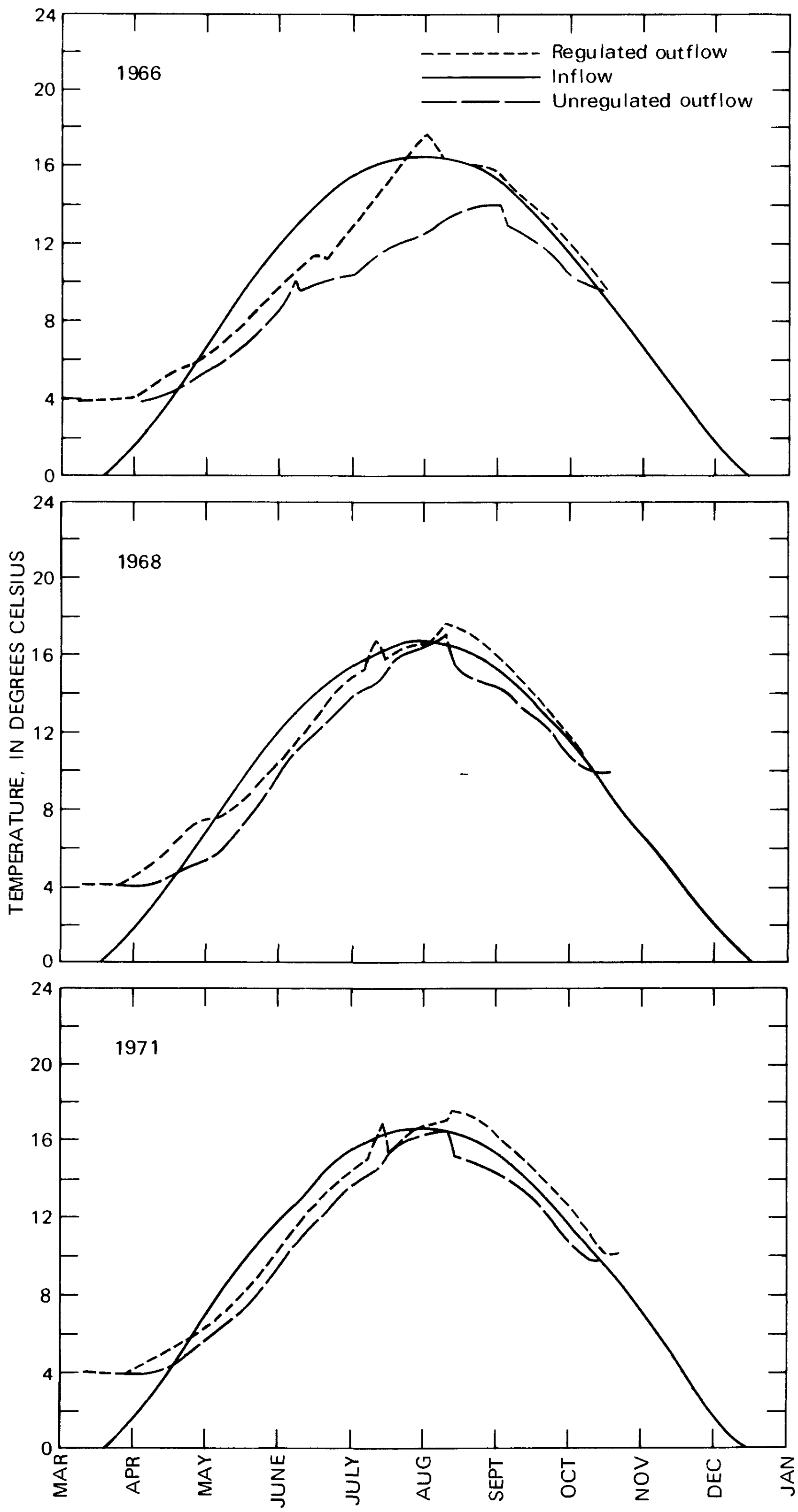


Figure 45.--Simulated temperatures of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Pot Hook Reservoir.

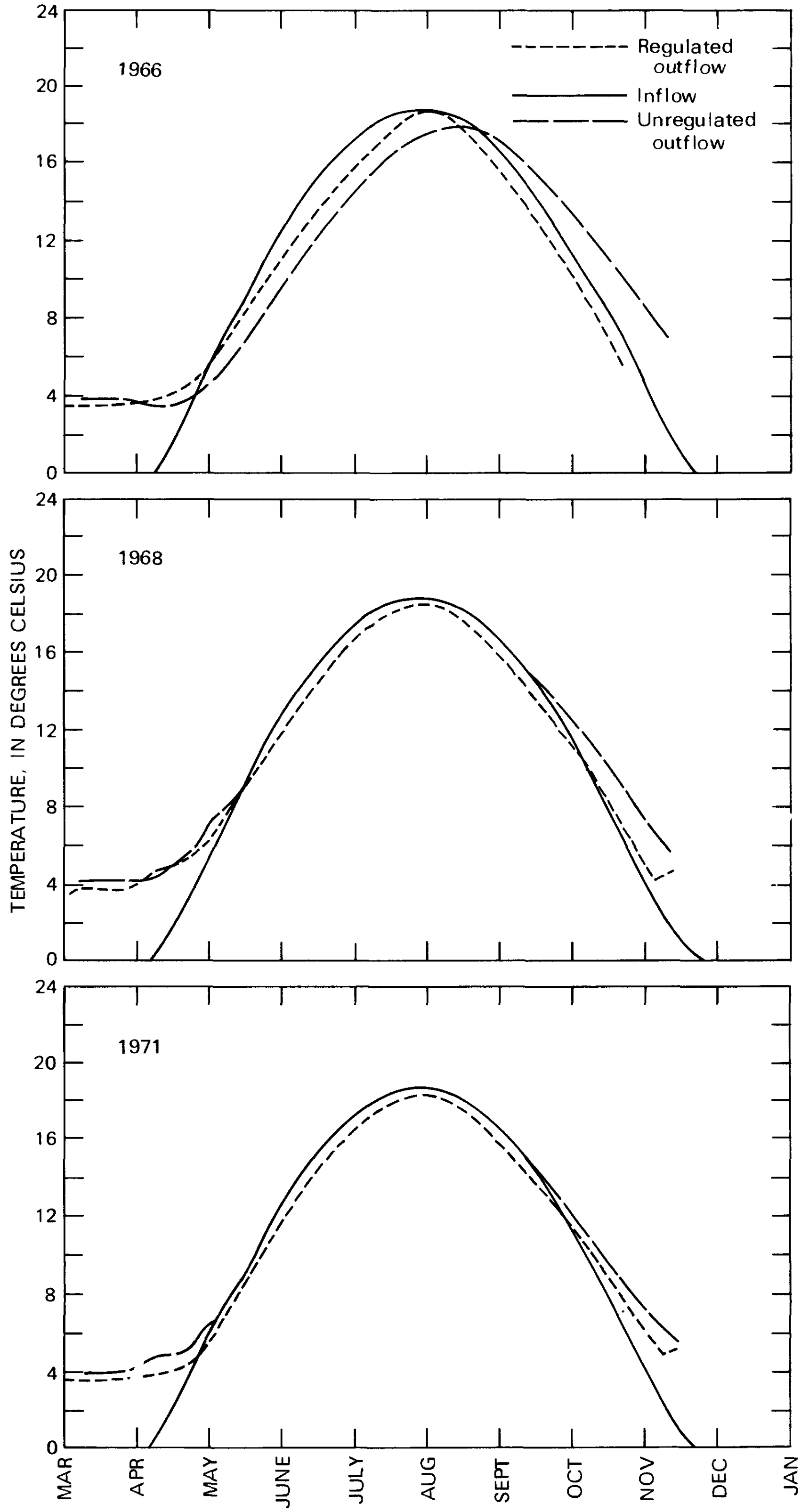


Figure 46.--Simulated temperatures of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Sandstone Reservoir.

Unregulated outflow temperatures for the proposed Blacktail, Lower Green Creek, Upper Middle Creek, Lower Middle Creek, and Juniper Reservoirs (figs. 38, 39, 41, 42, and 43) show discontinuities near the center of the cycles due to the thermocline temporarily rising above the assumed outlet elevation and discharging colder water. This indicates that the reservoir outlet design is critical; further study is warranted in order to reduce the possibility of ecosystem shock by a rapid change in outflow temperature.

Flaming Gorge Reservoir can be used to illustrate the effects on the ecosystem of discharging water with large temperature changes. The difference between water-temperature patterns before and after closure of the dam is shown in figure 47. The colder water temperatures downstream from the dam caused considerable damage to the ecosystem in a reach several miles long, as reported by a local newspaper (Salt Lake Tribune, May 19, 1972) and the U.S. Bureau of Reclamation (written commun., 1976). Modification of the penstock intake was completed in 1977 to rectify the problem (U.S. Bureau of Reclamation, written commun., 1976; Salt Lake Tribune, November 10, 1977).

Outflow Water Temperatures with Streamflow Regulation from Upstream Reservoirs

An essential difference between the models in the regulated and unregulated inflow configuration is that, for the unregulated condition, all reservoirs were modeled with inflow and outflow being equal and storage remaining constant at full capacity, while the regulated condition allows varying inflow, outflow, and storage at each reservoir. This allows stratification in the reservoir to more fully develop in the unregulated system.

Upstream reservoirs that are low in consumptive use, have unregulated inflow, and have regulated outflow show little effect on outflow temperatures. This is illustrated by Yamcolo (fig. 37) and Lower Green Creek (fig. 39) Reservoirs, and, to some extent, by Pot Hook (fig. 45) and Sandstone (fig. 46) Reservoirs.

In several instances outflow temperatures are warmer for the regulated case than for the unregulated case; examples include Blacktail (fig. 38) and Childress (fig. 40) Reservoirs. The specific operating conditions in these instances indicate a very low utilization of the reservoir-storage capacity.

For some cases, there was not sufficient water to allow downstream streamflow; examples include the 1966 less-than-normal calendar year for Lower Middle Creek (fig. 42) and Juniper (fig. 43) Reservoirs. During conditions when water was available for downstream flow, the outflow temperatures would be warmer than the inflow temperatures. Generally, warmer outflow temperatures would occur when only a small percentage of the proposed reservoir capacity would be used, with the result that the water would be more readily heated by solar energy.

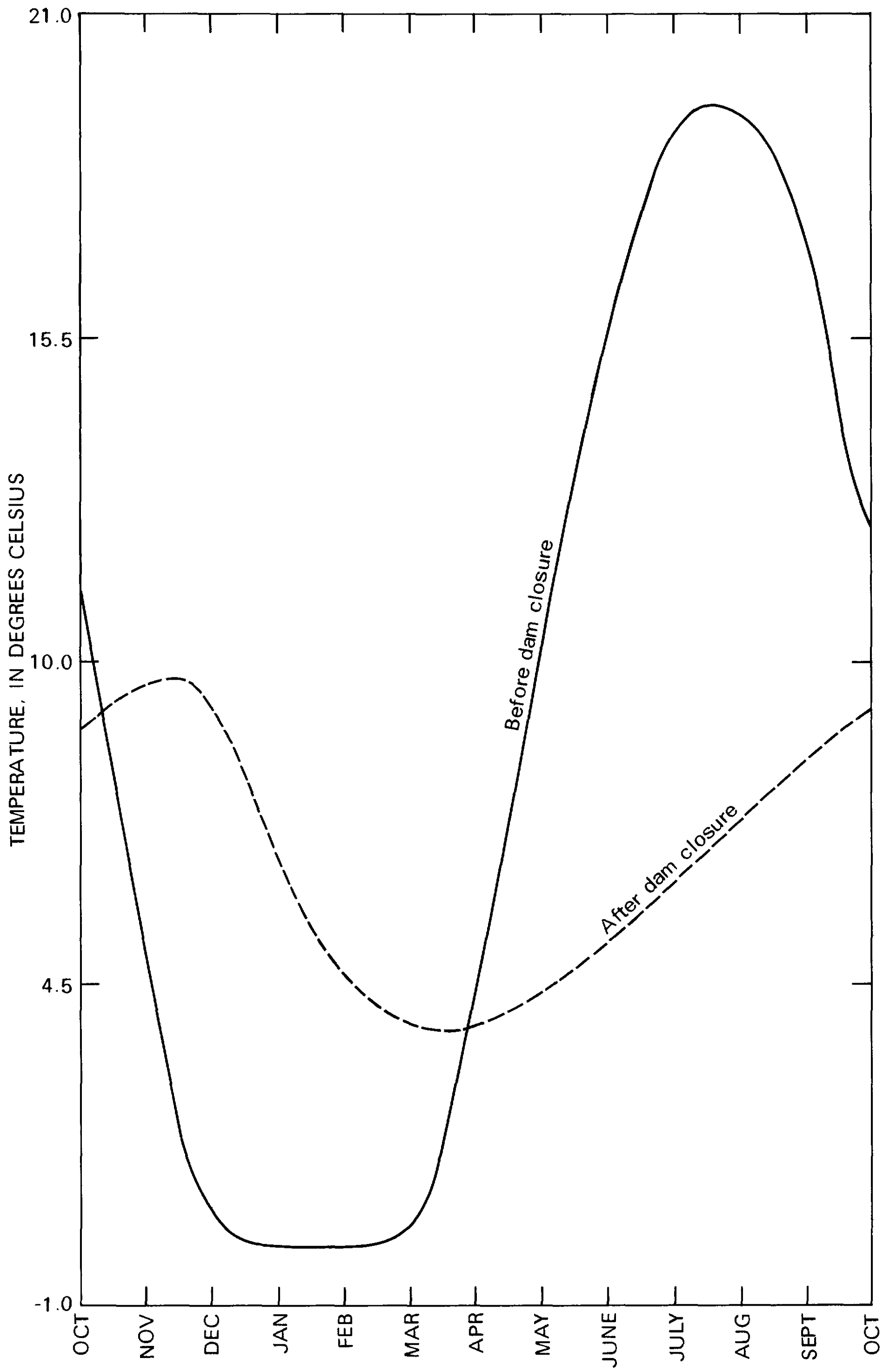


Figure 47.--Mean monthly temperature of the Green River downstream from Flaming Gorge Reservoir before and after closure of the dam (Modified from Bolke and Waddell, 1975).

Model Simulations of Specific Conductance

Specific-conductance values (an indicator of dissolved-solids concentrations) used in the model were representative values based on specific-conductance measurements of streamflow. Specific conductance was modeled as a conservative parameter; that is, it was assumed that there was no increase in dissolved-solids concentrations due to dissolving, leaching, or evaporation, or no decrease in dissolved-solids concentrations due to precipitation. Also, specific-conductance values were not routed from an upstream reservoir to a downstream reservoir in the single-reservoir simulation model. Streamflows used in the model were those simulated using the multireservoir-flow model for reservoir-development option 2.

Values of specific conductance in a reservoir usually stabilize and show little variation in a vertical profile, except for a slight increase with depth due to density differences (Adams, 1976). Specific-conductance values for outflow from stable reservoirs are therefore relatively constant. Therefore discontinuities in discharge temperature, such as those in figures 38, 39, 41, 42, 43, and 44, do not significantly affect the outflow values of specific conductance.

Specific conductance of water in a reservoir generally will be different from that of water in a stream only when the reservoir is relatively large and is operated at near full storage capacity. Of the 10 proposed reservoirs in reservoir-development option 2 only four--Yamcolo, Pot Hook, Sandstone, and Childress--would be operated at near capacity.

Outflow Specific-Conductance Values without Streamflow Regulation from Upstream Reservoirs

The general effect of a reservoir on a stream system is to act as a damper; that is the seasonal variation of specific-conductance values in outflows would be uniform compared with specific-conductance values of the inflows. This is demonstrated by the simulation results for Yamcolo, Pot Hook, Sandstone, and Childress Reservoirs (figs. 48 to 51). This is a "smoothing" and "shifting" of specific-conductance values and is characteristic of reservoirs with short detention times. During years with less-than-normal streamflow (illustrated by the data for 1966), maximum specific-conductance values in the outflow could be about 67 percent of the maximum inflow values, and minimum values in the outflow could be about 230 percent of the minimum inflow values. During years with greater-than-normal streamflow (illustrated by the data for 1971), maximum specific-conductance values in the outflow could be about 65 percent of the maximum inflow values, and minimum values in the outflow could be about 300 percent of the minimum inflow values.

Outflow Specific-Conductance Values with Streamflow Regulation from Upstream Reservoirs

The regulated flow condition shows varied responses resulting from the regulation of the proposed reservoirs. The results range from no outflow at all in Upper Middle Creek Reservoir for the 1966 calendar year to responses similar to the unregulated flow condition demonstrated by Pot Hook and Sandstone Reservoirs (figs. 49 and 50).

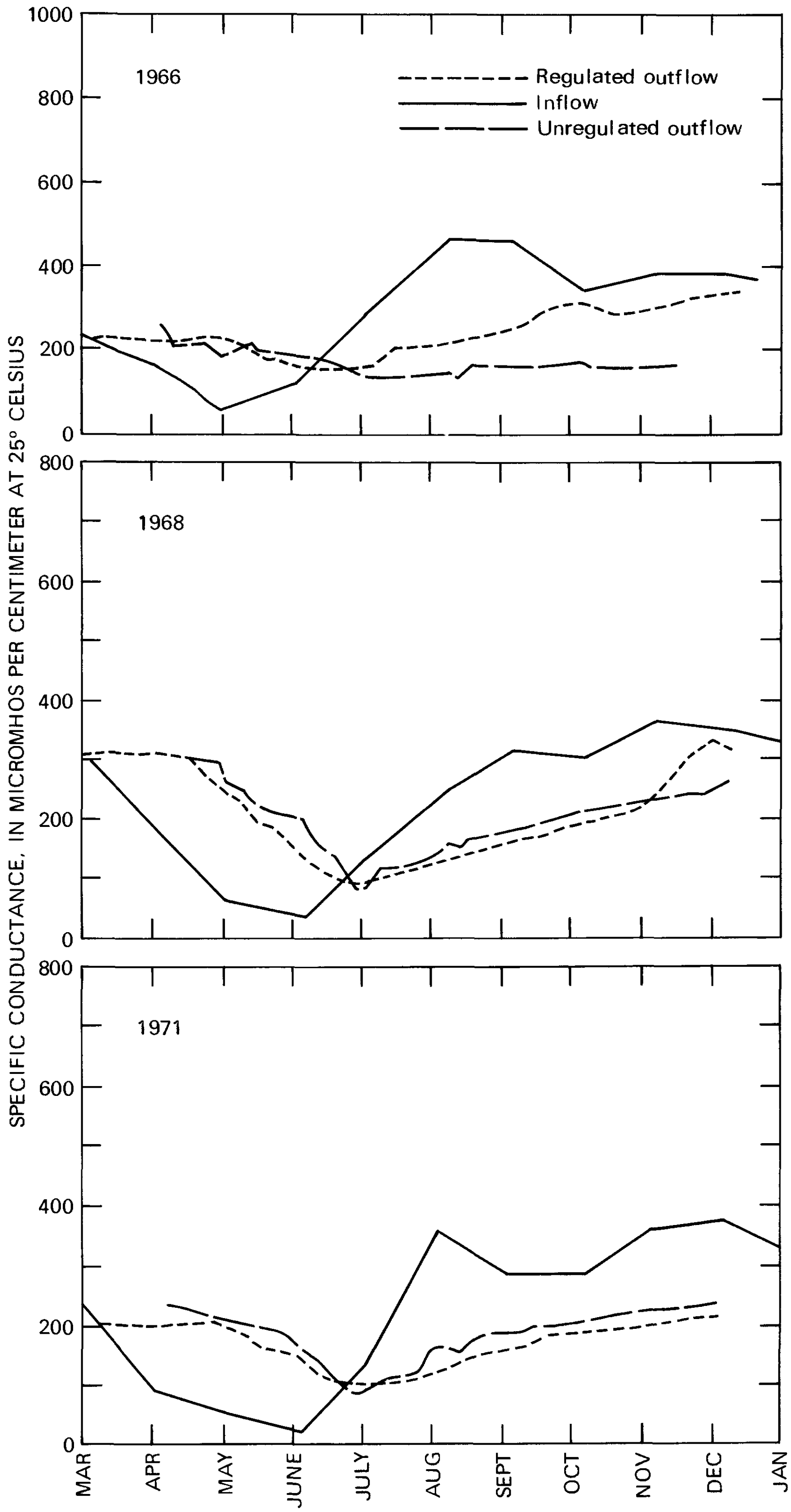


Figure 48.--Simulated specific-conductance values of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Yamcolo Reservoir.

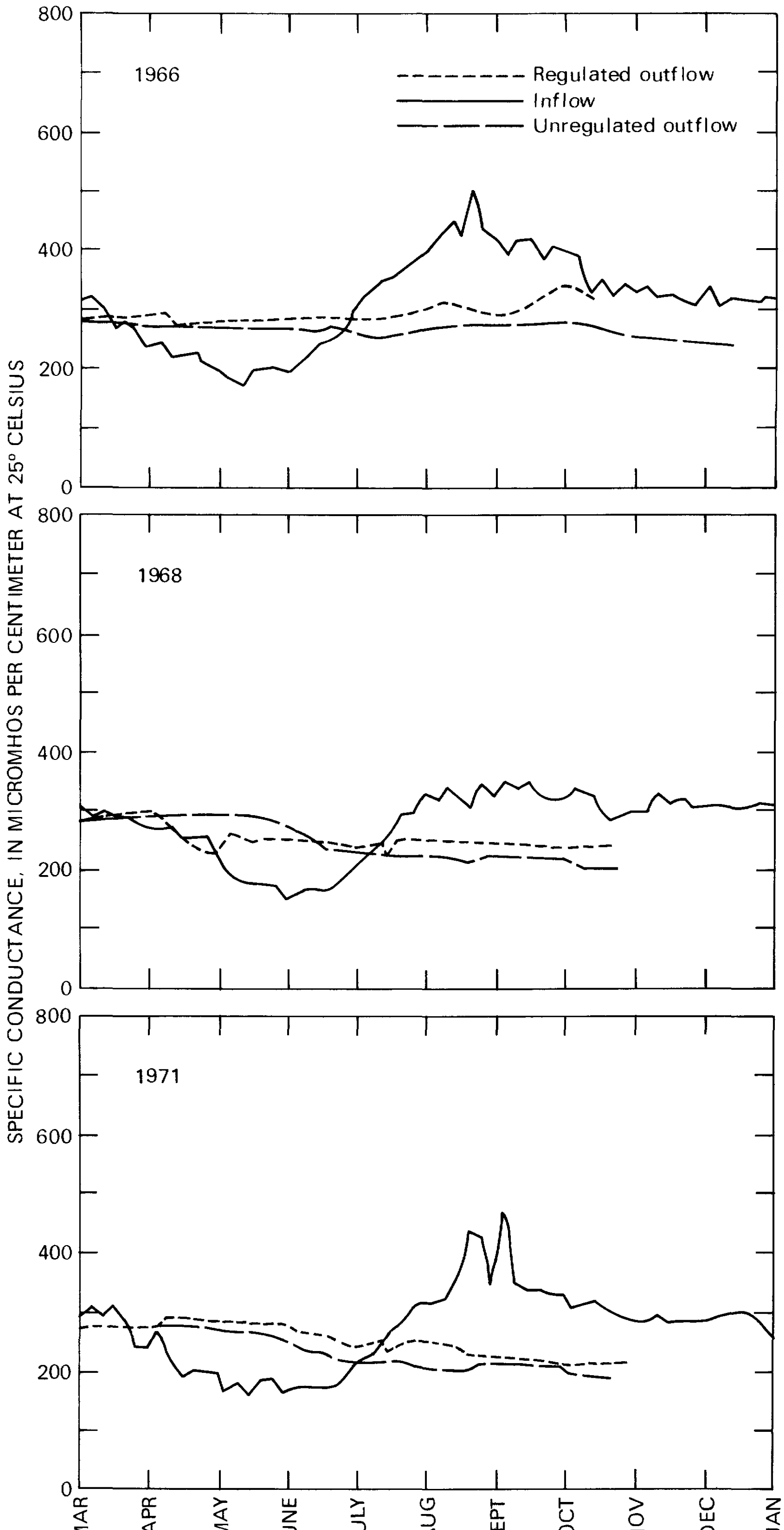


Figure 49. -- Simulated specific-conductance values of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Pot Hook Reservoir.

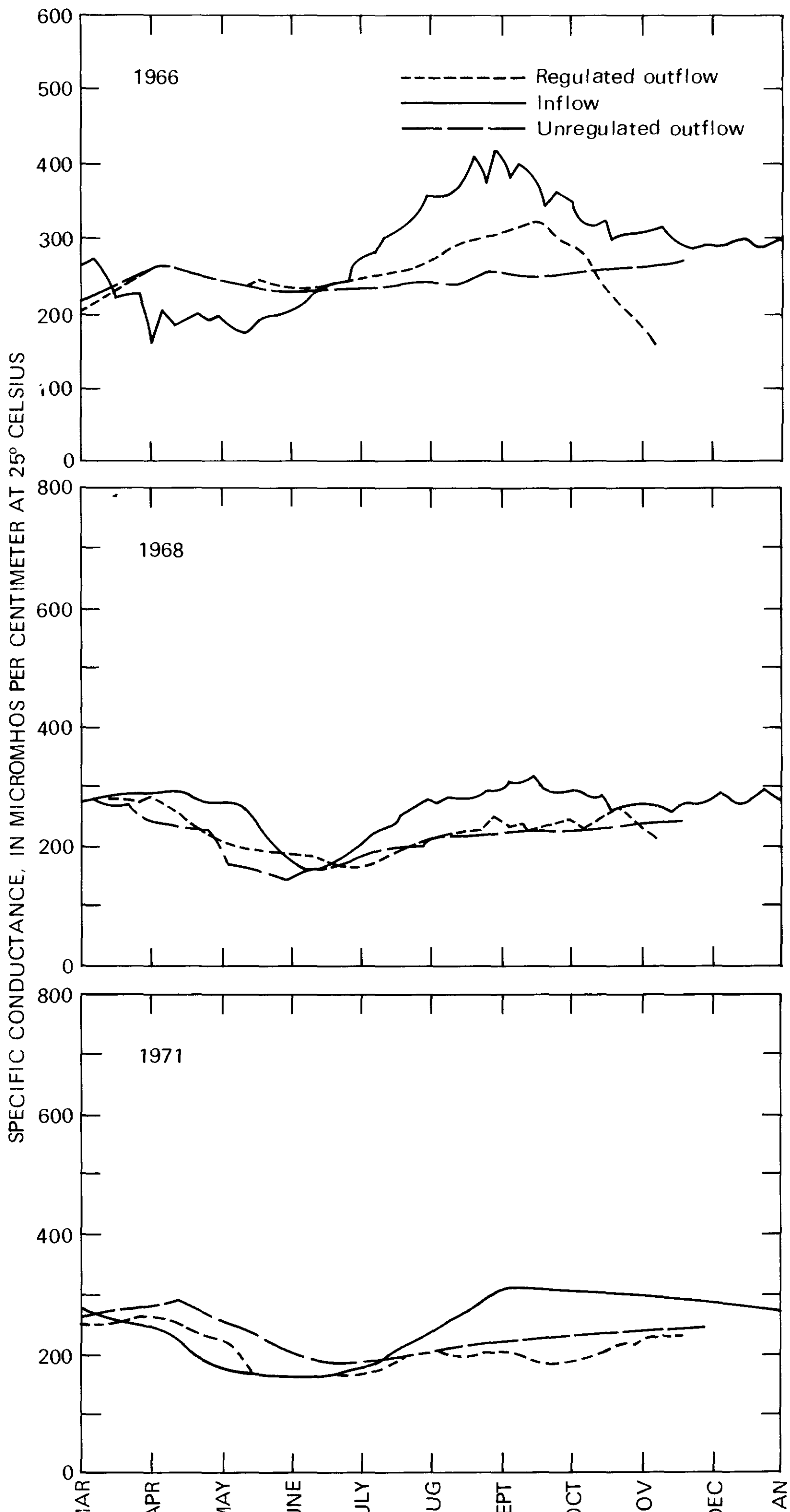


Figure 50.--Simulated specific-conductance values of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Sandstone Reservoir.

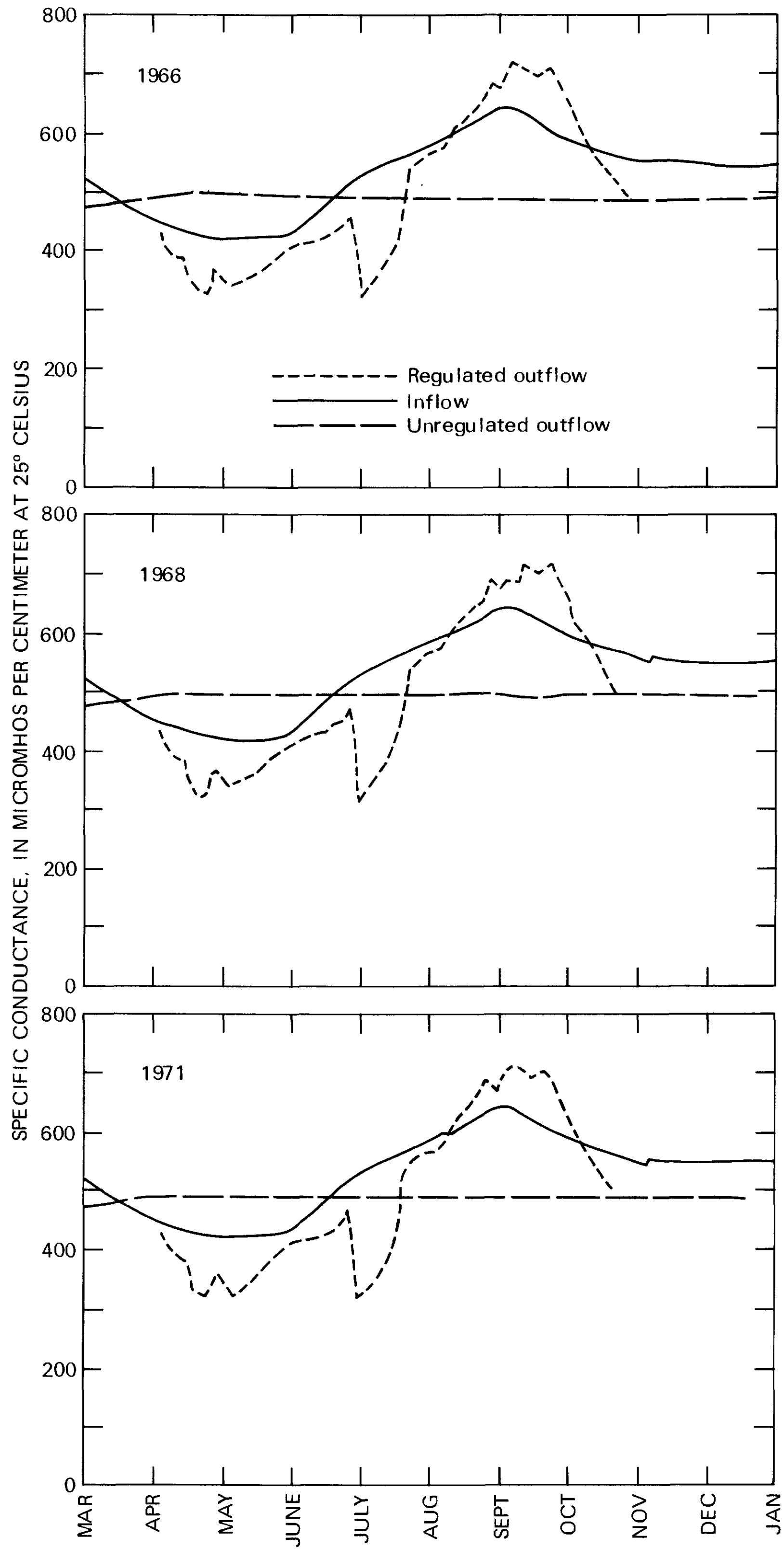


Figure 51.--Simulated specific-conductance values of inflow and outflow with and without streamflow regulation from upstream reservoirs, 1966, 1968, and 1971, Childress Reservoir.

Most reservoirs with upstream regulation show outflow specific-conductance values that follow closely the inflow values, indicating a low detention time as a result of little use of storage capacity. This is illustrated by Childress Reservoir (fig. 51), which has use of less than 37 percent of capacity for the regulated streamflow condition; the unregulated streamflow condition assumed 100 percent of capacity utilization. Because of insufficient reservoir storage, limited information can be given about the specific-conductance effect of the reservoirs under the basin-operating plans used.

As stated previously, the general effect of a reservoir on a stream system is to dampen the specific-conductance inflow values to a relatively narrow range. Yamcolo, Sandstone, and Pot Hook Reservoirs (figs. 48 to 50) show these specific-conductance discharge patterns. These are characterized by Yamcolo Reservoir, which exhibits a 74-percent decrease in the range of specific-conductance values for the regulated flow condition and 67-percent decrease for the unregulated flow condition from inflow values for 1966, the dry demonstration year. For 1971, the wet demonstration year, the range of reductions in specific-conductance outflow values is 68 percent for the regulated flow condition and 52 percent for the unregulated flow condition.

SUMMARY

Multireservoir-Flow Model

The comparison of the simulated historical and measured mean annual discharges indicated good agreement, within 5 percent, for the Yampa River at Steamboat Springs and Little Snake River near Lily, and only fair agreement, within 20 percent, for the Yampa River at Craig and Yampa River near Maybell. Numerous small unmeasured irrigation diversions and tributaries exist along the downstream portion of the Yampa River; these effects could only be approximated in the multireservoir-flow model analysis.

The multireservoir-flow model incorporated four reservoir development options and two proposed transmountain diversions--Vidler Tunnel (Sheephorn) on tributaries of the Yampa River and Hog Park on the Little Snake River. In many cases the desired amounts of transmountain diversions could not be met. Transmountain diversion shortages at the proposed Vidler Tunnel location occurred from 70 to 77 percent of the time with reservoir-development options 2, 3, and 4; whereas, the Hog Park diversion showed shortages an average of 20 percent of the time.

In many cases the projected within-basin irrigation or industrial uses could not be met because of reservoir-storage requirements. The greatest amounts and percentages of times occurred for the irrigation diversion at Juniper Reservoir and the industrial diversion at Blacktail Reservoir for development options 2 and 3. The maximum shortage at Juniper Reservoir was 5,032 ft^3/s (143 m^3/s), and monthly shortages ranged from 18 to 32 percent of the time. The maximum industrial shortage at Blacktail Reservoir was 130 ft^3/s (3.68 m^3/s), and monthly shortages ranged from 85 to 93 percent of the time.

For several locations within the Yampa River basin, arbitrary desired-flow values have been set. A desired flow of 750 ft^3/s (21.2 m^3/s) was selected for the Deerlodge Park location. This desired flow was established primarily on the basis of a regulated 690-ft^3/s (19.5-m^3/s) flow by the Colorado River Compact of 1948 at the Yampa River near Maybell location and Little Snake River drainage input. With this criterion, the multireservoir-flow analysis indicated flow shortages could occur from 16 to 60 percent of the time for the Deerlodge Park location.

A reservoir frequency analysis also was made for selected reservoir storage levels at selected reservoir control points. In most cases, results indicated the reservoirs to be operating at low percentages of the total reservoir-volume capacities. In some cases, the reservoirs were operating at less than 20 percent of the conservation pool. The Blacktail Reservoir, for example, operated at all times at less than 20 percent of the conservation pool and at least 50 percent of the time at less than 1 percent of the conservation pool.

Dissolved-Solids Model

For reservoir-development option 1 simulation, the only notable effect on the Yampa River at Steamboat Springs is a decrease in dissolved-solids concentrations during August and September caused by increased flow augmentation from reservoir storage during this low-flow period. In the Yampa River downstream from the proposed Juniper-Cross Mountain Reservoir complex, the historical flow is approximately twice the simulated regulated flow during April to August each year. This is due largely to losses from upstream irrigation flows. Computed dissolved-solids concentrations downstream from this location could then decrease from a range of 150 to 940 mg/L for the historical condition to a range of 320 to 640 mg/L for the simulated regulated configuration.

For reservoir-development option 2 simulations, the effects in the Yampa River downstream from the Juniper-Cross Mountain Reservoir complex would be essentially the same as noted for reservoir-development option 1. Under the assumptions of this reservoir-development option, the maximum flow of the Yampa River downstream from the confluence of the Yampa and the Little Snake Rivers could be reduced from 460,000 acre-feet (56.8 hm^3/s) per month to 250,000 acre-feet (30.8 hm^3/s) per month. The dissolved-solids concentrations could average 60 percent greater for the simulated regulated reservoir-development option 2.

For the simulation run of reservoir-development option 4, dissolved-solids concentrations in the Yampa River near Maybell, Colo., could be reduced about 55 percent over reservoir-development option 2 regulation. For the Yampa River at Deerlodge Park, Colo., the dissolved-solids concentrations could range from about 90 to 390 mg/L for the historical flow and from about 130 to 350 mg/L for the simulated regulated reservoir-development option 4 conditions.

Single-Reservoir Simulation Model

Reservoir stratification development did occur for the unregulated inflow-condition analysis. However, reservoir stratification did not occur for the regulated inflow-condition analysis due to the small utilization of reservoir storage. For the unregulated outflow condition--outflow water temperatures without streamflow regulation from upstream reservoirs--the outflow discharge patterns indicated a reduced range of temperatures for all reservoirs except Yamcolo, which showed increased temperatures in the outflow. For example, the estimated range of inflow temperatures for an upstream reservoir, such as Lower Green Creek Reservoir, could vary from 0°C to 14°C, while outflow temperatures could range from 4°C to about 9°C. For a reservoir at lower elevation, such as Juniper Reservoir, the inflow temperatures ranged from 0°C to about 26°C; whereas, unregulated outflow temperatures ranged from 4°C to about 18°C. These estimated temperature-discharge patterns would vary with inflow and outflow discharges and with outlet elevation and design.

The effect of reservoirs and stratification on specific conductance under either regulated or unregulated flow conditions would be to mix the waters and smooth out the seasonal variability of the values of inflow specific conductance. Yamcolo Reservoir, for example, would have estimated inflow specific conductance ranging from about 50 to 450 micromhos and outflow values ranging from 80 to 350 micromhos.

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