Hydrology of Hungry Horse Reservoir, Northwestern Montana

By W. D. SIMONS *and* M. I. RORABAUGH

GEOLOGICAL SURVEY PROFESSIONAL PAPER 682

Prepared in cooperation with the
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By W. D. SIMONS and M. I. RORABAUGH

ABSTRACT

Hungry Horse Project, on the South Fork Flathead River in northwestern Montana, is an important element in the comprehensive water-resources-development plan for the Columbia River basin. It is used primarily for at-site and downstream power generation and local and downstream flood control. Hungry Horse Reservoir has a usable storage capacity of 2.98 million acre-feet for at-site production of electrical energy. Previous studies have indicated that there may be an additional increment of ground-water storage in the permeable bed and banks of the reservoir that responds to changes in reservoir elevation. This is referred to as bank storage.

The existence of an additional amount of usable bank storage was established by a comprehensive water-budget analysis of Hungry Horse Reservoir for the period October 1964–April 1967. A theoretical model of the response of the aquifer adjacent to Hungry Horse Reservoir to changes in reservoir stage was developed. The constants used in the mathematical equations were based on the residuals from the water-budget computations.

A wide range of potential solutions is possible when the water-budget and model methods are used separately. But when they are used in conjunction with each other, the range of potential solutions can be reduced and a most probable solution inferred. The model solution, when used to predict additional water supplies available during drawdown periods or when used to adjust historical records for general hydrologic studies, is expected to give results which are within 25 percent of the true values of the bank-storage component.

The selected solution indicates that the ground-water storage in the alluvium adjacent to Hungry Horse Reservoir is 108,000 cfs-days between the elevations of 3,336 and 3,560 feet above mean sea level. This amount of added storage is not totally available as reservoir inflow under normal patterns of regulation because of the time-lag and hysteresis-loop effects of ground-water movement across the interface between the aquifer and the reservoir.

The computed additional inflows to Hungry Horse Reservoir from bank storage during the three drawdown periods studied are 34,000, 20,000, and 43,000 cfs-days. The amounts of ground-water inflow average about 60 percent of the corresponding ground-water storage. These are believed to be large enough to be considered in the operation of Hungry Horse Reservoir. Other patterns of reservoir regulation could increase or decrease the amount of effluent groundwater indicated above.

Forecasts of water available for project use should include the following components: Reservoir inflow (+), precipitation on the reservoir (+), evaporation from the surface of the reservoir (−), changes in reservoir storage (±), and changes in ground-water storage adjacent to the reservoir (±). The reservoir inflow and changes in reservoir storage are the largest components, but precipitation, evaporation, and changes in ground-water storage should be evaluated in order to enhance the efficient operation of Hungry Horse Reservoir.

Step-regression analysis of the water-budget data indicates that the inflow to Hungry Horse Reservoir, except for precipitation, can be satisfactorily estimated by a two-station index. This index is based on the discharge data for South Fork Flathead River above Twin Creek and for Sullivan Creek. The recession characteristics of these two streams provide a means for forecasting the assured inflows to the reservoir during the low-flow periods. The use of precipitation and temperature data from Hungry Horse Dam provides a potential means of adding refinements to the forecasting procedures based on recession characteristics.

INTRODUCTION

PURPOSE AND SCOPE

Hungry Horse Project, which includes a reservoir with total storage capacity of 3,468,000 acre-feet, is one of the major Federal multipurpose components of the water-development program in the Columbia River basin. It is used primarily for at-site and downstream power generation and for flood control. Since its completion in 1953, certain regulating problems dealing with an apparent imbalance between reservoir inflows and outflows have been encountered. Prior to this investigation several unsuccessful attempts were made to solve this problem. The hydrologic data collected during the period 1948–60 were inadequate to provide conclusive answers.

The basic objectives of this investigation were to determine more accurately the volume of water available at Hungry Horse Reservoir, including bank storage, and to improve the forecasting procedure for low-water periods. The keys to the success of this investigation were the accurate definition of the water budget for Hungry Horse Reservoir and the development of a suitable mathematical model of the ground-water movement in the aquifers adjacent to Hungry Horse Reservoir. The ability to assess and evaluate each of the variables involved led to the resolution of the apparent imbalance between reservoir inflows and outflows.

This study included (1) the collection of the data required to define accurately the inflow and outflow components of the hydrology of the reservoir and (2) the analysis of the water-budget components to improve the procedure for forecasting reservoir-inflow volumes during low-flow periods. The intensive data-collection program included direct measurement or an evaluation of the following: Surface inflow and outflow, change in reservoir contents, subsurface inflow including bank storage, and precipitation on, and evaporation from the water surface of the reservoir. Evaporation from the reservoir surface was determined by an energy-budget procedure. A separate basic-data supplement summarizes the field data collected for this project (Simons, 1968).

In previous collaborative programs with the Bonneville Power Administration, the methods of relating ground water to surface water were explored. These explorations tested certain theoretical concepts and developed equations for expressing bank-storage effects in terms of the hydraulic characteristics of the alluvium adjacent to a stream channel and river stage. The current study expands these theoretical concepts to the unique characteristics of a large reservoir in a mountain valley.

The low-flow-forecasting section was developed as an expansion of previous studies of the base-flow characteristics of streams in the Columbia River basin. This, also, has been a part of the long range collaborative program of hydrologic investigation with the Bonneville Power Administration.

BACKGROUND

HUNGRY HORSE PROJECT

LOCATION AND DESCRIPTION

The earliest investigations of hydroelectric power potentials in the South Fork Flathead River basin were carried on by the U.S. Geological Survey in 1921 and were continued periodically over the next 25 years. The U.S. Army Corps of Engineers made a preliminary study of this general area during the early 1930's, and in 1939 a damsite at Devils Elbow, 1 mile downstream from Hungry Horse Dam, was investigated in more detail.

The Hungry Horse Project was authorized by Congress in 1944 and was constructed by the U.S. Bureau of Reclamation during the period April 1948–July 1953. The initial storage of water began in September 1951, and full-pool elevation of 3,560 feet above mean sea level was reached in July 1954. The first power was generated in October 1952.

The principal features of the Hungry Horse Project include a dam, reservoir, and powerhouse. These are in the lower reaches of the South Fork Flathead River in northwestern Montana (fig. 1). The dam is about 5 miles upstream from the confluence of the South Fork Flathead and Flathead Rivers, about 20 miles northeast of Kalispell. It is in a deep, narrow canyon and is a variable-

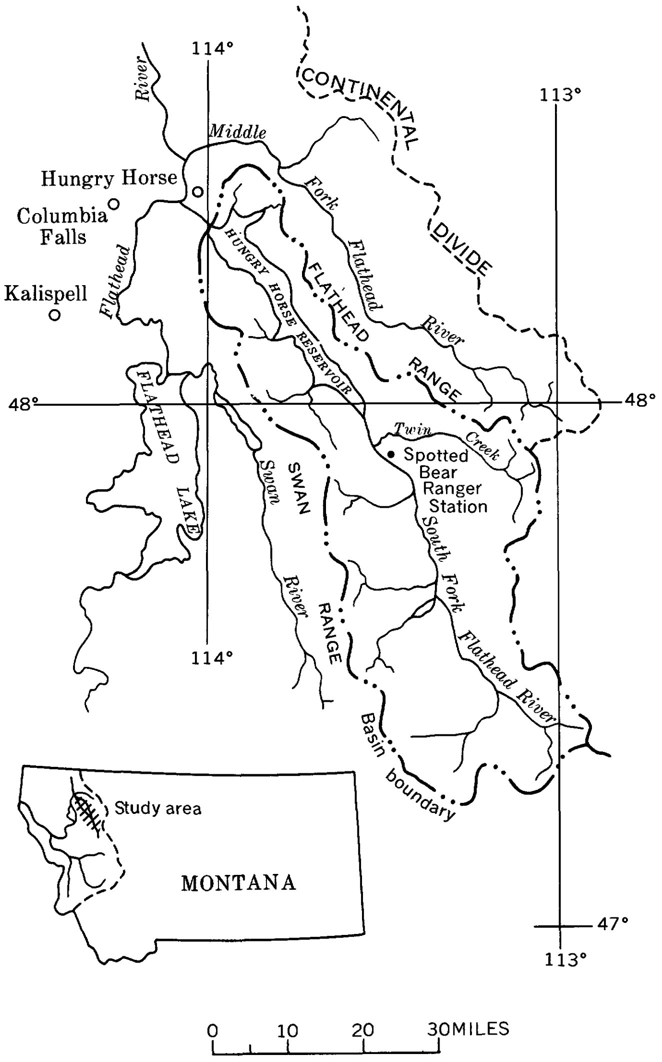

FIGURE 1.—Location of the Hungry Horse Project.

thickness concrete arch structure. The structural height of the dam is 564 feet, and it has a crest length of 2,115 feet.

The following tabulation lists elevations, in feet above mean sea level, of pertinent features of the project:

Feature	Elevation
Top of dam	3,565
Normal full pool	3,560
Crest of spillway	3,548
Limit of power storage	3,336
Penstock openings	3,319
Sill of river outlet openings	3,196
Powerhouse floor	3,113
Maximum tail water	3,101
Minimum tail water	3,074

The powerhouse is at the toe of the dam and contains four generating units with a total nameplate capacity of 285,000 kilowatts. The switchyard for the powerhouse is about one-fourth mile downstream on the right bank.

The reservoir is about 33 miles long and extends upstream to a point a short distance below Twin Creek. The reservoir ranges from ½ to 3½ miles in width and covers an area of about 24,000 acres, or nearly 37 square miles. Maximum depth of water is about 490 feet, total storage capacity is 3,468,000 acre-feet, and the usable storage for the production of electrical energy is 2,982,000 acre-feet between the elevations of 3,336 and 3,560 feet. The storage ratio (usable storage to average annual runoff) is 1.27 years. Thus the reservoir can be operated in a "cyclic" manner in which the drawdown period extends over more than one low-water season.

Primary benefits from this project are production of hydroelectric energy, flood control, and recreation. The basic operating plan for Hungry Horse Reservoir is to store most of the runoff during the snowmelt period—May, June, and July—and to release this stored water over the balance of the year as needed. This plan of operation provides flood control during the high-runoff period and provides additional water for the generation of electrical energy during periods of heavy power demands. The size of this reservoir and its potential for being operated on a cycle that is longer than 1 year make it an important element in the long-range program for the control and utilization of the water of the Columbia River.

Multipurpose guidelines for the operation of the Hungry Horse Project were developed jointly by the Bureau of Reclamation, the Corps of Engineers, and the Bonneville Power Administration, acting in collaboration with the Water Management Subcommittee, Columbia Basin Inter-Agency Committee (CBIAC). These guidelines are formalized in Memorandums of Understanding between the Bureau of Reclamation and the Corps of Engineers for flood control, and between the Bureau of Reclamation and the Bonneville Power Administration for the generation of power. Frequent reviews and discussions of proposed operating schedules are maintained by these agencies and the Columbia River Water Management Group.

Hungry Horse Project is an integral part of the Federal Columbia River Power System, which is composed of the hydroelectric generating facilities constructed and operated by the Corps of Engineers and the Bureau of Reclamation and the transmission network built and maintained by the Bonneville Power Administration. The generating plants and the transmission facilities are operated as an integrated electrical system. The Bonneville Power Administration acts as marketing agent for the coordinated system.

In 1966–67 this system included 22 projects with installed generating capacity (nameplate rating) of 6,758,150 kilowatts. The associated usable storage capacity is 11,946 million acre-feet. Hungry Horse Project supplies 4.2 percent of the generating capacity and contains about 25 percent of the usable storage in the system. Only Franklin D. Roosevelt Lake contains more of the system's usable storage capacity.

The prime power benefits that can be directly attributed to Hungry Horse Project were estimated at 1,054,000 kilowatts by the Bonneville Power Administration. This was based on the actual 1966–67 installed generating equipment and storage capacity and on the flows for the critical power year 1936–37. The details of this estimate are shown in table 1.

The gross head between the normal pool of Hungry Horse Reservoir, elevation 3,560 feet, and the tail water of Bonneville Dam, elevation 15 feet, is 3,545 feet. During power year 1967, the water released from Hungry Horse Reservoir passed through 17 powerplants utilizing a gross head of about 2,275 feet. Since that time, three additional powerplants have been put into operation and have increased the amount of head utilized to about 2,710 feet, or more than 75 percent of the available gross head. Additional powerplant sites downstream from Hungry Horse are being studied which, if developed, would utilize several hundred additional feet of head, making a total of more than 90 percent of the gross head.

TABLE 1.—*Prime power benefits of the Hungry Horse Project at site and at existing downstream projects*

[Average kilowatts, based on 1966–67 installations and minimum power year 1936–37. Includes U.S. plants only. From Bonneville Power Administration.]

	Without Hungry Horse	With Hungry Horse	Increase due to Hungry Horse
Federal system plants:			
Hungry Horse		222,000	222,000
Albeni Falls	20,000	28,000	8,000
Grand Coulee	1,132,000	1,331,000	199,000
Chief Joseph	638,000	733,000	95,000
McNary	525,000	570,000	45,000
The Dalles	559,000	604,000	45,000
Bonneville	399,000	426,000	27,000
Total	3,273,000	3,914,000	641,000
Non-Federal system plants:			
Kerr	64,000	155,000	91,000
Thompson Falls	28,000	38,000	10,000
Noxon Rapids	98,000	182,000	84,000
Cabinet Gorge	64,000	117,000	53,000
Box Canyon	43,000	60,000	17,000
Rocky Reach	385,000	440,000	55,000
Rock Island	114,000	129,000	15,000
Wanapum	336,000	381,000	45,000
Priest Rapids	328,000	371,000	43,000
Total	1,460,000	1,873,000	413,000
Combined total	4,733,000	5,787,000	1,054,000

The Bonneville Power Administration has estimated that each acre-foot of water at Hungry Horse Reservoir will produce at site and downstream about 1,700 kilowatt hours of firm power. Another way of expressing this is that a 1-percent increase in usable reservoir storage capacity is worth about $40,000 annually in firm power sales. Thus, the accurate determination of the amount of water available at Hungry Horse Project is important to the efficient operation of the Federal Columbia River Power System. That determination was the primary objective of this study.

SOUTH FORK FLATHEAD RIVER DRAINAGE BASIN

The South Fork Flathead River drains about 1,700 square miles of area lying on the west side of the Continental Divide in northwestern Montana. This stream flows generally northwestward between the Swan and Flathead Ranges for about 105 miles and joins the Flathead River about 10 miles northeast of Columbia Falls. The elevation of the drainage basin ranges from about 3,000 feet at its junction with Flathead River to mountain peaks as much as 10,000 feet above mean sea level. Hungry Horse Reservoir occupies most of the lower part of the basin lying between 3,070 and 3,560 feet.

The drainage basin of the South Fork Flathead River is almost exclusively within the boundaries of lands that are under the jurisdiction of the U.S. Forest Service. These lands are covered with moderate to sparse stands of evergreen trees, but the lower valleys have coverings of brush and some deciduous trees. Most of the drainage basin is in a natural state, although some logging has been and is being done under the supervision of the Forest Service in the area immediately surrounding Hungry Horse Reservoir.

Except for a few recreational facilities, there is no commercial development in the South Fork Flathead River basin. Roads extend upstream on both banks only as far as Spotted Bear Ranger Station. There are two small landing strips for light planes in the basin upstream from Hungry Horse Reservoir.

METEOROLOGICAL OBSERVATIONS

When construction of the Hungry Horse Project was started, there were no meteorological observations being made in the South Fork Flathead River drainage basin except intermittent records collected by the Forest Service during the fire season. Long-term weather records were available at Kalispell and West Glacier. In order to get data that would be more representative of conditions at the project, a meteorological station was established about 4 miles downstream from the dam in 1947 which provided daily observations of precipitation, maximum and minimum air temperatures, and evaporation (class A pan). This weather station was moved 3.3 miles upstream in December 1953 and was located within the switchyard of the project. Records for the two sites are considered to be equivalent.

Monthly data for this station for the water years 1948–68 are summarized in table 2. Average water-year precipitation at the dam is about 32 inches and during the period of record has ranged from about 22 to 42 inches. Larger amounts of precipitation occur in the high mountain ranges, especially to the west along the Swan Range. About 50 percent of the annual precipitation occurs in the period October–February as a result of general winter storms. Only 10 percent of the annual precipitation occurs during July and August and is generally in the form of summer showers which have limited areal extent.

The estimated average annual temperature at Hungry Horse Dam is about 42° F. Monthly mean temperatures normally range from 21° F. to 66° F., although during the period of record these have varied from a low of 2.5° to a high of almost 72° F. Monthly mean temperatures of 32° F. or lower normally occur during the period November–March.

The usual period of evaporation at Hungry Horse Reservoir extends from May through October, although some evaporation may take place in April

TABLE 2.—*Summary of monthly meteorologic observations, Hungry Horse Dam, for water years 1948–68*

	October	November	December	January	February	March	April	May	June	July	August	September
Monthly precipitation, in inches												
Average	3.32	3.48	3.31	3.49	2.66	2.15	2.24	2.54	3.05	1.57	2.00	2.46
Maximum	6.80	7.37	8.21	7.02	5.11	3.17	5.16	5.03	6.49	3.90	5.21	6.57
Minimum	.29	.72	1.03	1.30	.91	.36	.57	.65	.53	.10	.00	.28
Monthly mean temperature, in °F												
Average	43.6	32.0	26.1	21.4	26.8	31.0	41.0	51.1	57.8	65.8	63.7	54.2
Maximum	46.9	37.6	32.9	34.1	35.5	39.4	44.9	60.6	63.5	71.8	70.7	62.2
Minimum	39.4	23.0	15.8	2.5	17.1	23.1	37.5	46.8	53.2	60.4	59.1	45.7
Monthly evaporation, in inches, based on partly estimated data (class A pan)												
Average	1.55							4.98	5.82	8.13	6.73	3.54
Maximum	4.00							8.10	7.62	11.28	10.35	5.29
Minimum	.70							3.72	4.68	6.76	4.96	1.97

and November. The estimated seasonal evaporation from a class A pan at this site is 31 inches, about one-fourth of which occurs in July and more than two-thirds during the period June–August.

HYDROLOGY

When the Hungry Horse Project was authorized, there was only one gaging station in the South Fork Flathead River basin. Records for this station, South Fork Flathead River near Columbia Falls, are available as noted below:

Period	*Location (river mile)*	*Type of records*
1910–28	0.4	Fragmentary.
1928–52	2.1	Continuous.
1952–present	3.5	Do.

The current location is about 1¾ miles downstream from Hungry Horse Dam.

Records for this station provide a measure of the amount of water contributed to the Columbia River system by the South Fork Flathead River under both natural and controlled conditions. Initial storage of water in Hungry Horse Reservoir began on September 22, 1951. Thus all data prior to that date are a measure of the natural conditions that existed prior to the reservoir regulation. Subsequent data represent virtually completely controlled conditions, inasmuch as the active storage capacity of Hungry Horse Reservoir is larger than the average annual runoff.

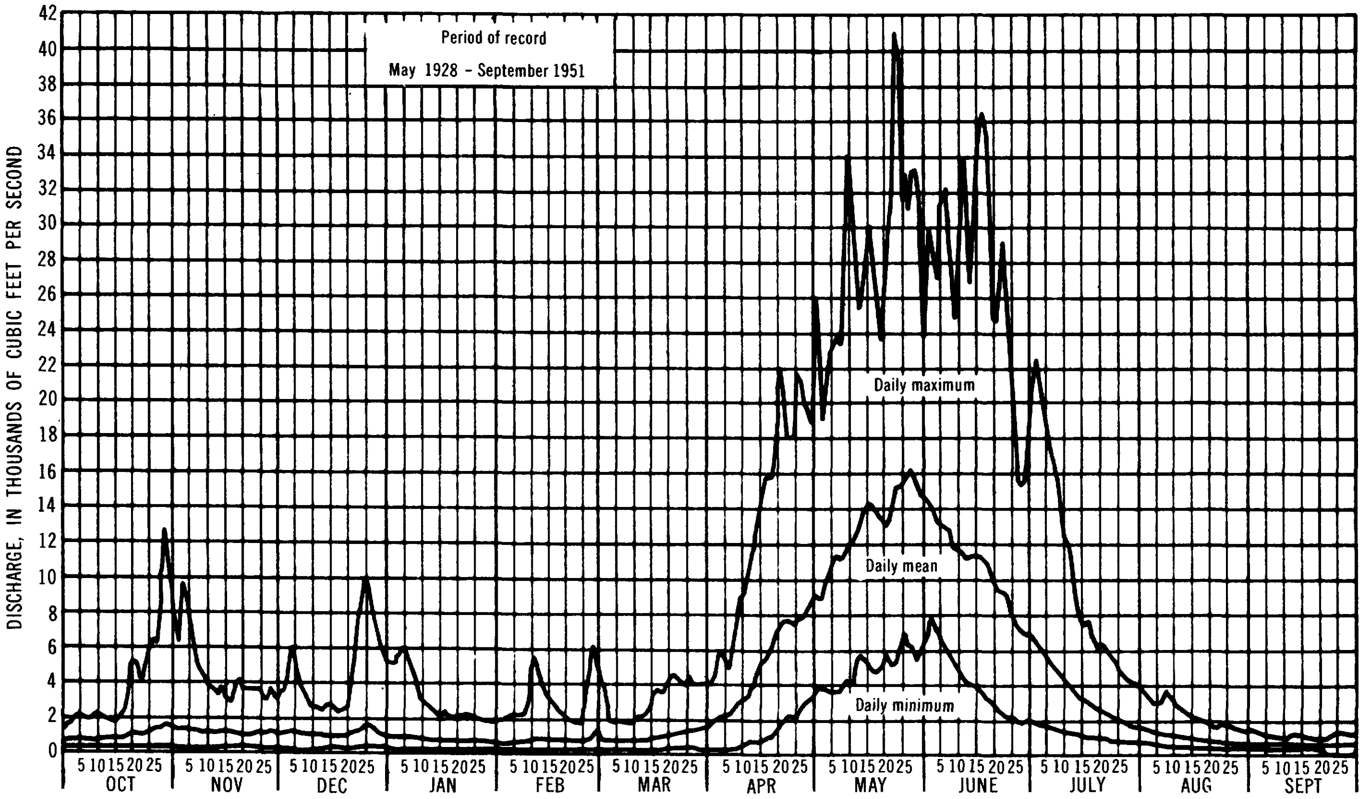

FIGURE 2.—Summary of daily discharges, South Fork Flathead River near Columbia Falls. Adaptation of diagram from the Water Management Subcommittee, Columbia Basin Inter-Agency Committee.

The natural runoff regimen for this gaging station is depicted in figure 2. This hydrograph shows the average, maximum, and minimum daily discharges for the period May 1928–September 1951. It was prepared by the Water Management Subcommittee of CBIAC in connection with its evaluation of runoff forecasts for this station.

The hydrograph shows that the natural discharge regimen of the South Fork Flathead River exhibits the usual characteristics of an alpine basin for this latitude. The stream is characterized by large discharges during the snowmelt period, May–July, followed by a gradual recession to low flows during wintertime. Minimum discharge commonly occurs during February. Flows during March and April usually exhibit slight or moderate rises as a result of the initial melting of accumulated snow and ice. During the late summer and early fall periods, increases in discharge are common as a result of localized showers or storms. There is an increase in discharge each fall with the lessening of evapotranspiration demands on the drainage basin. During an average winter there are times when the stage-discharge relationship is affected by the formation of ice in the stream channel. This effect can last for a few days or weeks inasmuch as it varies with the length and magnitude of the sequence of below-freezing temperatures. During the period of maximum precipitation, November–February, major increases in discharge are not common because the precipitation usually falls as snow and the cold temperatures prevent it from running off immediately.

Using water years 1929–51 as a measure of natural (unregulated) conditions, the average observed discharge was 3,297 cfs (cubic feet per second). The maximum discharge during this period was 43,400 cfs, which occurred during the 1948 flood. The minimum observed flow was 206 cfs, which was measured during December 1935. However, discharge may have been less during periods of severe ice conditions which periodically affect this stream. A summary of the natural monthly discharges for this station is contained in table 3 and shown in figure 3.

During construction of Hungry Horse Dam, the flow of the South Fork Flathead River was routed through a diversion tunnel on the right bank. On September 22, 1951, the tunnel was closed and storage of water in the reservoir area was initiated.

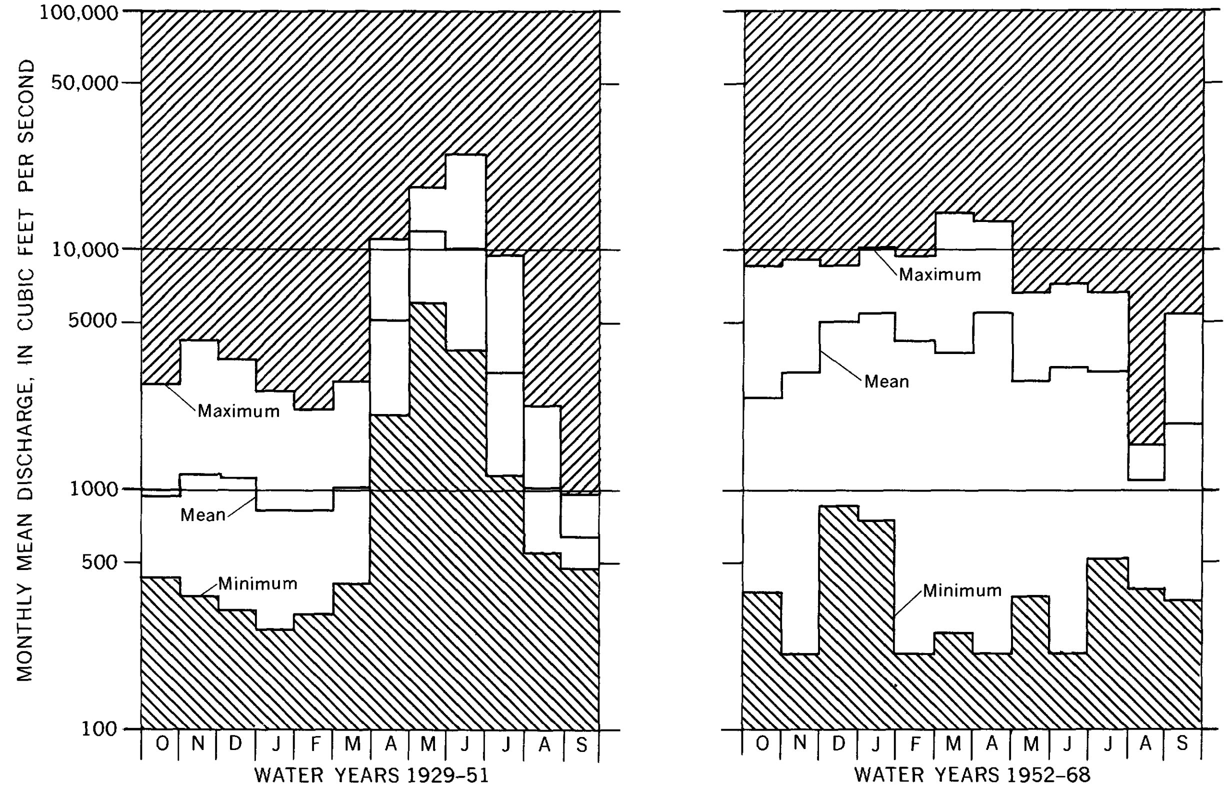

FIGURE 3.—Summary of monthly mean discharges, South Fork Flathead River near Columbia Falls, water years 1929–51 and 1952–68.

TABLE 3.—*Summary of monthly and annual discharges, South Fork Flathead River near Columbia Falls*

	October	November	December	January	February	March	April	May	June	July	August	September	Annual
						Discharges, in cubic feet per second, during natural period, water years 1929–51							
Mean	956	1,189	1,120	843	842	1,058	5,220	12,773	10,484	3,308	1,018	667	3,297
Maximum	2,899	4,128	3,504	2,729	2,210	2,945	11,770	18,140	25,000	9,717	2,282	978	4,650
Minimum	432	361	313	266	302	402	2,020	6,613	3,965	1,152	557	493	1,647
						Discharges, in cubic feet per second, during regulated period, water years 1952–68							
Mean	2,556	3,051	5,073	5,654	4,245	3,848	5,555	2,915	3,295	3,220	1,104	1,954	3,535
Maximum	8,803	9,092	8,985	10,030	9,447	14,840	13,270	[1] 6,817	7,345	6,914	1,650	5,540	5,326
Minimum	[1] 387	204	898	[1] 768	208	259	202	358	205	[1] 535	[1] 395	[1] 355	[1] 1,012

[1] Occurred during initial filling of Hungry Horse Reservoir.

By October 11, 1952, the stage had risen to an elevation of 3,215.4 feet and the flow was regulated through the river outlet tubes. During this period, the flow at the downstream gaging station averaged less than 20 cfs and the minimum observed was about 7 cfs.

The operation of Hungry Horse Reservoir has altered the pattern of water being added to the Columbia River system by the South Fork Flathead River. The largest flows below Hungry Horse Dam normally occur during December and January, and minimum flows occur during August. A summary of observed monthly flows for this station for water years 1952–68 is also shown in table 3 and figure 3. Except for the period of initial filling, the main effect of the operation of this project is a redistribution of the flows within the year.

The records for this station can be adjusted to approximate conditions by making adjustments for change in contents for Hungry Horse Reservoir. During construction and prior to May 1953, various nonrecording gages were used to measure the elevations of the water in the reservoir. Subsequent to

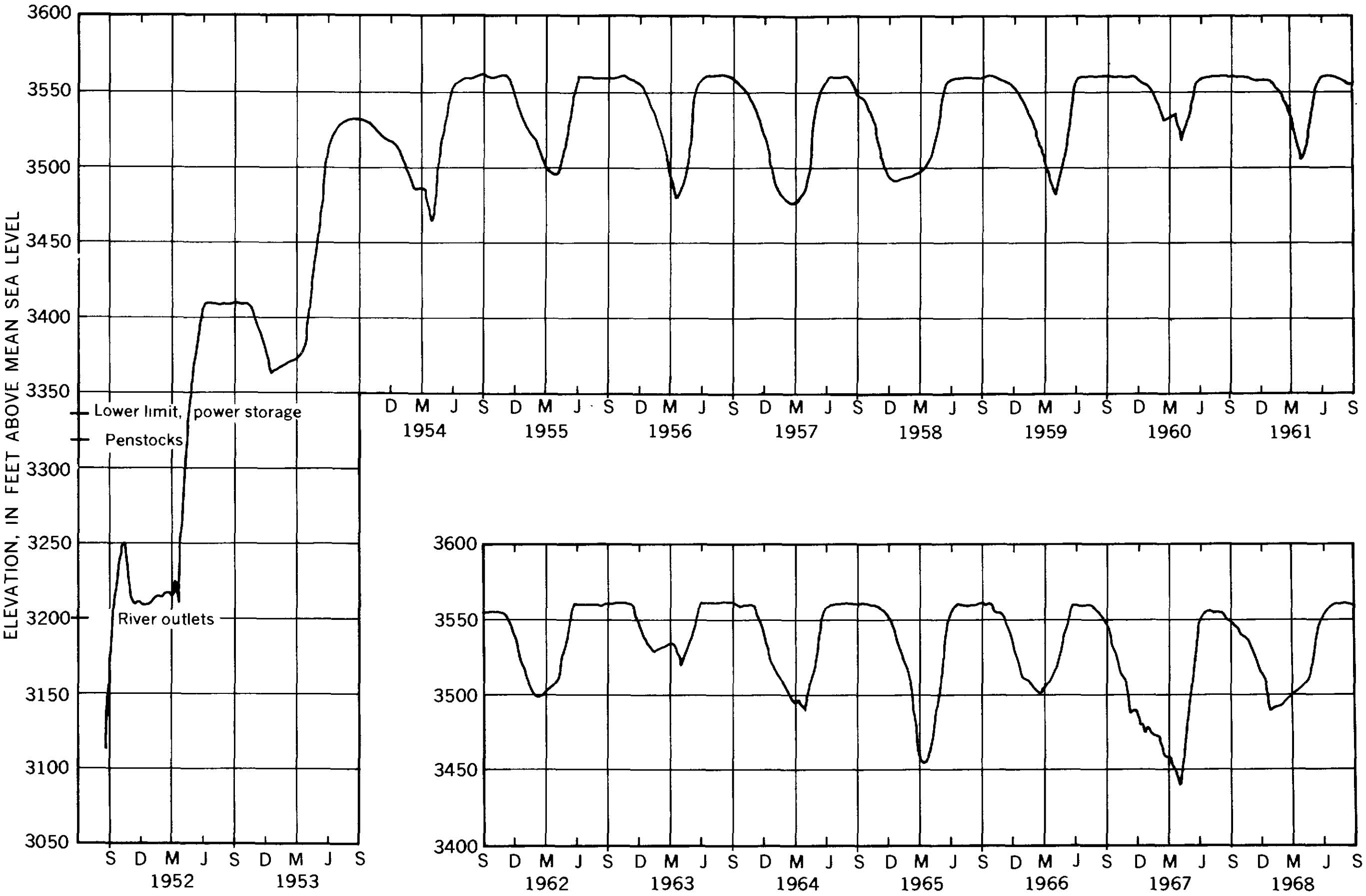

FIGURE 4.—Water-surface elevations, Hungry Horse Reservoir, water years 1952–68.

that date, continuous records of reservoir stage have been recorded by a gage in the south elevator tower of the dam.

A hydrograph of the water-surface elevations of Hungry Horse Reservoir is shown in figure 4. A summary of the monthly change in contents is given in table 4 and shown in figure 5. These changes are based on the midnight reservoir elevations and the capacity table furnished by the Bureau of Reclamation. The range in monthly change in contents of Hungry Horse Reservoir has been from −803,000 acre-feet during March 1965 to +1,103,000 acre-feet during June 1967.

TABLE 4.—*Summary of monthly change in contents, in acre-feet, Hungry Horse Reservoir, water years 1952–68*

	Mean	Range	
		Upper	Lower
October	−72,535	[1] +100,000	−498,000
November	−93,970	+32,000	−495,000
December	−234,110	[1] −7,190	−469,000
January	−282,730	[1] +1,720	−555,000
February	−179,325	[1] +34,300	−434,000
March	−162,950	+27,000	−803,000
April	−77,805	+225,000	−550,000
May	+637,875	+991,100	+392,000
June	+668,750	+1,103,000	+369,000
July	+60,810	[1] +292,000	−12,000
August	−690	[1] +46,000	−39,000
September	−54,785	[1] +15,000	−294,000
Annual	+204,380	[1] +1,807,400	−291,000

[1] Occurred during period of initial filling, September 1951 through July 1954.

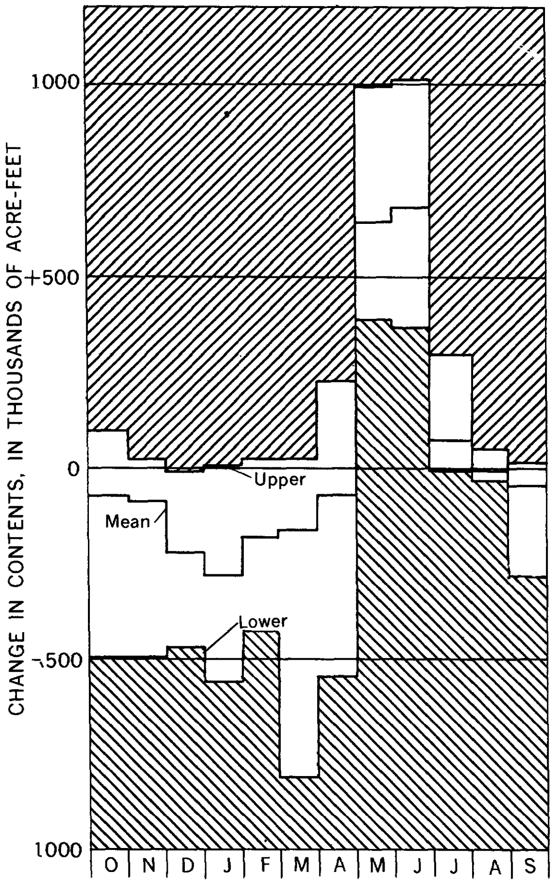

FIGURE 5.—Range of monthly change in contents, Hungry Horse Reservoir, water years 1952–68.

At the time of the initial construction of the Hungry Horse Project, six additional gaging stations were installed on tributaries to Hungry Horse Reservoir. During the construction period, a gaging station was established on Hungry Horse Reservoir to collect records of reservoir stage and contents. These gaging stations are listed below along with the periods of record prior to October 1964:

South Fork Flathead River at Spotted Bear Ranger Station near Hungry Horse	Sept. 1948–Sept. 1957; Sept. 1959–Sept. 1964.
Spotted Bear River near Hungry Horse	Oct. 1948–Sept. 1956.
Twin Creek near Hungry Horse	Sept. 1948–Sept. 1956.
Lower Twin Creek near Hungry Horse	Do.
Sullivan Creek near Hungry Horse	Oct. 1948–Sept. 1956; Oct. 1959–Sept. 1964.
Graves Creek near Hungry Horse	Sept. 1948–Sept. 1956.
Hungry Horse Reservoir near Hungry Horse	Sept. 1951–Sept. 1964.

The locations of these gaging stations are shown in figure 6.

About 80 percent of the drainage of the South Fork Flathead River near Columbia Falls is encompassed by this upstream group of stream-gaging stations. The data for these stations exhibit the same general characteristics as the downstream station in its natural state.

PREVIOUS INVESTIGATIONS

During the early stages of the operation of Hungry Horse Project, the inflows to the reservoir were computed by adjusting the observed outflow for the changes in contents in the reservoir. When this was done on a daily basis, the resulting hydrograph was very irregular, especially during the fall and winter months. During these periods, water is withdrawn from storage to meet the large and sometimes variable electrical loads. The amount of stored water released is large in comparison to the actual inflow. Even a small difference in the observed stage of the reservoir could indicate a greatly different adjustment to project outflows.

Even under these conditions, it became apparent that the inflow computed by this procedure exhibited characteristics that were different from the characteristics of the tributaries flowing into the reservoir and of other nearby unregulated streams.

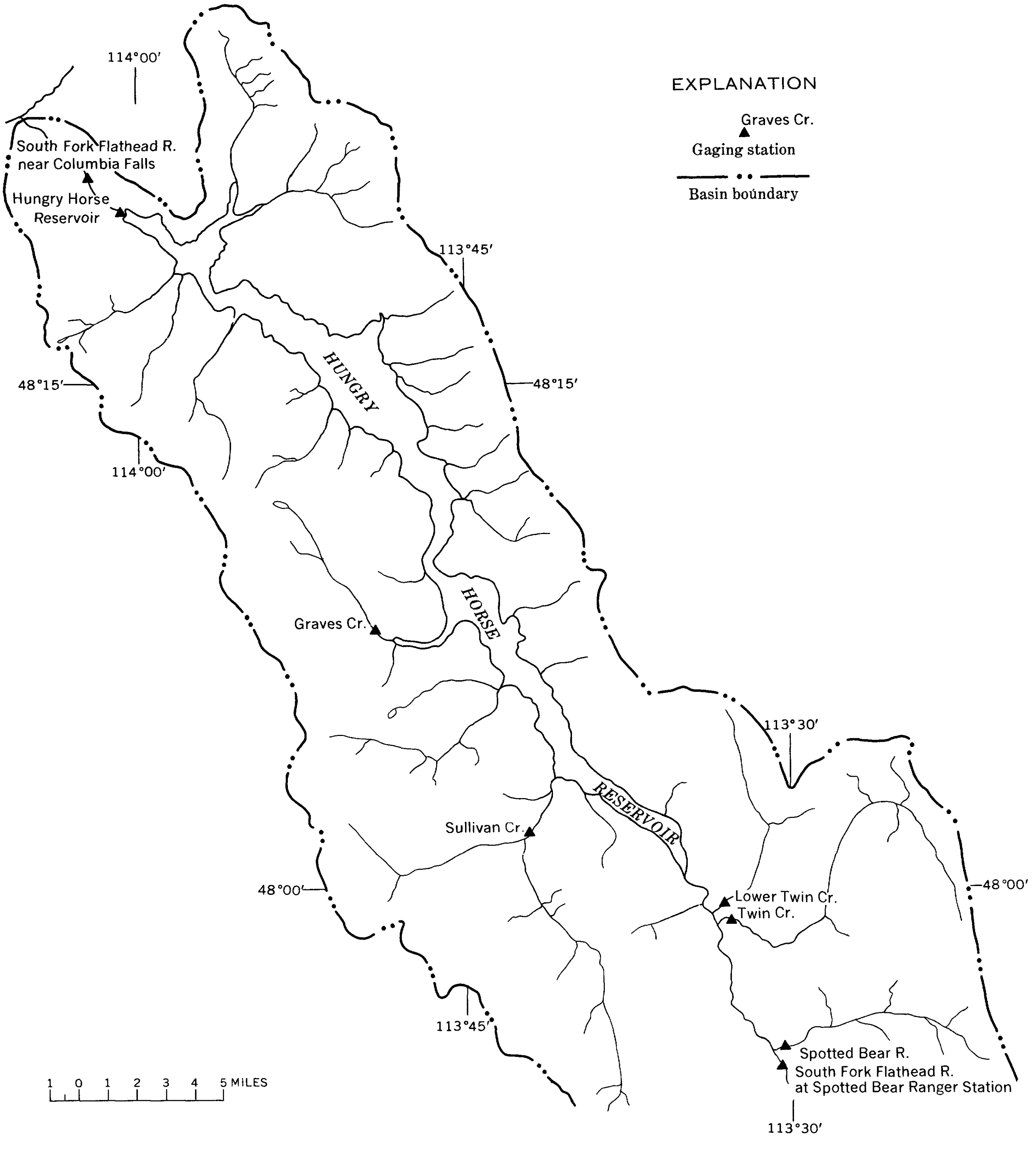

Figure 6.—Location of gaging stations prior to the start of this investigation.

The most noticeable difference appeared when large amounts of water were withdrawn from Hungry Horse Reservoir. Computed inflow increased even though the discharge at other stations was continuing to follow a natural recession. When water was being stored in Hungry Horse Reservoir, the opposite effect was noticed, although to a lesser degree. This imbalance between inflows and outflows was apparently related to the change in contents of the reservoir.

In 1957, the Bonneville Power Administration requested the Geological Survey to make an examination of this phenomenon. A preliminary study of the problem was conducted by the Technical Coordination Branch office in Tacoma, Washington. Graphical correlations of monthly mean discharge for water years 1949–56 were made between the computed inflow (outflow ± change in contents) and the flow in tributary and nearby streams. The results of this analysis suggested the use of the following formula:

$$I=1.19Q_1+7.4Q_2$$

where I = natural monthly mean inflow to Hungry Horse Reservoir, in cubic feet per second,

Q_1 = monthly mean discharge, South Fork Flathead River at Spotted Bear Ranger Station, in cubic feet per second,

and Q_2 = monthly mean discharge, Sullivan Creek near Hungry Horse, in cubic feet per second.

For purposes of that preliminary study, this index of the natural inflow to Hungry Horse Reservoir was considered satisfactory, even though some seasonal variation was evident.

Estimates of natural inflow were prepared for water years 1952–56 using the above formula and were compared to the inflow computed by adjusting the outflow for change in contents in Hungry Horse Reservoir. The comparison indicated that during periods of reservoir drawdown the adjusted outflow records showed more water than the index of inflow. During periods when the reservoir was full or being filled, the opposite effect was noted. Thus it was tentatively concluded that bank storage existed in Hungry Horse Reservoir and that additional studies would be needed to refine the index of inflow. Such studies should include a geologic examination of the reservoir area and the collection of data from ground-water observation wells around the periphery of the reservoir.

During 1959 and 1960, the Bonneville Power Administration made additional studies to define the cause of this phenomenon and the quantitative amount of the effect of reservoir operation on computed inflow to Hungry Horse Reservoir. These studies included the extension of the earlier Geological Survey studies to the winter of 1959–60 and a special program of withdrawals from Hungry Horse Reservoir in which the reservoir was alternately drafted and held steady. The results of the studies indicated the existence of a difference of about 6 percent between the two methods of estimating reservoir inflow. This could be attributed to an error in the reservoir-capacity table or to excess ground-water inflow (bank storage). Corrections were made by computing a reservoir "use" table by multiplying the values in the existing storage-capacity table by a factor of 1.06. The Bonneville Power Administration recommended that this "use" table be used for all determination of power available from the Federal Columbia River Power System and that the reservoir inflow be computed by the index developed in earlier studies.

During 1961, the Bureau of Reclamation reviewed the studies by the Geological Survey and the Bonneville Power Administration and made several separate analyses and comparisons. One dealt specifically with the capacity table for the reservoir. The comparison indicated that the capacity of the reservoir between elevations of 3,360 and 3,500 feet based on surveys made by the Geological Survey before the reservoir was cleared and by the Bureau of Reclamation after the reservoir was cleared differed by only one-fourth percent. Thus any difference between methods of computing the inflow to the reservoir was unlikely to be due to errors in the capacity table. Several inconsistencies in the data and related analysis suggested that there was insufficient evidence to justify making any changes in the capacity table at that time.

The Water Management Subcommittee of CBIAC reviewed in qualitative terms the results of the studies by the Geological Survey, the Bonneville Power Administration, and the Bureau of Reclamation. This review generally concluded that:

1. Bank storage probably existed in Hungry Horse Reservoir but quantity was unknown.
2. The capacity table was probably not in error.
3. Other hydrologic considerations such as wintertime precipitation, evaporation, and changes in hydrologic conditions were not evaluated as fully as possible.
4. Further study, including the collection of additional data, should be done before making any changes in the capacity table for this reservoir.

Therefore, in December 1961 the Water Management Subcommittee recommended that the original capacity table be used until such time as additional data could be collected and presented to this subcommittee to prove or disprove the existence of the 6-percent factor recommended by the Bonneville Power Administration.

ACKNOWLEDGMENTS

This investigation is part of the long-range collaborative program of hydrologic investigations in the Columbia River basin undertaken by the Geological Survey and the Bonneville Power Administration. The Bonneville Power Administration requested the current study and furnished most of its financial support. It also furnished considerable background data and information, especially on the power aspects of the Hungry Horse Project and the operating problems. The authors wish to acknowledge the active participation of F. A. Limpert, Head, Hydrology Section, Bonneville Power Administration, in the overall guidance of the project.

The investigation was made by the Water Resources Division, U.S. Geological Survey, under the project leadership of M. I. Rorabaugh who developed the sections dealing with ground-water analyses, including the mathematical model and its optimization to the field setting. W. D. Simons was project coordinator and developed the sections dealing with the water-budget analyses and the runoff-forecasting procedure. The energy-budget data on evaporation was developed under the leadership of J. S. Meyers, Denver, Colo. The collection of field data was primarily carried on by E. J. Blank, Kalispell, Mont., under the general supervision of C. W. Lane, District Chief, Water Resources Division, Montana. Part of the cost of the energy-budget study, test drilling, and ground-water analyses was financed by the Geological Survey.

The Bureau of Reclamation furnished financial support for the outflow and reservoir-stage gaging stations. It also furnished historical data on the Hungry Horse Project, observer services, and storage and work facilities at the dam. The Corps of Engineers, Seattle District, furnished meteorologic and water-temperature data for previous years and loaned some instruments used during this investigation. The Forest Service constructed the gaging station Goldie Creek near Hungry Horse and furnished some financial support for the miscellaneous discharge measurements. In addition, it supplied planimetric maps of the Flathead National Forest and ancillary precipitation data collected at Spotted Bear Ranger Station. The U.S. Weather Bureau furnished precipitation and evaporation instruments used for the ancillary meteorological observations. The Montana State Department of Fish and Game supplied water-temperature data for the gaging station South Fork Flathead River near Columbia Falls.

THEORETICAL CONSIDERATIONS

The basic problem facing this investigation is the apparent imbalance between the two methods of computing the inflow to Hungry Horse Reservoir. In its simplest form, the problem requires solution of this basic relationship:

$$\text{Inflow} = \text{outflow} \pm \text{change in storage.}$$

Each term in the equation is composed of many items which are often interrelated. A qualitative discussion of each of the items to be measured or evaluated in this investigation follows.

INFLOW

The inflow to Hungry Horse Reservoir is composed of surface and subsurface runoff from the area tributary to the reservoir and the precipitation that falls directly on the reservoir surface. The index of reservoir inflow developed from previous studies was based on data from six gaging stations that measured the runoff from about 1,310 square miles. Principal deficiencies of the index are that it was based on runoff from too small a proportion of the total drainage area and that records for critical periods were lost.

The drainage area above Hungry Horse Dam is about 1,654 square miles, the reservoir occupying about 37 square miles. The remaining 1,617 square miles is the land area that contributes the bulk of the inflow to Hungry Horse Reservoir.

A well-defined network of streams drains this area. The drainage basins range in size from about 1,240 square miles, where the South Fork Flathead River enters the reservoir, to less than 1 square mile. One of the simplest ways of measuring a larger part of the reservoir inflow was to establish a gaging station on the South Fork Flathead River as close to the reservoir as possible. Since it was not feasible to put a gaging station on all the remaining streams tributary to the reservoir, it was necessary to determine part of the inflow by indirect means.

One indirect method is to utilize a network concept in the gaging-station operation. In this procedure, a primary network of full-time gaging stations is established. This basic network is supported by subsidiary networks of stations where only partial data are collected. Data from these subsidiary networks can be expanded by correlation techniques to provide larger areal coverage. This method was adopted for use in this study.

The primary network of gaging stations included those already in operation and eight additional stations to provide coverage of the different sizes, shapes, exposures, and terrains represented by the various segments of the tributary drainage area. Priority was given to the reestablishment of discontinued gaging stations and to the establishment of a station on the South Fork Flathead River as close to the reservoir as feasible.

The secondary network of partial-year gaging stations was composed of 20 locations selected to provide broad areal coverage of the remaining tributary area. At each location, the stage-discharge relationship was determined and supplemental stage records collected at periodic intervals. The time interval between observations was selected to cover the range in discharge for each location.

A tertiary network of observation points was established to provide partial coverage for the remaining or ungaged parts of the drainage basin. This network consisted of miscellaneous discharge determinations on all other streams entering the reservoir. Measurements were normally made during high- and low-flow periods only.

The areas not drained by surface streams are small, and their contribution to the reservoir inflow is correspondingly small. It was estimated that the yield of these areas may be similar to that of the small streams measured in the gaging-station networks. Thus the runoff from these areas was included in the estimates of runoff from the ungaged area which was sampled by the tertiary network of observation points.

Ground-water flow to the reservoir may be assumed to be accounted for in the runoff determinations. Ground-water movement in the hard rocks flanking the valley and seepage through the overlying soil cover are considered to be of minor importance. For the unconsolidated material adjacent to the reservoir, the assumption does not fully satisfy field conditions. In areas of high permeability, such as gravel terraces, water from precipitation and snowmelt recharges to the water table and then moves laterally to the reservoir. The timelag in the ground-water system ranges from a few days in the open gravels to many months in the fine-grained material. The estimates of reservoir inflow based on the gaging networks are considered to be reasonable on an annual basis; in other words, total yield is not greatly in error, although monthly values may be affected by the timelag in the ground-water system. In areas of very high permeability, where timelag is small, inflow to the reservoir as indexed is reasonable irrespective of whether it moved as surface runoff or by way of the subsurface route.

Precipitation falling directly on the surface of the reservoir immediately adds to the available water supply of the project. As such, it is a separate component of inflow to the reservoir. Snow falling on top of ice cover on the reservoir acts in the same fashion. Records of daily precipitation at Hungry Horse Dam were used to compute the portion of inflow from precipitation. The total inflow to Hungry Horse Reservoir is considered to be the sum of the inflows for the primary and secondary networks of gaging stations plus inflow from the ungaged area plus inflow resulting from precipitation on the reservoir.

OUTFLOW

The gaging station South Fork Flathead River near Columbia Falls measures all the water that flows past Hungry Horse Dam and includes runoff from the area between the dam and the gaging station. Flow at the downstream gaging station was modified for this latter factor using the flow of Aurora (Fawn) Creek as an index of the runoff from the intervening area.

The amount and seasonal variation of evaporation from the water surface of Hungry Horse Reservoir were not known in specific detail at the onset of this investigation. The Bureau of Reclamation had collected readings on a class A evaporation pan as part of their meteorological observations since 1948. Currently, the instruments for these observations are in the switchyard about one-fourth mile downstream from the dam. Normally, reservoir evaporation is considered to be seven-tenths of the evaporation from a class A pan. Tests have indicated that this may be satisfactory on an annual basis, but it is subject to some variation for short periods of time. Thus, it was decided to make an energy-budget study of evaporation from Hungry Horse Reservoir as an integral part of the water-budget analysis.

In the energy-budget procedure, the amount of evaporation for any time period is computed from the net change in energy content of the reservoir divided by the heat of vaporization. This method of computing evaporation was extensively tested at Lake Hefner (Anderson, 1954) and used in the water-loss studies at Lake Mead (Koberg, 1958).

A modified form of the basic equation is as follows:

$$E = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_\nu}{L(1 + R) + T_0}$$

where E = Reservoir evaporation,
Q_s = Solar radiation incident to the water surface,
Q_r = Reflected solar radiation,
Q_a = Long-wave radiation from the atmosphere,
Q_{ar} = Reflected long-wave radiation,
Q_{bs} = Long-wave radiation from the reservoir,
Q_v = Net amount of heat added to the reservoir by advection,
Q_ν = Increase in energy stored in the reservoir,
L = Latent heat of vaporization of water at temperature T_0,
T_0 = Surface temperature of water in the reservoir,
and R = Bowen Ratio.

The Bowen Ratio is the ratio of the energy conducted to (or from) the air as sensible heat to the energy utilized for evaporation. For computation the above terms were expressed on a unit-area, unit-time basis in metric units.

Consumptive use of water from the reservoir by vegetation around the shoreline does occur in some areas; but the areal extent is not great owing in most part to the steep banks and the shallow root systems of the plants. The amount of water used consumptively after the reservoir was initially filled is probably less than that which was used in the natural state. The evaluation of this factor was not included in the project investigations. The total outflow from the Hungry Horse Reservoir is considered to be runoff as measured by the gaging station South Fork Flathead River near Columbia Falls, plus evaporation from the surface of the reservoir, minus runoff from the area between the dam and the gaging station.

CHANGE IN STORAGE

The change in reservoir storage for any period of time depends upon the change in water-surface elevation and the relation of the elevation to the amount of water stored within the topographically defined reservoir area. Each of these factors is briefly discussed below.

The capacity table for Hungry Horse Reservoir was based on surveys made by the Bureau of Reclamation immediately following the reservoir-clearing operations. The mapping was done on the scale of 1 inch = 400 feet, the contour interval was 10 feet, and intermediate contours at 5-foot intervals were determined in some places. The capacity table developed from these surveys was used throughout this investigation.

One procedure for estimating the inflow to Hungry Horse Reservoir is to adjust the measured outflow by the changes in reservoir contents. During the period July–April, this procedure frequently results in a very erratic hydrograph of daily inflows. The change in contents in the reservoir is frequently large in comparison to the estimated inflow, and a small difference in elevation of the reservoir can result in a large difference in the estimated inflow. A measure of the magnitude of the deviation, in equivalent cfs-days, that could be caused by a difference of 0.01 foot in determining the change in elevation of the water surface is shown in the following tabulation:

Reservoir elevation (feet above mean sea level)	*Deviation (cfs-days per 0.01 ft)*
3,560	118
3,500	89
3,450	53
3,400	45
3,336	28

Continuous records of the water surface in Hungry Horse Reservoir are maintained by a float-operated water-stage recorder at the dam. This gage is in the south elevator tower in block 14. A 24-inch gage well extends from elevation 3,300 to 3,570 feet and is connected to the reservoir by a 4-inch brass-pipe inlet. The water-level recorder has a 1:6 gage scale and a time scale of 9.2 inches per day. It is equipped with a selsyn attachment so that readings of the water levels in the reservoir may be made from the powerplant operator's headquarters. There is no outside gage, and prior to 1964 there was no regular program of comparing water-surface elevations in the reservoir to those in the gage well or to those indicated in the operator's headquarters.

In September 1963, the Bureau of Reclamation investigated the effect of the temperature-density profiles of water in the gage well and in the reservoir on the gaging of the reservoir-surface elevations. They found the water in the gage well to be 0.09 foot higher than in the reservoir and estimated that a maximum difference of +0.16 foot would be possible during the period when the water in the reservoir was the coldest. The gage was reset in December 1963. A program of periodic checking of water elevations of the reservoir and in the gage well was started in 1964.

Change in storage of ground water is not directly evaluated and is included in the water-budget residual along with errors and unevaluated minor items. The ground-water system for natural conditions (no regulation of reservoir) is represented by the following equation:

$$G_R - G_d = \Delta S_a$$

where G_R is ground-water recharge, G_d is ground-water discharge, and ΔS_a is change in storage in the aquifer. Superimposed on the natural system is the effect of stage changes of the reservoir. For a simple case of a horizontal water table at reservoir level, water moves into or out of the permeable bed or banks of the reservoir in response to changes in reservoir elevation. When superimposed on a natural ground-water system, ground-water flow toward the reservoir may be slowed or delayed by the reduced gradients caused by a rise in reservoir stage. Thus, as the result of "underground backwater," aquifer water is stored in response to a rise in reservoir levels even though reservoir water may or may not have entered the aquifer. For a given change in reservoir stage, the amount of storage change in the aquifer is the same regardless of which type of water is stored, and no separation of water types is needed for this study. This change in storage (ΔS_B) is referred to as bank storage.

For most reservoirs storage extends through the topographically defined bed and banks into the adjacent geologic formations. The amount of additional subterranean storage and the rate of movement in either direction between the reservoir and the formations are controlled by the areal extent and thickness of the formations, the water-bearing characteristics (hydraulic conductivity and specific storage) of the material, the degree of connection of permeable zones with the reservoir, and the time-dependent natural ground-water gradients on which are superimposed the effects of time-stage manipulation of the reservoir. For equal volumes of material this added increment of storage may be small for tight materials such as consolidated rocks or glacial till and large for unconsolidated alluvium or glacial-outwash materials.

The rate at which reservoir water will enter the banks in response to a rising stage or return in response to a falling stage depends, in part, on the hydraulic conductivity and the hydraulic gradient. Thus movement would be sluggish in material of low hydraulic conductivity such as clay or till and rapid in materials of high hydraulic conductivity such as clean sand or gravel. The effect of a stage change in the reservoir is transmitted landward as a wave whose travel rate is controlled by the aquifer characteristics. Thus it may take days, months, or years for complete response. For a reservoir with an adjacent aquifer of very large areal extent or one of sluggish characteristics, annual cycles of regulation may be too rapid for storage in or drainage of more than the part of the formation immediately adjacent to the reservoir. Storage in the remote area would be filled at a diminishing rate over a period of several or perhaps many years. This filling loss could not be recovered unless the reservoir were held at low stage for several years.

The manipulation of reservoir stage is an important control on movement of water to or from bank storage. The thickness of aquifer available for storage or release of water is directly related to the stage change in the reservoir. When the amount of drawdown is small, the amount of usable bank storage is small; when drawdown is large, the amount of usable bank storage could be large—depending on the character of the adjacent materials.

The amount of, and the time distribution of, available bank storage can be computed by a mathematical model from a knowledge of the geology of the bank materials, their hydraulic characteristics, and the stage fluctuations of the reservoir. Bank storage can also be computed from a water-budget analysis as a residual in the change-in-storage component:

Bank storage = outflow − inflow ± change in reservoir storage.

Separately, these methods are subject to a wide range in possible solutions; but when used in conjunction with each other, the range of potential solutions can be reduced.

A water budget for the combined reservoir and adjacent aquifer is:

$$(R_b + R_u + G_R) + P - O = \Delta S_r + \Delta S_a + \Delta S_B,$$

where R_b = inflow from the drainage basin except for the alluvim adjoining the reservoir,
R_u = surface runoff from the alluvium,
G_R = ground-water recharge to the aquifer adjacent to the reservoir,
P = precipitation on the reservoir,
O = outflow including flow past the dam and evaporation,
ΔS_r = change in reservoir storage,
ΔS_a = change in natural ground-water storage,
and ΔS_B = change in bank storage.

The sum of R_u and G_R is water yield for the area adjacent to the reservoir. In the water budget for the reservoir, this area was indexed on the basis of measured flow of streams which, for the most part, drain areas that permit very little recharge to ground water. It is apparent that the three terms in parentheses are equal to the runoff-inflow item of the reservoir budget. Terms O, P, and ΔS_r are identical in both budgets. Thus, for the reservoir water budget the residual includes $(\Delta S_B + \Delta S_a)$—that is, changes in bank storage plus changes in storage which would have occurred in the natural ground-water system under unregulated conditions.

In a later section equations are derived to describe bank-storage responses to reservoir-stage changes. The mathematical model does not include changes in aquifer storage which would have occurred in the unregulated ground-water system. The residual of the water budget for the reservoir does include this item as well as bank storage and unevaluated minor items, so results by the two procedures are not exactly compatible. The effects of the difference will be discussed in a later section.

DATA-COLLECTION PROGRAM

During September 1962, representatives of the Bonneville Power Administration and the Geological Survey made a field reconnaissance of the Hungry Horse Project area. As a result of this inspection and subsequent discussions, the decision was made to initiate a detailed study of the hydrology of Hungry Horse Reservoir. This study would seek to furnish a definitive answer to the basic problem of an apparent imbalance between reservoir inflows and outflows. Such an investigation would, within the limits of funds available, utilize both the water-budget and ground-water approaches previously discussed. The data-collection programs carried on for this investigation are outlined in the following sections.

During the summer of 1964, selection was made of the data-collection sites included in each of the various categories. Most of the construction and instrumentation was done at the same time. The data-collection program was started in October 1964, and was scheduled to continue until about November 1966. However, it was extended through April 1967, when it appeared that the reservoir drawdown during water year 1967 could be the maximum of record.

GAGING-STATION NETWORKS

The following gaging stations were in operation at the start of the investigation:

South Fork Flathead River at Spotted Bear Ranger Station near Hungry Horse
Sullivan Creek near Hungry Horse
Hungry Horse Reservoir near Hungry Horse
South Fork Flathead River near Columbia Falls

Data from the station South Fork Flathead River near Columbia Falls were used as a measure of outflow from the project. Data from the stations South Fork Flathead River at Spotted Bear Ranger Station near Hungry Horse and Sullivan Creek near Hungry Horse were used in the computation of inflow to the reservoir. Changes in reservoir contents were determined from the station Hungry Horse Reservoir near Hungry Horse.

To supplement this sparse network of gaging stations, eight additional gaging stations were installed to provide data on the reservoir inflow. These included:

South Fork Flathead River above Twin Creek near Hungry Horse
Twin Creek near Hungry Horse
Soldier Creek near Hungry Horse
Graves Creek near Hungry Horse
Canyon Creek near Hungry Horse
Goldie Creek near Hungry Horse
Wounded Buck Creek near Hungry Horse
Emery Creek near Hungry Horse

The location of these sites is shown in figure 7.

The runoff from about 82 percent of the total drainage area above Hungry Horse Reservoir was measured by gaging stations in this network. Their locations were selected to represent different sizes, shapes, and orientations of streams tributary to the reservoir. The primary network of gaging stations for measurement of reservoir inflow includes all stations shown in figure 7 except South Fork Flathead River near Columbia Falls and Hungry Horse Reservoir near Hungry Horse.

All the new gaging stations were temporary-type stations and were run only during the period of investigation with the exception of the station South Fork Flathead River above Twin Creek. This station replaced the gaging station South Fork Flathead River at Spotted Bear Ranger Station near Hungry Horse as a primary inflow station to Hungry Horse Reservoir. These two stations were operated concurrently for water years 1965–67 to develop correlation between the data for the two sites. The gaging station South Fork Flathead River above Twin Creek includes about 200 square miles more drainage area and measures a larger percentage of the total inflow to the reservoir.

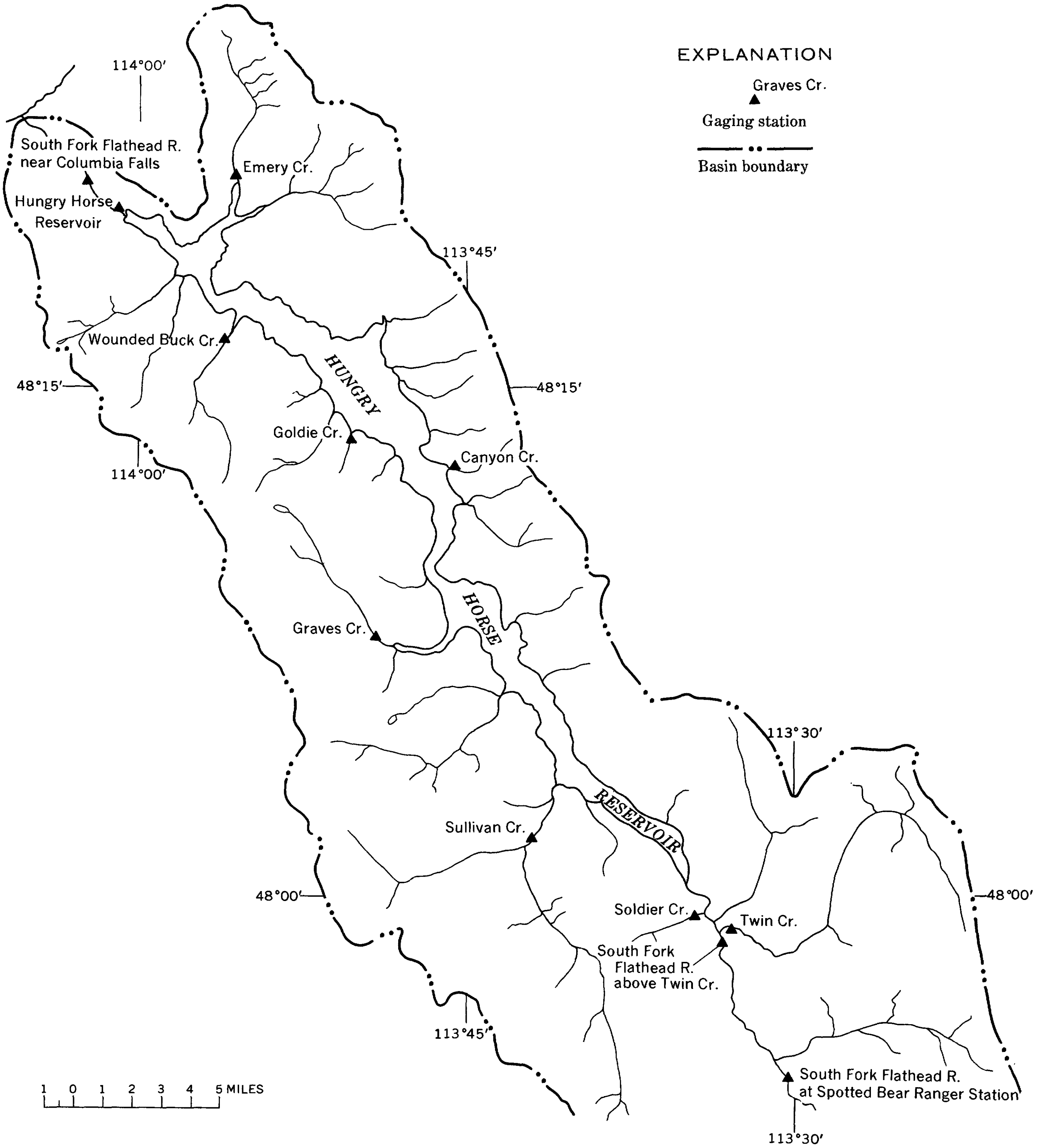

FIGURE 7.—Location of gaging stations in primary network, water years 1965–67.

In addition to the primary network of regular gaging stations listed above, a secondary network of partial-year gaging stations was established which included 20 sites. They are listed in table 5 (Nos. 12–31) and shown in figure 8.

Nineteen stations on streams directly tributary

Figure 8.—Location of gaging stations in secondary network, water years 1965–67.

to Hungry Horse Reservoir were selected to give broad areal coverage of the tributaries to Hungry Horse Reservoir not included in the primary gaging-station network. Size of drainage area, convenience of operation, and channel stability were the prime criteria used to select these sites. The drainage areas for these stations range in size from about 1 square mile, for Dry Park Creek, to more than 23 square miles, for Hungry Horse Creek. Eleven of these sites were on streams entering the east bank of the reservoir with a total drainage area of about 83 square miles. Eight sites were on streams entering the west bank with a total drainage area of about 64 square miles.

Aurora Creek, which enters the South Fork Flathead River below Hungry Horse Dam and above the outflow gage, was included in this network. The drainage area at this site is about 6.5 square miles, and the records provide data for the refinement of the evaluation of the outflow from the reservoir.

A staff gage or reference point was established at each site in this secondary gaging-station network. A partial record of stream stage was collected. Discharge measurements were made at intervals chosen to provide data covering a wide range in flow conditions.

Supplementing the primary and secondary network of gaging stations, miscellaneous discharge measurements were made at 40 additional sites on streams tributary to the Hungry Horse Reservoir. Measurements were normally made during the high-flow and low-flow periods only. Data collected at these sites were used as a guide in estimating the ungaged inflow to Hungry Horse Reservoir. The ungaged area encompasses about 125 square miles, of which 61 square miles is on the west side of the reservoir and 64 square miles on the east side.

DRAINAGE AREAS

During this investigation, the South Fork Flathead River basin was not completely covered by modern topographic maps. Earliest determinations of the drainage areas were computed from Forest Service planimetric maps at a scale of one-half inch=1 mile. The area of primary concern of this investigation deals with the drainage basin extending from the gaging station South Fork Flathead River at Spotted Bear Ranger Station near Hungry Horse downstream to the gaging station South Fork Flathead River near Columbia Falls. This area is covered by Forest Service planimetric maps in 15-minute quadrangles which were compiled from aerial photographs at a scale of 1:31,680, or 2 inches=1 mile. Generally, ridge lines and drainage direction were indicated on the maps. The individual drainage basins for the gaging stations in the primary and secondary networks and other miscellaneous areas used in this study were outlined on individual quadrangle maps. The subareas were planimetered and balanced for each quadrangle sheet and are summarized in table 5 and shown in figure 9.

TABLE 5.—*Drainage areas of subbasins, South Fork Flathead River basin, downstream from Spotted Bear Ranger Station*

No.	Subbasin	Area (sq mi)	Side of Hungry Horse Reservoir	Remarks
1	South Fork Flathead River at Spotted Bear Ranger Station near Hungry Horse	958		Primary network.
2	South Fork Flathead River above Twin Creek near Hungry Horse	1,160		Do.
3	Between Hungry Horse Dam and South Fork Flathead River near Columbia Falls	8.7		
4	Soldier Creek near Hungry Horse	4.77	West	Primary network.
5	Sullivan Creek near Hungry Horse	71.3	do	Do.
6	Graves Creek near Hungry Horse	27.0	do	Do.
7	Goldie Creek near Hungry Horse	3.29	do	Do.
8	Wounded Buck Creek near Hungry Horse	13.6	do	Do.
	Total	120		
9	Twin Creek near Hungry Horse	47.0	East	Primary network.
10	Canyon Creek near Hungry Horse	5.8	do	Do.
11	Emery Creek near Hungry Horse	26.4	do	Do.
	Total	79.2		
12	Clark Creek near Hungry Horse	4.38	West	Secondary network.
13	Battery Creek near Hungry Horse	2.45	do	Do.
14	Wheeler Creek near Hungry Horse	22.2	do	Do.
15	Forest Creek near Hungry Horse	4.69	do	Do.
16	Clayton Creek near Hungry Horse	6.13	do	Do.
17	Flossy Creek near Hungry Horse	1.60	do	Do.
18	Lost Johnny Creek near Hungry Horse	9.51	do	Do.
19	Doris Creek near Hungry Horse	13.5	do	Do.
	Total	64.5		
20	Lower Twin Creek near Hungry Horse	22.4	East	Secondary network.
21	Dry Park Creek near Hungry Horse	1.11	do	Do.
22	Hoke Creek near Hungry Horse	3.00	do	Do.
23	Logan Creek near Hungry Horse	6.73	do	Do.
24	Felix Creek near Hungry Horse	9.13	do	Do.
25	Harris Creek near Hungry Horse	2.79	do	Do.
26	Deep Creek near Hungry Horse	2.68	do	Do.
27	McInernie Creek near Hungry Horse	2.57	do	Do.
28	Murray Creek near Hungry Horse	3.08	do	Do.
29	Riverside Creek near Hungry Horse	5.83	do	Do.
30	Hungry Horse Creek near Hungry Horse	23.3	do	Do.
	Total	82.6		
31	Aurora Creek near Hungry Horse	6.5		Secondary network.
32	Ungaged area	61	West	
33	do	64	East	
34	Reservoir at full pool	37.2		

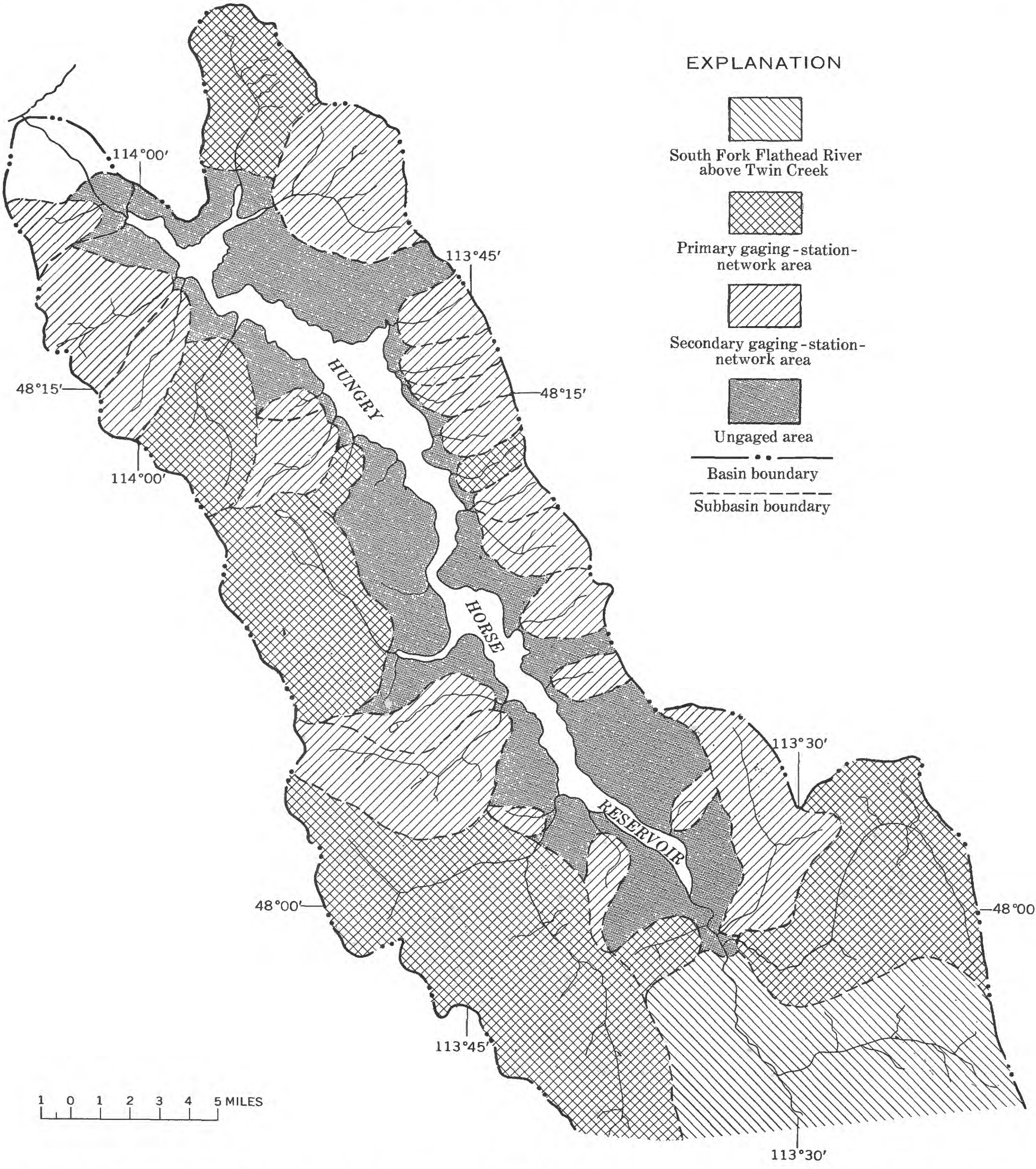

Figure 9.—Drainage areas of subbasins in South Fork Flathead River basin, downstream from Spotted Bear Ranger Station.

A part of this area was, at the time of this investigation, also covered by Geological Survey topographic maps. The drainage areas of 11 small tributary basins, common to both sets of maps, were planimetered and compared. This indicated an overall degree of comparability of about 1 percent.

In the area of primary concern, the incremental drainage area computed from the recent Forest Service maps was about 14 square miles larger than that computed from data in "Water Resources Data for Montana—Part 1, Surface Water Records" for water year 1965 (available from the U.S. Geol. Survey, Helena, Mont.). Since the Forest Service quadrangle maps were of a more recent edition and published at a larger scale, the drainage areas computed from them were used as needed throughout this report. The Bonneville Power Administration computed and furnished these drainage-area determinations as a contribution to the study.

CHANGE IN RESERVOIR CONTENTS

The collection of records at the gaging station Hungry Horse Reservoir near Hungry Horse was continued. The midnight reservoir elevations were furnished by the Bureau of Reclamation, and these were used to compute the change in contents of the reservoir.

Since 1964, direct determinations of the water level in the gage well and the reservoir have been made about twice a month by means of an electric tape gage. Thermal profiles of the water in the gage well and reservoir were made for various seasons of the year. Three temporary gages for recording the water-surface elevations of the reservoir were maintained for short periods of time to study local variations in water-surface elevations during periods of near-full pool.

EVAPORATION

The general procedures developed for the Lake Hefner and Lake Mead studies (p. 12) were adopted for use at Hungry Horse Reservoir. The inflow, outflow, and change-in-contents data needed were collected as part of the water-budget studies.

The measurements of radiation and vapor pressure were made at the south (left) elevator tower of the dam. Sensing elements consisting of an Eppley pyrheliometer, a flat-plate radiometer, and a thermocouple psychrometer were placed on the roof of the elevator tower. These were connected to an eight-channel recording potentiometer located inside the elevator tower. Observations of radiation and vapor pressure were recorded at 8-minute intervals on the potentiometer charts. Supplemental accumulating dials attached to each channel of the potentiometer were read daily.

The water-surface temperature and wind movement over the reservoir were recorded at two raft stations. One raft was at the log boom about 1,000 feet upstream from the dam, and the second was opposite the confluence of Graves Creek with the reservoir. These raft stations were serviced weekly. The mean daily water-surface temperatures were computed directly from the recorder charts. The wind movement at the 2-meter level was measured by an anemometer equipped with dials which accumulated the total wind movement in 10-mile units. In addition, the passage of each 10 miles of wind was recorded on the temperature-recorder charts by means of tick marks. Because daily wind records were not required in the energy-budget procedure, the total wind movement as determined by readings of the anemometer dials was used as the basic data.

Thermal surveys of the water stored in the reservoir were made at about 2-week intervals. Each thermal survey consisted of measuring the vertical water-temperature profile at 23 locations evenly spaced along the axis of the reservoir. The water-temperature observations were made from a boat utilizing a Whitney underwater thermometer. Additional thermal-profile data were collected at the log boom upstream from the dam to cover the balance of the period April 1966–April 1967 not included in the energy-budget evaporation study.

Continuous records of the water temperatures of seven streams tributary to Hungry Horse Reservoir were maintained at the following gaging stations:

South Fork Flathead River above Twin Creek, near Hungry Horse
Twin Creek near Hungry Horse
Soldier Creek near Hungry Horse
Sullivan Creek near Hungry Horse
Graves Creek near Hungry Horse
Canyon Creek near Hungry Horse
Emery Creek near Hungry Horse

The location of these sites is shown in figure 10.

A recording thermometer was also maintained at the gaging station downstream from Hungry Horse Dam (South Fork Flathead River near Columbia Falls). When releases were small or intermittent, however, the temperature of the water leaving the reservoir could change appreciably while flowing down the stream channel from the dam to the gaging station. Mean outflow temperature was therefore derived from the three components of flow:

1. Power flow, withdrawn at an elevation of 3,319 feet, whose temperature was measured as the water passed through the turbines.

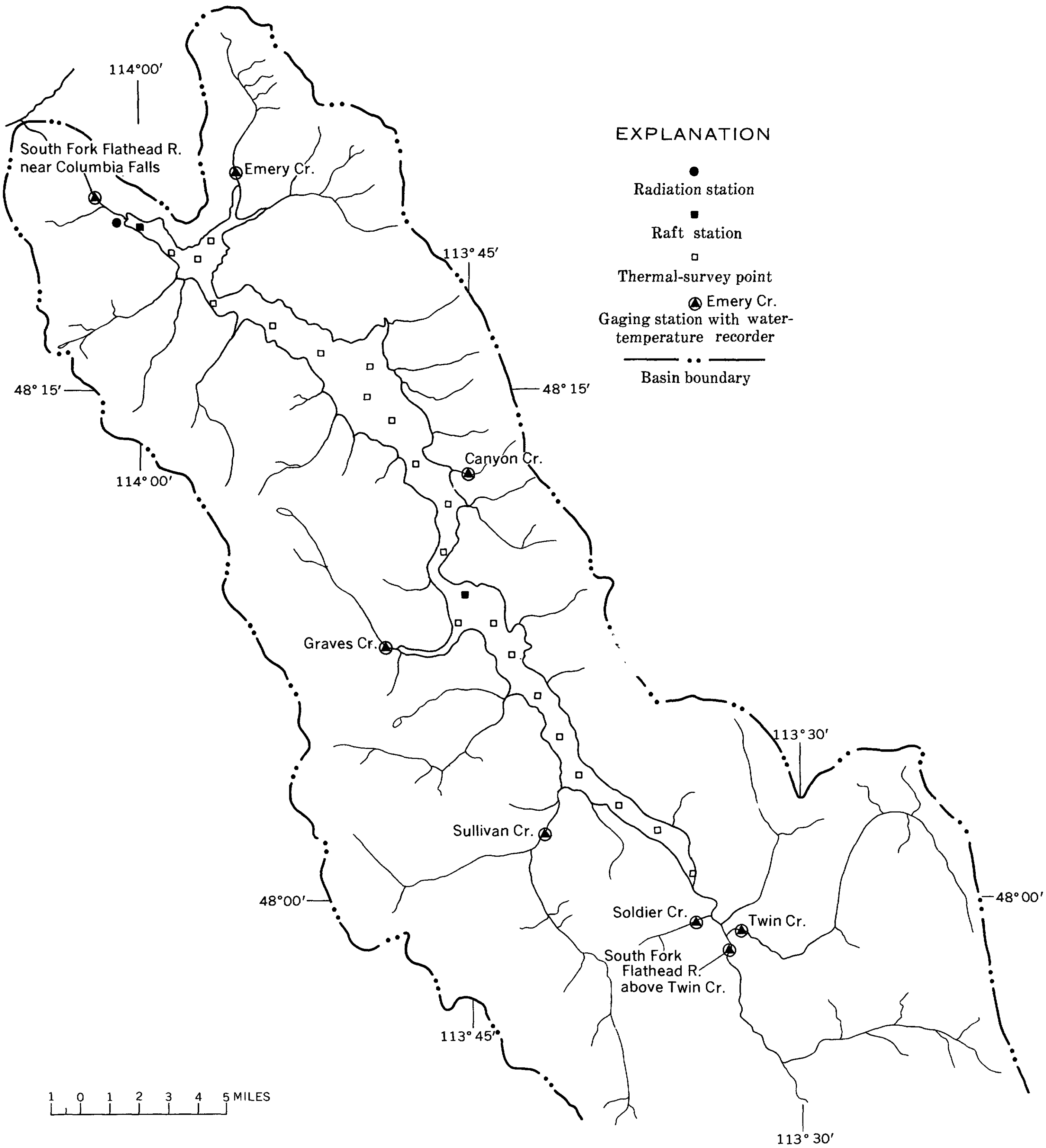

FIGURE 10.—Location of data-collection sites for energy-budget study of evaporation.

2. Spillway flow, from the surface of the full reservoir, whose temperature was measured by a recording thermometer on the instrument raft.
3. Reservoir release, withdrawn infrequently at an elevation of 3,196 feet, whose temperature was obtained from periodic reservoir surveys.

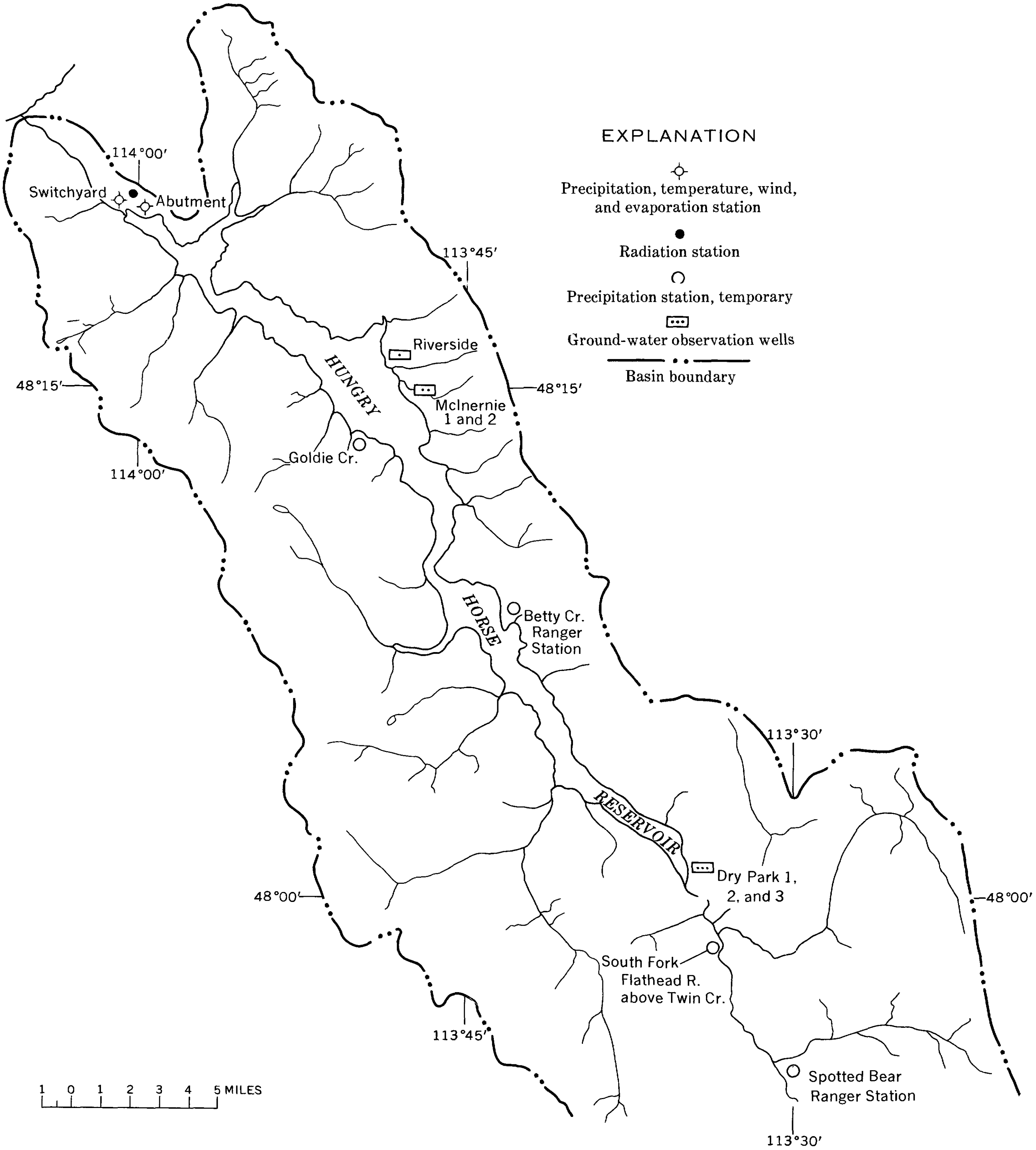

FIGURE 11.—Location of ancillary meteorological observation sites and ground-water observation wells.

ANCILLARY METEOROLOGICAL OBSERVATIONS

The Bureau of Reclamation has made daily weather observations at a site about one-fourth mile downstream from the dam in the project switchyard. Records for this station are included in the State Climatological Observations for the State of Montana as Hungry Horse Dam. Daily observations include maximum and minimum temperatures, precipitation, wind, and evaporation from a class A evaporation pan. The evaporation observations were normally made from about May through September. Since these observations might not be representative of the conditions at the surface of the reservoir, ancillary meteorological observations were made on the right abutment of the dam, just above the reservoir flow line. Daily temperature and humidity data were recorded in a standard Weather Bureau shelter. These were supplemented by observations of maximum and minimum air temperatures measured on Monday, Wednesday, and Friday of each week during the summertime period. Total solar radiation was also recorded at this site. On the Monday, Wednesday, and Friday schedule, observations were made of total wind movement at 5.5-foot and 11.5-foot levels, evaporation measurements were made from a class A pan, and precipitation amounts were measured in a standard 8-inch Weather Bureau gage.

Intermittent observations of precipitation were made by Geological Survey personnel during the summer seasons of 1965 and 1966 at the gaging stations Goldie Creek near Hungry Horse and South Fork Flathead River above Twin Creek and at Betty Creek Ranger Station. The Forest Service made daily observations of precipitation at the Spotted Bear Ranger Station during the fire seasons. The location of these ancillary meteorological observation sites is shown in figure 11.

GROUND-WATER OBSERVATION WELLS

During the summer of 1964, three ground-water observation wells were drilled in a 1500-foot-wide river terrace on the right bank of the reservoir about 2 miles downstream from the head of the reservoir and just upstream from Dry Park Creek. These wells were on a line which was perpendicular to the shore of the reservoir and extended toward the drainage divide on the eastern side of the reservoir. The wells were 195, 410, and 800 feet from the bank of the reservoir at full pool. Each of these wells was cased with steel pipe seated in gravel and equipped with a water-stage recorder.

During June 1966 three additional ground-water observation wells were drilled on the right bank of the reservoir about 10 miles upstream from Hungry Horse Dam. One of these observation wells was near a Forest Service boat-landing area at the mouth of Riverside Creek about 210 feet from the reservoir. Two other observation wells were about one-half mile upstream from the mouth of McInernie Creek, at distances of 115 and 340 feet from the reservoir. Each of these observation wells was cased with perforated steel pipe and equipped with a water-stage recorder.

The location of these ground-water observation wells is shown in figure 11. Geologic samples were obtained at each site. The thermal profiles of the water were measured at periodic intervals in the Dry Park and Riverside observation wells.

GEOLOGY OF THE RESERVOIR AREA

CONSOLIDATED ROCKS

The basin of the South Fork Flathead River is underlain principally by sedimentary rocks of the Belt Supergroup (Ross, 1959). In the lower part of the basin three formations of the Belt Supergroup are of interest. The oldest, the Ravalli Group, includes the Grinnell Formation, which is about 4,000 feet thick and consists of mostly siliceous argillite and a top unit of calcareous argillite. Overlying the Ravalli Group is the Piegan Group which includes the Siyeh Limestone, a laminated massive limestone about 5,000 feet thick having impurities of magnesia, silica, and argillaceous material. The Missoula Group, of much greater thickness, overlies the Piegan and consists of argillite, quartzitic argillite, and quartzite.

Major parallel faulting which trends north-northwest, uplift, and tilting produced a topography of high mountains and troughs. Formations dip toward the east-northeast at about 2,000 feet per mile. Hungry Horse Reservoir occupies a structurally controlled trough. Vertical displacement in the fault zone is several miles, the upthrown side being on the east.

The oldest rocks, the Grinnell Formation, crop out along the high-mountain basin divide about 8 miles west of the reservoir. Major streams entering the reservoir from the west head in the Grinnell flow across the younger Siyeh Limestone and thence across the Missoula Group. Main-channel valleys are partly filled with glacial-outwash deposits where they cross the Siyeh Limestone. Minor west-side tributaries to the reservoir head in and flow across the Missoula Group. Principal streams on the west side have tributary systems that are strongly influenced by the geologic dip. Westerly flowing secondary tributaries which flow across the bedding planes are short and have steep gradients. In contrast, easterly flowing secondary tributaries are longer, have less steep gradients, and have minor branches.

On the east side of the reservoir, the basin divide is in the upthrown Grinnell Formation and Siyeh Limestone. Tributaries to the reservoir flow westward across the bedding of the Grinnell. The east-side tributaries, compared to those on the west, are shorter, have steeper gradients, and contain much less glacial material in their valleys. An exception to the contrast in stream patterns is found in the headwater area on the east side where local faulting has produced a setting whereby Twin Creek and Lower Twin Creek have tributary systems which resemble Sullivan Creek on the west side.

Consolidated rocks which could be related to bank storage are (1) the Siyeh Limestone on which the dam was built and which forms the valley base and sides in the lowermost reaches of the reservoir and (2) part of the Missoula Group which is exposed along the western side of the valley and which underlies the alluvial fill in much of the reservoir area.

The limestone is generally resistant to solution. Joints which have been enlarged at the surface by weathering narrow with depth. They are commonly clay filled and in places have been filled with calcite. Very little movement of reservoir water to or from this limestone would be expected because of the very limited void space for storage and because only a small volume of this material is adjacent to the reservoir.

Rocks of the Missoula Group are fairly tight, and only in weathered zones would they be expected to transmit significant quantities of water. They are in direct contact with the reservoir in very limited areas—in the river bed near the head of pool and along the lower reaches of Graves, Hungry Horse, and Emery Creeks.

Because of limited exposure to the reservoir and small storage capability, these rocks are considered unimportant in the bank-storage studies. It is probable that there is a seepage zone at the contact of the soil zone and the top of the consolidated rocks. This would be consistent with observations of seeps and water in roadside ditches during a fairly dry period, September 24–27, 1962. Small amounts of water undoubtedly seep into the unconsolidated sediments adjacent to the reservoir.

UNCONSOLIDATED ROCKS

In the main valley of the South Fork Flathead River and in the lower reaches of some tributaries, rocks of the Belt Supergroup are covered by old alluvium and associated deposits. Ross (1959) grouped Tertiary and Pleistocene valley fill of sand, gravel, and silt as a unit. The map shows these materials as a 4-mile-wide deposit reaching an elevation of about 3,800 feet near the dam and about 4,300 feet near the head of the lake. The river flows through this material, and is flanked by modern alluvium of gravel, sand, and silt in a band ranging from one-fourth to 1 mile in width.

At the time the reservoir area was cleared, A. F. Bateman, Jr., Conservation Division, Geological Survey, mapped the unconsolidated deposits in and adjacent to the reservoir. He also constructed 80 cross sections. Very few subsurface data were available; hence these sections represent a large degree of interpretation. This unpublished material was of considerable value in the project studies.

Bateman (unpub. data, 1951–52) classified the unconsolidated material as follows:

Pleistocene till made up of well-graded mixtures of angular to rounded boulders, cobbles, pebbles, and sand with a matrix of silt or silty clay.

Pleistocene outwash consisting of glaciofluvial deposits underlying terraces from 10 to 150 feet above the Flathead River or associated with tributary streams. Mostly unconsolidated mixtures of gravel and sand with cobbles and boulders and minor amounts of interbedded sands and silts.

Pleistocene ponded deposits of laminated clay, silt, or interbedded clay and silt, mostly of very limited areal extent.

Holocene terrace gravel, reworked glacial-outwash material redeposited on terraces, consisting of clean mixtures of gravel and sand with minor amounts of interbedded silt and clay.

Holocene inactive alluvium consisting of coarse gravel-sand mixtures containing cobbles and boulders and in places silt with interbedded sand and silt, located in streambanks and beds below the depth of scour and in alluvial fans and cones.

Holocene active alluvium of similar character and location as the inactive alluvium but occasionally reworked during floods.

Alluvial deposits of slope wash, talus, and landslide deposits. Amounts of material in these classes are small.

The unconsolidated materials under and adjacent to the reservoir are by far the most important part of the bank-storage problem. Distribution of the types of material is complex. Using Bateman's unpublished map and sections, sediments were lumped into two groups, (1) those predominantly gravel and sand which might be expected to have a large storage coefficient and moderate to high hydraulic conductivity (permeability), and (2) till, which would be expected to have a low hydraulic conductivity. Volumes of saturated sediments were computed for the two groups by 20-foot increments of elevation for reservoir elevations between 3,560 and 3,320 feet (table 6 and fig. 12).

In the operating range of elevations of the power pool (above 3,336 feet), there are about 250,000 acre-feet of material of high bank-storage potential and about 1 million acre-feet of material of low bank-storage potential.

TABLE 6.—*Vertical distribution of saturated unconsolidated material in the reservoir area*

Range of elevation (feet above mean sea level)	Volume of material between given elevations (thousands of acre-feet)		
	Sand and gravel	Till	Total
3,560–3,540	18.2	84.4	102.6
3,540–3,520	21.1	97.0	118.1
3,520–3,500	22.5	98.4	120.9
3,500–3,480	24.1	101.9	126.0
3,480–3,460	25.4	104.6	130.0
3,460–3,440	23.4	96.8	120.2
3,440–3,420	19.8	82.9	102.7
3,420–3 400	14.9	75.4	90.3
3,400–3,380	15.3	71.0	86.3
3,380–3,360	17.1	66.6	83.7
3,360–3,340	16.2	59.4	75.6
3,340–3,320	16.7	52.3	69.0
Total	234.7	990.7	1,225.4

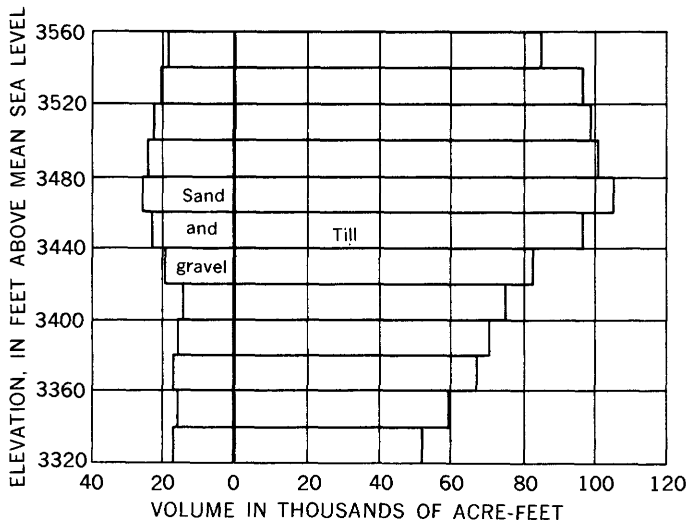

FIGURE 12.—Vertical distribution of unconsolidated sediments adjacent to Hungry Horse Reservoir.

ANALYSIS OF DATA

APPROACH TO PROBLEM

The apparent bank-storage effect was computed by two independent methods, (1) water budget and (2) mathematical model.

In the water-budget method, after all measured and (or) estimated components have been evaluated, the residual represents the bank-storage effect plus or minus the total accumulation of the errors in the components. The true value of bank storage may be masked by the error accumulation to such an extent that the results would be unusable. For the mathematical model, the aquifer constants are unknown and must be assumed. By the theoretical approach, any number of solutions can be computed, depending on the input constants assumed.

Either method taken alone will produce bank-storage values having a wide range of uncertainty. The two methods, when used jointly, provide a powerful tool for reducing some of the uncertainties in the bank-storage determination. Comparison of theoretical models with field data pointed to discrepancies which led to correction of several mistakes in record calculation, reanalysis of two rating curves, and reestimate of ungaged inflow. The range of values for the aquifer constants in the mathematical model was narrowed on the basis of the modified field data. The principal purpose for constructing and refining the mathematical model was to provide a working tool for predicting availability of water for power generation, both for this study and for application at other sites.

WATER BUDGET

Bank-storage estimates were computed by the water-budget method as one approach in this investigation. Basically, the procedure involves balancing the measured and (or) estimated inflows against the outflows modified for changes in reservoir content. This is simple in theory, but many complications are inherent when the object is the degree of accuracy required to evaluate the potential magnitude of bank storage.

The computations for the water budget were made in terms of monthly runoff volumes, expressed as cfs-days. The monthly volumes were derived from daily records or estimates.

Monthly totals were computed to the same number of significant figures used in the publication of the data and were then rounded off to the nearest cfs-day. These monthly values were used throughout the study until the final values were selected. This produced a greater number of significant figures in the basin totals than might be warranted, but excessive rounding of the larger components of the budget could distort the final values beyond usable limits.

Most of the basic data for this study have been presented in "Water Resources Data for Montana—Part 1, Surface Water Records" and "Part 2, Water Quality Records," for water years 1965, 1966, and 1967 (available from the U.S. Geol. Survey, Helena, Mont.). A basic-data supplement containing these and other data collected for this study was released to open file in 1968 (Simons, 1968).

INFLOW

The inflow to Hungry Horse Reservoir was assumed to be the runoff from the tributary streams included in the primary and secondary gaging-station networks plus the runoff from the ungaged area plus that resulting from precipitation on the surface of the reservoir. Each component of reservoir inflow is outlined in the following sections.

PRIMARY GAGING-STATION NETWORK

Part of the inflow to Hungry Horse Reservoir was measured at nine stations in the primary gaging-station network. These stations have a combined drainage area of about 1,360 square miles and include one station on the South Fork Flathead River, three stations on east-side tributaries, and five stations on west-side tributaries.

The following are the gaging stations on the east-side tributaries:

Twin Creek near Hungry Horse
Canyon Creek near Hungry Horse
Emery Creek near Hungry Horse

These stations have a total drainage area of 79.2 square miles (see table 5). The discharge records for these stations are complete for the period of study and have been used as published. They are summarized in table 7.

The following are the gaging stations on the westside tributaries:

Soldier Creek near Hungry Horse
Sullivan Creek near Hungry Horse
Graves Creek near Hungry Horse
Goldie Creek near Hungry Horse
Wounded Buck Creek near Hungry Horse

These stations have a combined drainage area of 120 square miles (see table 5). The records for these stations are complete for the period of study and were used as published except as noted below.

TABLE 7.—*Summary of monthly runoff for gaging stations on east-side tributaries to Hungry Horse Reservoir*

Month	Monthly runoff (cfs–days)			
	Twin Creek	Canyon Creek	Emery Creek	Total (rounded)
1964				
Oct	1,231	121.7	274.6	1,628
Nov	1,005	107.1	257.2	1,369
Dec	1,465	133.6	532	2,131
1965				
Jan	1,160	72.2	348.8	1,581
Feb	1,075	74.7	289.9	1,440
Mar	1,126	81.3	423	1,630
Apr	7,253	456.8	2,926	10,436
May	15,027	1,249	4,648	20,924
June	12,686	1,810	2,608	17,104
July	2,446	376.4	726	3,548
Aug	926	136.7	359	1,422
Sept	1,880	187.9	340	2,408
Oct	1,155	144.1	295.9	1,595
Nov	952	90.8	227.7	1,271
Dec	1,091	75.3	237.4	1,403
1966				
Jan	594	58.8	170.9	824
Feb	432	41.6	132.2	606
Mar	1,388	109.3	268.3	1,765
Apr	6,499	338.1	1,689	8,526
May	15,378	1,266.3	2,893	19,537
June	10,015	1,032	2,604	13,651
July	1,935	302.3	924	3,161
Aug	612	106.2	362.2	1,080
Sept	360	62.1	214.4	636
Oct	352	61.6	190.1	604
Nov	503	69.9	190.3	763
Dec	789	104.0	314.5	1,207
1967				
Jan	705	84.5	311.5	1,101
Feb	800	78.8	398	1,277
Mar	863	62.5	316.6	1,244
Apr	3,294	201.7	750	4,246
Total	94,997	9,097.3	26,022.5	130,118

The low-water records for Graves Creek near Hungry Horse were revised for the period October 1, 1964—April 19, 1965. The rating curve used during this period lacked definition below 45 cfs. Low-water measurements made during water years 1966 and 1967 indicated that a redefinition of the lower end of that rating curve was justified.

The discharge records for the gaging station Goldie Creek near Hungry Horse were not collected prior to May 1965. Daily discharges for October 1964–April 1965 were estimated by means of correlation with the daily discharges for Graves and Sullivan Creeks. The comparisons between these stations were of good quality, and the runoff estimated by the above method is comparable in accuracy to later runoff determinations.

The daily discharge records for Wounded Buck Creek near Hungry Horse during August and September 1966 were corrected for purposes of this study. Summaries of monthly runoff for this group of gaging stations are shown in table 8.

The remaining gaging station in the primary network is the South Fork Flathead River above Twin Creek. This station, with a drainage area of

TABLE 8.—*Summary of monthly runoff for gaging stations on west-side tributaries to Hungry Horse Reservoir*

Month	Monthly runoff (cfs-days) Soldier Creek	Sullivan Creek	Graves Creek	Goldie Creek	Wounded Buck Creek	Total (rounded)
1964						
Oct	130.0	3,646	[1] 2,125	[2] 185	1,296	7,382
Nov	146.4	3,041	[1] 2,297	[2] 193	1,271	6,948
Dec	414.5	4,843	[1] 3,275	[2] 254	2,214	11,000
1965						
Jan	229.9	2,438	[1] 1,197	[2] 110	1,031	5,006
Feb	178.1	2,084	[1] 888	[2] 89	801	4,040
Mar	164.9	2,065	[1] 939	[2] 95	823	4,087
Apr	893.2	11,708	[1] 4,942	[2] 593	2,950	21,086
May	1,491	26,701	12,379	1,636	7,225	49,432
June	872	27,088	18,741	1,612	10,448	58,761
July	237.2	5,989	6,018	298.3	4,452	16,994
Aug	148.9	2,957	1,875	75.2	1,617	6,674
Sept	145.8	5,368	3,034	136.2	1,302	9,986
Oct	123.1	2,737	1,369	72.8	925	5,227
Nov	180.9	2,476	1,940	177.8	1,061	5,836
Dec	185.6	2,236	1,162	128.9	806	4,519
1966						
Jan	131.8	1,359	809	76.2	658	3,034
Feb	89.3	938	519	39.1	472	2,057
Mar	224.5	2,347	871	109.9	686	4,238
Apr	801	10,519	4,183	428.5	2,475	18,406
May	1,226	24,407	12,158	1,401	6,618	45,811
June	665.9	20,061	12,131	1,069	6,993	40,920
July	223.6	5,996	4,131	236.3	2,689	13,276
Aug	115.9	1,440	829	61.7	[1] 1,297	3,744
Sept	86.6	951	512	40.5	[1] 720	2,310
Oct	89.8	1,110	786	67.6	810	2,863
Nov	105.4	1,451	1,241	105.9	882	3,785
Dec	214.8	2,413	1,955	217.7	1,249	6,050
1967						
Jan	189.1	1,866	1,300	161.8	1,064	4,581
Feb	186.1	1,703	1,094	134.9	841	3,959
Mar	143.1	1,353	767	102.0	627	2,992
Apr	431.0	3,803	1,579	162.3	930	6,905
Total	10,465.4	187,094	107,047	10,070.6	67,233	381,909

[1] Revised.
[2] Estimated.

1,160 square miles, replaced the station at Spotted Bear Ranger Station as the main inflow gage. It measures a larger part of the inflow to Hungry Horse Reservoir, has better physical and hydraulic characteristics, and should in the long run provide a better index of reservoir inflow. The exposed location of this gaging station and its channel characteristics should tend to decrease the number and frequency of ice-affected periods. The two rating curves used for the computation of high-water records showed some divergence in shape, and the low-water periods were affected slightly by road-construction activities. But for the initial comparison, no revisions in published data were made. The total inflow to the reservoir as indicated by the primary network of gaging stations is summarized in table 9.

SECONDARY GAGING-STATION NETWORK

Another part of the inflow to Hungry Horse Reservoir was measured at 19 sites included in the secondary gaging-station network. Eleven of these sites, with a total drainage area of 82.6 square miles, were on streams entering the east side of the reservoir. Eight sites, with a total drainage area of 64.5 square miles, were on west-side tributary streams.

TABLE 9.—*Summary of monthly inflow to Hungry Horse Reservoir from stations in primary gaging-station network*

Month	Monthly runoff (cfs-days) South Fork Flathead River above Twin Creek	East-side gaging stations	West-side gaging stations	Total
1964				
Oct	25,968	1,628	7,382	34,978
Nov	18,596	1,369	6,948	26,913
Dec	25,932	2,131	11,000	39,063
1965				
Jan	18,751	1,581	5,006	25,338
Feb	14,160	1,440	4,040	19,640
Mar	16,794	1,630	4,087	22,511
Apr	87,746	10,436	21,086	119,268
May	264,480	20,924	49,432	334,836
June	346,460	17,104	58,761	422,325
July	118,010	3,548	16,994	138,552
Aug	35,559	1,422	6,674	43,655
Sept	47,496	2,408	9,986	59,890
Oct	30,939	1,595	5,227	37,761
Nov	18,811	1,271	5,836	25,918
Dec	16,374	1,403	4,519	22,296
1966				
Jan	12,773	824	3,034	16,631
Feb	9,657	606	2,057	12,320
Mar	15,642	1,765	4,238	21,645
Apr	75,620	8,526	18,406	102,552
May	254,450	19,537	45,811	319,798
June	202,610	13,651	40,920	257,181
July	66,592	3,161	13,276	83,029
Aug	20,119	1,080	3,744	24,943
Sept	12,703	636	2,310	15,649
Oct	10,783	604	2,863	14,250
Nov	11,390	763	3,785	15,938
Dec	12,327	1,207	6,050	19,584
1967				
Jan	11,903	1,101	4,581	17,585
Feb	11,737	1,277	3,959	16,973
Mar	11,896	1,244	2,992	16,132
Apr	28,389	4,246	6,905	39,540
Total	1,854,667	130,118	381,909	2,366,694

Discharge measurements were made to define the stage-discharge relationship at each site. The average number of discharge measurements made at each location was 15. Most of the stage-discharge curves were of good to excellent quality, and a few maintained a single relationship during the entire period of study. However, a few streams, notably Lower Twin and Deep Creeks, shifted almost continuously as a result of channel modifications caused by the 1964 high water.

Stage readings at each site were made at irregular intervals throughout the year, the largest number being made during periods of high runoff. Fewer readings were made during the recession and base-flow periods.

A partial record of daily discharges for each site was computed from these discharge and stage data. These partial-year discharge records were graphically compared to the discharge records for all stations in the primary gaging-station network. Most of these secondary stations correlated well with one or more of the stations in the primary network. A complete record of daily discharges for each secondary site was developed from these comparisons, using a consistent pattern for the 31 months studied.

TABLE 10.—*Summary of monthly runoff for secondary-network stations on east side of Hungry Horse Reservoir*

Month	Monthly runoff (cfs-days)											
	Lower Twin Creek	Dry Park Creek	Hoke Creek	Logan Creek	Felix Creek	Harris Creek	Deer Creek	McInernie Creek	Murray Creek	Riverside Creek	Hungry Horse Creek	Total
1964												
Oct	793	28	186	155	294	140	97	70	67	116	636	2,582
Nov	700	23	167	136	245	116	86	57	59	101	530	2,220
Dec	1,042	34	240	169	381	170	107	90	75	129	830	3,267
1965												
Jan	747	26	147	93	272	90	52	64	41	69	604	2,205
Feb	695	25	112	96	248	87	54	60	42	70	540	2,029
Mar	729	25	114	106	282	96	60	63	47	77	619	2,218
Apr	4,149	161	302	726	1,738	380	279	376	309	404	3,739	12,563
May	7,865	334	630	1,861	3,670	736	726	920	877	1,114	8,382	27,115
June	9,310	294	989	2,551	3,657	1,097	1,136	722	1,290	2,175	6,507	29,728
July	1,988	80	488	567	765	276	297	134	245	532	1,442	6,814
Aug	707	41	233	201	226	120	107	54	80	171	557	2,497
Sept	1,180	61	176	274	309	119	149	104	130	272	859	3,633
Oct	877	36	118	192	251	121	114	73	90	194	443	2,509
Nov	727	30	96	122	211	93	71	45	55	117	345	1,912
Dec	826	35	81	101	225	86	57	39	44	88	320	1,902
1966												
Jan	448	20	65	78	132	72	42	32	33	59	253	1,234
Feb	337	16	47	54	101	51	29	23	23	39	178	898
Mar	839	28	106	136	262	115	82	68	67	149	554	2,406
Apr	3,700	75	287	414	1,048	282	260	312	342	588	2,622	9,930
May	8,545	178	619	1,619	2,779	614	892	808	820	2,388	5,825	25,087
June	5,807	148	708	1,507	2,049	736	731	570	448	1,728	4,624	19,056
July	1,328	59	346	479	528	257	224	101	125	351	1,078	4,876
Aug	440	22	157	121	187	111	82	35	48	100	341	1,644
Sept	253	10	98	72	108	78	49	27	36	57	202	990
Oct	242	9	86	86	96	75	41	31	38	54	181	939
Nov	344	12	95	99	125	84	46	38	41	60	227	1,171
Dec	555	20	146	145	196	122	71	62	54	88	361	1,820
1967												
Jan	517	18	125	114	179	100	62	55	41	73	327	1,611
Feb	563	19	108	114	211	93	60	64	36	67	384	1,719
Mar	610	20	72	91	200	72	47	63	36	54	374	1,639
Apr	2,198	84	103	262	684	204	143	213	123	160	1,273	5,447
Total	59,061	1,971	7,247	12,741	21,659	6,793	6,253	5,373	5,762	11,644	45,157	183,661

TABLE 11.—*Summary of monthly runoff for secondary-network stations on west side of Hungry Horse Reservoir*

[Values for Aurora not included in total values]

Month	Monthly runoff (cfs-days)									
	Clark Creek	Battery Creek	Wheeler Creek	Forest Creek'	Clayton Creek	Flossy Creek	Lost Johnny Creek	Doris Creek	Total (rounded)	Aurora Creek
1964										
Oct	85.6	99.1	1,398	333	453.6	92.4	502	610	3,574	207.1
Nov	98.6	106.1	1,313	279	484.1	96.5	496	592	3,465	204.8
Dec	293.3	201.2	2,283	439.5	675.6	126.8	874	1,047	5,940	362.7
1965										
Jan	154.7	106.5	937	215.5	269.2	55.3	402	480	2,620	168.8
Feb	119.4	85.3	814	182.0	225.1	44.5	317	373	2,160	132.0
Mar	112.2	79.4	790	181.0	223.2	47.3	325.6	382.5	2,141	136.5
Apr	841.4	425.4	4,344	1,042.5	1,384	251.2	1,106.9	1,376	10,771	498.9
May	1,635	964	9,775	2,308	3,591	728.2	2,898	3,394	25,293	1,621
June	995	1,041	12,330	2,103	3,675	647.3	4,216	5,120	30,127	2,266
July	193.1	277.8	3,193	518.3	845.8	85.3	1,738	2,198	9,049	847
Aug	92.3	117.1	1,443	183.2	236.9	32.3	586	932	3,623	312.2
Sept	137	111.3	2,078	202.7	307.8	59.2	512	767	4,175	300.1
Oct	90.1	99.5	1,153	147.9	189.9	43.3	256.5	588	2,568	217.6
Nov	121.6	123	1,095	166.1	305.6	102.4	317.1	631	2,862	207.9
Dec	123	103	807	138.5	181.6	73.7	223.4	451	2,101	130.7
1966										
Jan	88.2	79.0	564	113.5	147.3	43.6	180.4	365	1,581	106.6
Feb	58.4	47.5	368	91.5	99.6	22.1	128.1	262.5	1,078	76.7
Mar	159.6	81.5	713	187.0	202.5	55.8	190.5	375.7	1,966	98.6
Apr	688	278.0	3,352	673	903	194.3	787	1,353	8,228	353.0
May	1,485	827	9,710	1,560	2,554	704.5	2,557	3,642	23,040	1,583
June	839	592.6	7,908	1,329	2,303	427.1	3,169	3,896	20,464	1,964
July	176	179.5	2,884	370.5	667.1	67.6	989	1,513	6,847	733
Aug	81.8	94.0	679	141.5	136.1	11.5	334.3	691	2,169	294.3
Sept	51.8	65.0	446	89.0	124.1	7.1	193.5	371	1,348	158.3
Oct	66.1	72.0	442	101	162.6	12.9	202.5	336.6	1,396	147.3
Nov	78.8	88.3	570	130.5	201.3	20.4	220.5	354.2	1,664	158.3
Dec	158.0	175.5	966	295.3	342.6	41.7	312.2	506	2,797	223.4
1967										
Jan	136.8	151.1	735	216.6	296.0	31.5	266.0	428	2,261	189.7
Feb	138.2	153.4	682	244.4	241.8	26.5	210.2	343	2,040	152.3
Mar	104.4	117.2	528	207.4	178.0	19.2	156.8	254.8	1,566	114.4
Apr	310.5	344.8	1,463	420.4	419.4	30	232.5	374.0	3,595	165.0
Total	9,712.9	7,286.1	75,763	14,610.8	22,026.8	4,201.5	24,900	34,007.3	192,509	14,131.2

Monthly runoff for each site, in cfs-days and in inches, was computed from the daily discharges. All stations in the primary and secondary networks were compared as a test of regional homogeneity, and adjustments were made where justified. Estimates of the inflow to the reservoir from this secondary network of stations are considered to be good and are almost as reliable as the runoff derived from the stations in the primary network. The results of these computations are summarized in tables 10, 11, and 12.

TABLE 12.—*Summary of monthly inflow to Hungry Horse Reservoir from stations in secondary gaging-station network*

	Monthly inflow (cfs-days)		
Month	East side	West side	Total
1964			
Oct	2,582	3,574	6,156
Nov	2,220	3,465	5,685
Dec	3,267	5,940	9,207
1965			
Jan	2,205	2,620	4,825
Feb	2,029	2,160	4,189
Mar	2,218	2,141	4,359
Apr	12,563	10,771	23,334
May	27,115	25,293	52,408
June	29,728	30,127	59,855
July	6,814	9,049	15,863
Aug	2,497	3,623	6,120
Sept	3,633	4,175	7,808
Oct	2,509	2,568	5,077
Nov	1,912	2,862	4,774
Dec	1,902	2,101	4,003
1966			
Jan	1,234	1,581	2,815
Feb	898	1,078	1,976
Mar	2,406	1,966	4,372
Apr	9,930	8,228	18,158
May	25,087	23,040	48,127
June	19,056	20,464	39,520
July	4,876	6,847	11,723
Aug	1,644	2,169	3,813
Sept	990	1,348	2,338
Oct	939	1,396	2,335
Nov	1,171	1,664	2,835
Dec	1,820	2,797	4,617
1967			
Jan	1,611	2,261	3,872
Feb	1,719	2,040	3,759
Mar	1,639	1,566	3,205
Apr	5,447	3,595	9,042
Total	183,661	192,509	376,170

UNGAGED AREAS

Figure 9 shows the ungaged areas interspersed between streams in the primary and secondary gaging-station networks and around the periphery of Hungry Horse Reservoir. Miscellaneous discharge measurements made at 40 locations in these areas, sampled the runoff from about one-half of the residual area were considered to be representative of the entire ungaged area.

Discharge measurements at these locations were made during high-flow and low-flow periods only, each miscellaneous set being made within a period of a few days. Estimates of reservoir inflow from various segments of the ungaged drainage area were based on these data. Composite estimates were prepared for the ungaged inflow from the east-side and west-side areas separately and were compared to individual stations and groups of stations in the primary and secondary networks.

For the drainage area on the east side of the reservoir, a coefficient of 0.75 times the total inflow of the east-side stations in the secondary gaging-station network provided the best apparent means of computing this segment of reservoir inflow. The ratio of the east-side drainage areas for the ungaged and secondary networks is 64/82.6 or 0.775. The coefficient of 0.75 is slightly smaller than the drainage-area ratio and was used to compute the reservoir inflow from the east-bank ungaged area.

On the west bank, a coefficient of 0.9 times the total inflow of the west-bank secondary stations appeared to give the best results. The drainage-area ratio for the west-side ungaged and secondary-network areas is 61/64.5, or 0.946. The coefficient of 0.9 was used to compute reservoir inflow from this residual area.

The total reservoir inflow from the ungaged area was assumed to be the sum of the east-side and west-side estimates. These are summarized in table 13. Estimates of the reservoir inflow for other combinations of segments of the ungaged drainage area were prepared, but no significant differences from

TABLE 13.—*Summary of monthly inflow to Hungry Horse Reservoir from the ungaged areas*

[Based on $0.75 \times \Sigma$ east-side secondary stations and on $0.9 \times \Sigma$ west-side secondary stations]

	Monthly inflow (cfs-days)		
Month	East side	West side	Total
1964			
Oct	1,936	3,217	5,153
Nov	1,665	3,118	4,783
Dec	2,450	5,346	7,796
1965			
Jan	1,654	2,358	4,012
Feb	1,522	1,944	3,466
Mar	1,664	1,927	3,591
Apr	9,422	9,694	19,116
May	20,336	22,764	43,100
June	22,296	27,114	49,410
July	5,110	8,144	13,254
Aug	1,873	3,260	5,133
Sept	2,725	3,758	6,483
Oct	1,882	2,311	4,193
Nov	1,434	2,576	4,010
Dec	1,426	1,890	3,316
1966			
Jan	926	1,423	2,349
Feb	674	970	1,644
Mar	1,804	1,769	3,573
Apr	7,448	7,405	14,853
May	18,815	20,736	39,551
June	14,292	18,418	32,710
July	3,657	6,162	9,819
Aug	1,233	1,952	3,185
Sept	742	1,212	1,954
Oct	704	1,256	1,960
Nov	878	1,498	2,376
Dec	1,365	2,517	3,882
1967			
Jan	1,208	2,035	3,243
Feb	1,289	1,836	3,125
Mar	1,229	1,409	2,638
Apr	4,085	3,236	7,321
Total	137,744	173,255	310,999

those shown in table 13 were indicated. Thus it was assumed that the above procedure provides reasonable estimates of this segment of the inflow to Hungry Horse Reservoir.

PRECIPITATION

In the water-budget studies, precipitation falling directly on the reservoir was treated as an inflow component and was added to other increments of inflow. The precipitation data for Hungry Horse Dam, the only complete year-round record available within the drainage basin, were used in these computations. Comparison with short-term precipitation records collected at the top of the dam, on the right abutment, at Spotted Bear Ranger Station, at South Fork Flathead River above Twin Creek, at Goldie Creek, and at Betty Ranger Station indicates that these data are fairly representative. Some variations are known to exist, but data are insufficient to make any real distinctions.

Daily estimates of inflow to the reservoir were prepared by applying the observed precipitation amounts to the area of the full reservoir pool (24,000 acres). Monthly totals were computed from the daily values. This procedure was modified during the period December–April to account for snow accumulation on that part of the reservoir area between actual water surface and reservoir flow line. During this period, daily inflow amounts were computed using the actual water-surface area. The precipitation falling on the remaining area below the flow line and above the reservoir surface was assumed to be snow which did not contribute immediately to reservoir inflow. This amount was accumulated for the period December–March and was assumed to melt during April and to become effective reservoir inflow at that time. Thus for April the inflow would be the effective precipitation falling on the total surface of the reservoir plus the December–March accumulation. This is not precise but for purposes of this study was assumed to be satisfactory.

TOTAL RESERVOIR INFLOW

The total monthly inflow to Hungry Horse Reservoir is assumed to be the sum of the runoff measured by the gaging-station networks, plus that estimated for the ungaged area, plus that for precipitation falling on the reservoir surface. The inflow for the period of study is summarized in table 14.

TABLE 14.—*Summary of monthly inflow to Hungry Horse Reservoir*

Month	Monthly inflow (cfs-days)					
	From primary network	From secondary network	From ungaged area	Subtotal (columns 2–4)	Precipitation	Total
1964						
Oct	34,978	6,156	5,153	46,287	2,928	49,215
Nov	26,913	5,685	4,783	37,381	4,881	42,262
Dec	39,063	9,207	7,796	56,066	7,931	63,997
1965						
Jan	25,338	4,825	4,012	34,175	3,485	37,660
Feb	19,640	4,189	3,466	27,295	2,612	29,907
Mar	22,511	4,359	3,591	30,461	212	30,673
Apr	119,268	23,334	19,116	161,718	5,067	166,785
May	334,836	52,408	43,100	430,344	1,730	432,074
June	422,325	59,855	49,410	531,590	3,771	535,361
July	138,552	15,863	13,254	167,669	1,246	168,915
Aug	43,655	6,120	5,133	54,908	4,331	59,239
Sept	59,890	7,808	6,483	74,181	3,558	77,739
Oct	37,761	5,077	4,193	47,031	907	47,938
Nov	25,918	4,774	4,010	34,702	3,253	37,955
Dec	22,296	4,003	3,316	29,615	1,552	31,167
1966						
Jan	16,631	2,815	2,349	21,795	2,922	24,717
Feb	12,320	1,976	1,644	15,940	1,308	17,248
Mar	21,645	4,372	3,573	29,590	2,278	31,868
Apr	102,552	18,158	14,853	135,563	3,937	139,500
May	319,798	48,127	39.551	407,476	2,166	409,642
June	257,181	39,520	32,710	329,411	6,518	335,929
July	83.029	11,723	9,819	104,571	1,579	106,150
Aug	24,943	3,813	3,185	31,941	2,153	34,094
Sept	15,649	2,338	1,954	19,941	641	20,582
Oct	14,250	2,335	1,960	18.545	3,360	21,905
Nov	15,938	2,835	2,376	21,149	5,428	26,577
Dec	19,584	4,617	3,882	28,083	2,945	31,028
1967						
Jan	17,585	3,872	3,243	24,700	4,068	28,768
Feb	16,973	3,759	3,125	23,857	861	24,718
Mar	16,132	3,205	2,638	21,975	1,236	23,211
Apr	39,540	9,042	7,321	55,903	6,034	61,937
Total	2,366,694	376,170	310,999	3,053,863	94,898	3,148,761

OUTFLOW

The determination of the outflows from the Hungry Horse Project requires the consideration of three items: (1) runoff measured at the gaging station South Fork Flathead River near Columbia Falls, (2) runoff from the intervening area between Hungry Horse Dam and the outflow gaging station, and (3) evaporation from the water surface of Hungry Horse Reservoir. The last two are small in comparison to the measured discharge at the gaging station, except during the summer months when minimum releases are being made from the reservoir.

The gaging station South Fork Flathead River near Columbia Falls has been considered as measuring the outflow from the Hungry Horse Project and has been at its present site, 1¾ miles downstream from the dam, since October 1953. The control section and the stage-discharge relationship for this gaging station has remained very stable, and most records have been rated as excellent. Two stage-discharge relation curves, with a spread of about 3 percent, were used in the computation of daily discharges during the period of this investigation. There were no periods of ice-affected record during the period of study. Records for the period October 9–22, 1964, were revised to correct for a minor instrument malfunction. Other than this, the published records were used in the preliminary water-budget computations.

The amount of channel storage between the dam and the gaging station was evaluated by considering the range in stage and the average areas of the channel in its 1¾-mile length. This would amount to about 12 cfs per foot of range in stage at the tail water of the dam. This could be a factor that should be included if modifications were made on a daily basis when the change in stage would amount to 8 or 12 feet, but on a monthly basis the potential amount of channel storage is minor. Thus in this investigation it was not considered.

The record for the downstream gaging station includes not only the water discharged past the dam but also the runoff from the 8.7 square miles of intervening area. Consideration was given to the possibility of moving the outflow gaging station upstream to a point where the intervening drainage area would be much smaller, but it was not considered feasible at that time. In lieu thereof, the contribution of this intervening drainage area was estimated by use of a partial-year gaging station on Aurora Creek. The drainage area of Aurora Creek amounts to 6.5 square miles. The contribution for the total 8.7 square miles was estimated by multiplying the contribution in Aurora Creek by a factor of 1.34. This amount was subtracted from the runoff for the station at South Fork Flathead River near Columbia Falls, giving a more precise measure of the flow passing Hungry Horse Dam.

Evaporation from the water surface of Hungry Horse Reservoir was computed by the energy-budget method for 23 periods extending from May 11 to October 20, 1965, and from May 11 to November 2, 1966. These computations produced small negative values for evaporation during periods 1 (May 11–26, 1965) and 13 (May 25–June 2, 1966). Inflow volumes and changes in stored energy were very large for both of these periods, and conditions were unfavorable. Also, the balance motor in the recording potentiometer for the radiation station burned out during period 13 and had to be replaced. Most of the radiation and humidity data for period 13 were estimated rather than observed.

Evaporation was also computed by the mass-transfer formula, developed by the Lake Hefner studies, which has the form

$$E = Nu\Delta e,$$

where E = evaporation from reservoir,
u = wind speed over the reservior,
Δe = vapor-pressure difference between air over the reservoir and water in the reservoir,
and N = an empirical coefficient.

The coefficient was determined from the values of evaporation computed by the energy-budget method, and it varies depending upon whether the metric or the English system of units is used.

Evaporation data for class A pans are available for stations in the switchyard at the foot of the dam and on the right abutment at the top of the dam. The average rates of evaporation for these stations are compared to those for energy-budget and mass-transfer computations in table 15.

TABLE 15.—*Comparison of average rates of evaporation from three sources: energy budget, mass transfer, and class A pans, Hungry Horse Reservoir, 1965 and 1966*

Date of thermal survey	Period	Days	Average rates of evaporation (inches per day)			
					Class A pan	
			Energy budget	Mass transfer	Top of dam	Foot of dam
1965 May 11						
	1	15	---------	0.046	---------	0.149
May 26						
	2	14	0.122	.086	---------	.214
June 9						
	3	14	.101	.097	---------	.214
June 23						
	4	14	.086	.084	.172	.178
July 7						
	5	14	.128	.139	.246	.255
July 21						
	6	14	.161	.151	.247	.254
Aug. 4						
	7	14	.201	.155	.211	.227
Aug. 18						
	8	14	.102	.127	.108	.094
Sept. 1						
	9	15	.089	.144	.070	.073
Sept. 16						
	10	19	.118	.101	.076	.055
Oct. 5						
	11	15	.058	.073	.074	.055
Oct. 20						
1966 May 11						
	12	14	.096	.079	.149	.144
May 25						
	13	8	---------	.081	.209	.231
June 2						
	14	13	.068	.075	[1].162	.143
June 15						
	15	14	.085	.118	.172	.203
June 29						
	16	21	.158	.125	.223	.124
July 20						
	17	14	.229	.191	.291	.304
Aug. 3						
	18	14	.209	.196	.246	.257
Aug. 17						
	19	14	.142	.177	.169	.161
Aug. 31						
	20	14	.142	.131	.185	.167
Sept. 14						
	21	21	.116	.120	.107	.079
Oct. 5						
	22	14	.118	.128	.058	.050
Oct. 19						
	23	14	.041	.086	.056	.036
Nov. 2						

[1] Pan overflowed on June 4, 1966.

The evaporation from Hungry Horse Reservoir for the 23 periods, derived by energy-budget computations, is shown in table 16. Monthly totals of evaporation, in cfs–days, were computed from the

TABLE 16.—*Evaporation from Hungry Horse Reservoir, by energy-budget method, 1965 and 1966*

Date of thermal survey	Period	Days	Evaporation for period (acre-feet)
1965 May 11			
	1	15	843
May 26			
	2	14	2,600
June 9			
	3	14	2,490
June 23			
	4	14	2,300
July 7			
	5	14	3,500
July 21			
	6	14	4,420
Aug. 4			
	7	14	5,490
Aug. 18			
	8	14	2,790
Sept. 1			
	9	15	2,600
Sept. 16			
	10	19	4,400
Oct. 5			
	11	15	1,690
Oct. 22			
Season total	11	162	33,123
1966 May 11			
	12	14	2,350
May 25			
	13	8	1,221
June 2			
	14	13	1,700
June 15			
	15	14	2,320
June 29			
	16	21	6,450
July 20			
	17	14	6,260
Aug. 3			
	18	14	5,710
Aug. 17			
	19	14	3,870
Aug. 31			
	20	14	3,850
Sept. 14			
	21	21	4,640
Oct. 5			
	22	14	2,950
Oct. 19			
	23	14	980
Nov. 2			
Season total	12	175	42,301

data in table 16. Daily records from the class A pan in the switchyard were used to prorate a period total for parts of 2 months. The energy-budget study did not cover the complete May–October period of each year, and estimates were made for October 1964; May 1–10 and October 21–31, 1965; and May 1–10, 1966.

The normal period of evaporation from Hungry Horse Reservoir is believed to be from May through October. The exact beginning and ending dates are subject to variation each year. However, the use of evaporation data in reservoir-operation studies could well be limited to the above period.

For the period May–October, approximately 20 inches of evaporation from the water surface of the reservoir is indicated by the 2 years' study. This amounts to about 20,000 cfs–days or an approximate daily average of 100 cfs–days. However, from the data at hand it appears that 50 percent of the seasonal total occurs during July and August, 30 percent during September and October, and 20 percent during May and June.

Evaporation amounts computed by the energy-budget and mass-transfer procedures were nearly equal. The use of one or the other would not greatly change the results of the water-budget study. There seemed to be a small seasonal bias; that is, the mass-transfer values were lower when the reservoir was warming and higher when the reservoir was cooling. The overall differences are not considered significant at this stage of the analysis.

Comparisons were also made of the data from the evaporation pan below the dam in the switchyard and near the spillway on the right abutment. Seasonal totals were in very close agreement, but there is an indication of a small seasonal bias. The readings from the evaporation pan in the switchyard were higher when the reservoir was warming and lower when the reservoir was cooling.

The outflow from Hungry Horse Reservoir is the sum of the runoff at gaging station South Fork Flathead River near Columbia Falls, plus the evaporation, minus the runoff from the intervening area. These components are summarized in table 17.

TABLE 17.—*Summary of monthly outflow, Hungry Horse Reservoir*

Month	Monthly outflow (cfs-days)			
	Runoff at South Fork Flathead River near Columbia Falls	Runoff from area between gaging station and reservoir	Evaporation	Total outflow
1964				
Oct	[1] 44,530	278	2,200	46,452
Nov	59,430	274	----	59,156
Dec	162,534	486	----	162,048
1965				
Jan	254,850	226	----	254,624
Feb	264,520	177	----	264,343
Mar	459,960	183	----	459,777
Apr	183,625	669	----	182,956
May	80,230	2,172	979	79,037
June	6,144	3,036	2,652	5,760
July	84,793	1,135	4,134	87,792
Aug	51,144	418	4,557	55,283
Sept	75,190	402	2,904	77,692
Oct	89,519	291	2,074	91,302
Nov	68,204	278	----	67,926
Dec	255,420	175	----	255,245
1966				
Jan	258,771	143	----	258,628
Feb	74,835	104	----	74,731
Mar	66,636	130	----	66,506
Apr	29,526	470	----	29,056
May	85,460	2,119	2,266	85,607
June	130,670	2,632	2,227	130,265
July	102,933	931	5,520	107,472
Aug	48,587	393	5,555	53,749
Sept	146,886	212	3,906	150,580
Oct	272,900	200	2,275	274,975
Nov	230,377	211	----	230,166
Dec	151,092	298	----	150,794
1967				
Jan	129,177	254	----	128,923
Feb	69,404	204	----	69,200
Mar	125,196	153	----	125,043
Apr	176,049	217	----	175,832
Total	4,238,592	18,921	41,249	4,260,920

[1] Revised.

CHANGE IN RESERVOIR CONTENTS

The change in reservoir contents is the third major item in the water budget. This was computed from the midnight (11:59 p.m.) stage readings of Hungry Horse Reservoir and the table of reservoir contents dated Ocotber 19, 1953. The data have been used as published.

The published daily stage readings are determined from the gage in the operator's control room, which is electrically connected to the water-stage recorded in the south elevator tower. A correction of −0.10 foot was made in December 1963, presumably based on levels and the temperature profiles run in September 1963. Comparative readings have been made of the water surface in the reservoir and that indicated by the control-room gage since May 1964. The differences range from +0.078 to −0.045 foot, and the average during the period of this study was +0.020 foot. There does not appear to be any definite seasonal trend in these differences, and they were assumed to be of a random nature for purposes of this study. No other corrections have been applied, nor was the recorder chart used in the determination of midnight readings. The month-end reservoir elevations and the monthly changes in reservoir stage and contents are summarized in table 18.

TABLE 18.—*Month-end reservoir elevations and monthly changes in reservoir stage and contents, Hungry Horse Reservoir*

[Month-end reservoir elevation: Add 3,000 to obtain elevation, in feet above mean sea level]

Date	Month-end reservoir elevation (feet)	Change in reservoir stage (feet)	Change in reservoir contents (cfs-days)
1964			
Sept	560.53	+0.02	+242
Oct	560.55	−1.52	−17,904
Nov	559.03	−7.88	−92,385
Dec	551.15	−18.82	−207,478
1965			
Jan	532.33	−22.20	−222,067
Feb	510.13	−50.11	−404,940
Mar	460.02	−.25	−1,650
Apr	459.77	+43.55	+343,213
May	503.32	+50.66	+525,733
June	553.98	+6.52	+76,867
July	560.50	0	0
Aug	560.50	−.42	−5,082
Sept	560.08	−3.79	−44,492
Oct	556.29	−2.56	−30,190
Nov	553.73	−20.05	−223,280
Dec	533.68	−23.01	−231,186
1966			
Jan	510.67	−5.84	−54,849
Feb	504.83	−3.23	−29,309
Mar	501.60	+12.14	+113,568
Apr	513.74	+29.59	+306,181
May	543.33	+16.96	+195,939
June	560.29	−.12	−1,452
July	560.17	−1.67	−19,704
Aug	558.50	−11.02	−128,279
Sept	547.48	−23.38	−250,807
Oct	524.10	−21.25	−204,089
Nov	502.85	−13.19	−113,305
Dec	489.66	−11.83	−93,920
1967			
Jan	477.83	−5.16	−39,946
Feb	472.67	−13.88	−98,202
Mar	458.79	−17.51	−109,866
Apr	441.28	--- --	--- ----

The period of study covers three drawdown and two refill periods. These are summarized in the following tabulation:

Period	*Change in stage (feet)*	*Change in contents (cfs-days)*
September 1964–October 1964	+.02	+242
November 1964–April 1965	−100.78	−946,424
May 1965–August 1965	+100.73	+945,813
September 1965–March 1966	−58.90	−618,388
April 1966–June 1966	+58.69	+615,638
July 1966–April 1967	−119.01	−1,059,570

The drawdown periods for water years 1965 and 1967 are the two largest since the reservoir was filled during July, 1954. This was fortunate for this study, as it permitted a wider range of values to be examined for bank-storage potentials.

WATER-BUDGET RESIDUAL

The three components of the water budget just discussed were algebraically combined on a monthly basis to give a preliminary evaluation of potential bank storage in Hungry Horse Reservoir. These components and the residuals are shown in table 19. A plus sign signifies that more water is available than is indicated by the water budget, and a negative sign signifies that less water is available. These values range from +24,164 cfs-days in March 1965 to −17,904 cfs-days in May 1965.

The water-budget residuals were accumulated on a monthly basis over the 31-month period and plotted against month-end reservoir elevations. This is shown in figure 13. This plot reveals several inconsistencies which suggest that further study of the data used in this method should be made.

If the reservoir and ground-water storage had reached a state of equilibrium prior to the start of each drawdown period, then the residual of the water-budget computations for a drawdown period should be approximately balanced by that computed

TABLE 19.—*Components of water-budget computations, in cfs-days, for Hungry Horse Reservoir*

Month	Outflow	Inflow	Change in contents	Residual	Accumulated residuals
1964					
Oct	46,452	49,215	+242	−2,521	−2,521
Nov	59,156	42,262	−17,904	−1,010	−3,531
Dec	162,048	63,997	−92,385	+5,666	+2,135
1965					
Jan	254,624	37,660	−207,478	+9,486	+11,621
Feb	264,343	29,907	−222,067	+12,369	+23,990
Mar	459,777	30,673	−404,940	+24,164	+48,154
Apr	182,956	166,785	−1,650	+14,521	+62,675
May	79,037	432,074	+343,213	−9,824	+52,851
June	5,760	535,361	+525,733	−3,868	+48,983
July	87,792	168,915	+76,867	−4,256	+44,727
Aug	55,283	59,239	0	−3,956	+40,771
Sept	77,692	77,739	−5,082	−5,129	+35,642
Oct	91,302	47,938	−44,492	−1,128	+34,514
Nov	67,926	37,955	−30,190	−219	+34,295
Dec	255,245	31,167	−223,280	+798	+35,093
1966					
Jan	258,628	24,717	−231,186	+2,725	+37,818
Feb	74,731	17,248	−54,849	+2,634	+40,452
Mar	66,506	31,868	−29,309	+5,329	+45,781
Apr	29,056	139,500	+113,568	+3,124	+48,905
May	85,607	409,642	+306,131	−17,904	+31,001
June	130,265	335,929	+195,939	−9,725	+21,276
July	107,472	106,150	−1,452	−130	+21,146
Aug	53,749	34,094	−19,704	−49	+21,097
Sept	150,580	20,582	−128,279	+1.719	+22,816
Oct	274,975	21,905	−250,807	+2,263	+25,079
Nov	230,166	26,577	−204,089	−500	+24,579
Dec	150,794	31,028	−113,305	+6,461	+31,040
1967					
Jan	128,923	28,768	−93,920	+6,235	+37,275
Feb	69,200	24,718	−39,946	+4,536	+41,811
Mar	125,043	23,211	−98,202	+3,630	+45,441
Apr	175,832	61,937	−109,866	+4,029	+49,470
Total	4,260,920	3,148,761	−1,062,689	+49,470	-----

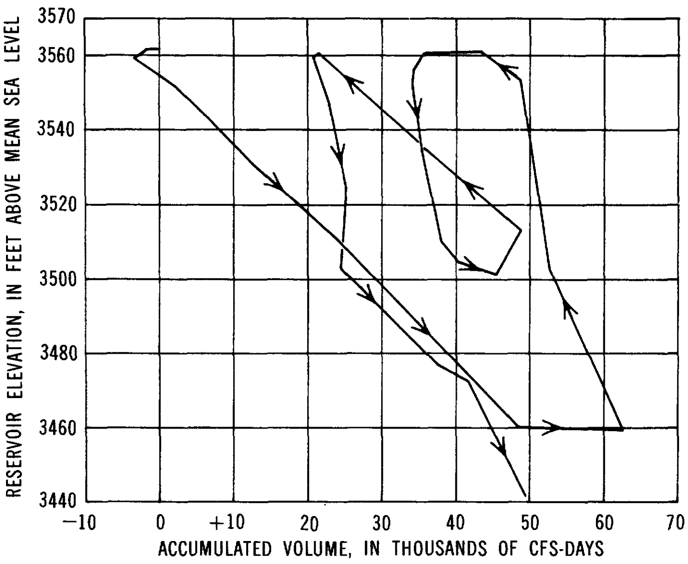

FIGURE 13.—Mass curve of accumulated water-budget residuals and month-end reservoir elevations.

for the following refill period. In the two complete cycles of drawdown and refill studies, this is not the case. In the 1965 cycle the residual was +66,206 cfs-days on the drawdown and only −28,380 cfs-days on the refill. During the 1966 cycle, the situation was reversed with a residual of +14,610 cfs-days on the drawdown and −27,808 cfs-days on the refill. Even if the two seasons were considered together, there was a residual of 21,097 cfs-days more water on drawdown cycles than on refill cycles. The apparent inconsistencies, which might be related to nonequilibrium ground-water conditions and unaccounted-for ground-water inflow, will be considered in relation to theoretical concepts.

The residual of the water-budget computations was divided by the range in reservoir stage for each drawdown and refill period. The average volumes, in cfs-days per foot of change in reservoir stage, are shown in the following tabulation:

Year	*Drawdown*	*Refill*
1965	657	282
1966	248	474
1967	238	-----

These values also suggest a lack of consistency that needs further study.

MATHEMATICAL MODEL

DEVELOPMENT OF EQUATIONS

Bank-storage changes in response to reservoir fluctuations can be calculated. In the section which follows, theoretical ground-water concepts are used to derive a mathematical model which relates reservoir-stage fluctuations both to movement of water across the boundary between the reservoir and adjacent geologic materials and to changes in bank storage. The reliability of results, when applied to a field situation, depends on how closely the dimensions and characteristics of the aquifer match those of the theoretical model.

Assumptions are made as follows:

1. The unconsolidated material adjacent to the reservoir is the principal aquifer in which bank storage takes place.
2. The aquifer shape can be described as two identical wedges separated by the reservoir (see fig. 14).
3. There is a free hydraulic connection through the vertical planes forming the boundaries between the reservoir and aquifer.
4. The vertical planes forming the landward boundaries between the aquifer and the consolidated rocks flanking the valley are parallel to the reservoir boundaries and are impervious.
5. The planes forming the bottom and downstream ends of the aquifer are impervious.
6. There is no vertical recharge to the aquifer.
7. Material is homogeneous and isotropic. Initially, ground-water level is everywhere at initial reservoir level.

For convenience, most of the mathematical symbols are listed in table 20. Some are explained where

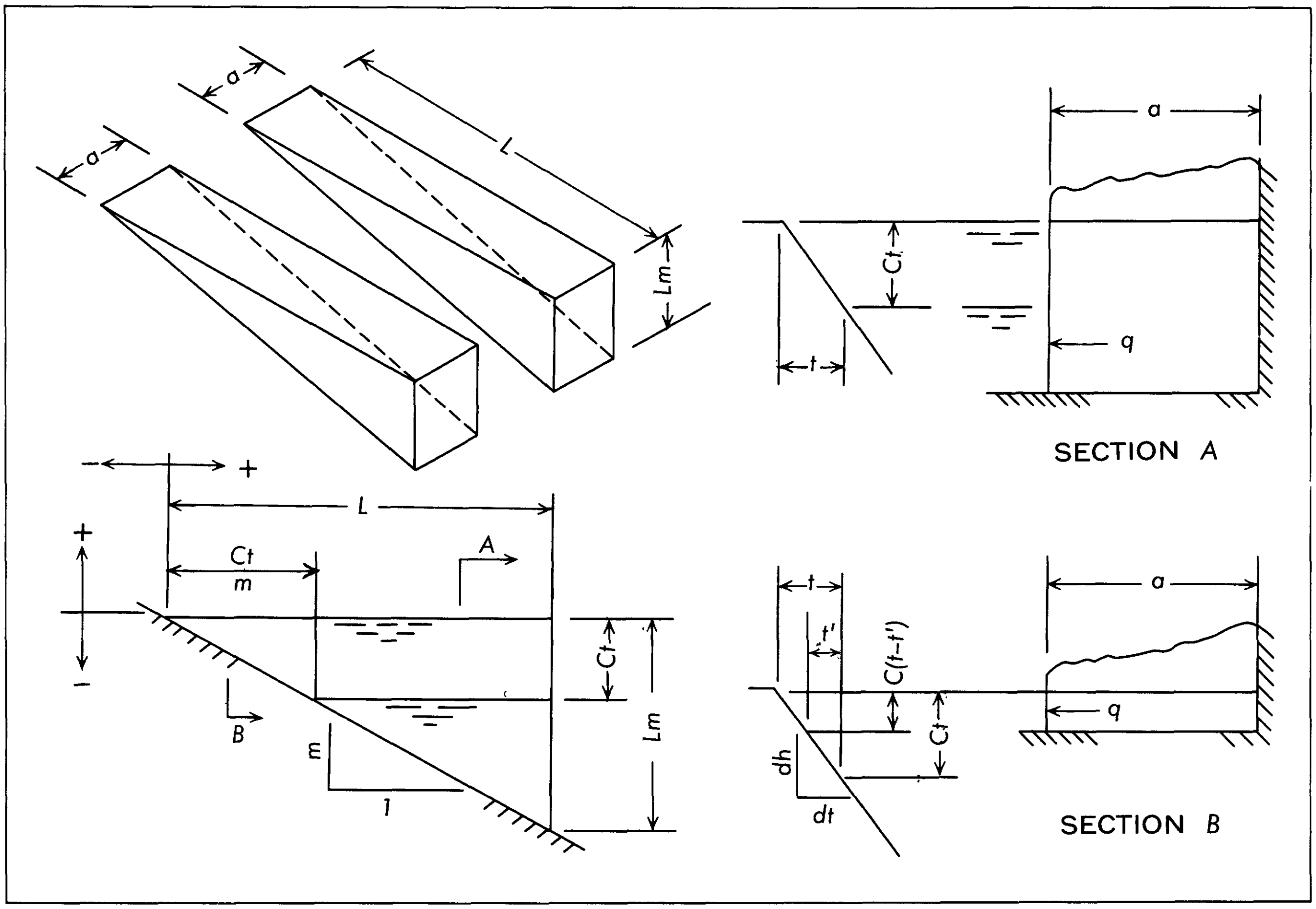

FIGURE 14.—Schematic sketches of aquifer showing assumed conditions.

first introduced in the text. Schematic sketches of the aquifer shape showing assumed conditions are shown in figure 14.

TABLE 20.—*Symbols and dimensions used in the mathematical model*

Symbol	*Description*	*Dimensions*
a	Distance from reservoir to valley wall	L
C	Rate of change of reservoir level; $C=dh/dt$	LT^{-1}
e	Napierian log base, 2.71828	None
L	Length of reservoir pool at beginning of any change	L
L_v	Distance from head of pool to section in unponded reach	L
m	Slope of reservoir bed	None
Q	Flow to (+) or from (−) the aquifer for both sides of the reservoir	L^3T^{-1}
q, q_a, q_u	Flow to (+) or from (−) the aquifer per unit length for one side of reservoir	L^2T^{-1}
S	Coefficient of storage of aquifer	None
T	Transmissivity of the aquifer	L^2T^{-1}
t	Time from beginning of change in reservoir level	T
t'	Time from cessation of change in reservoir level	T
t_1	Duration of a constant rate change in reservoir level	T
V	Volume gain (+) or loss (−) of water in aquifer	L^3
α	A descriptor of the aquifer shape and its hydrologic characteristics; $\alpha=\pi^2T/4a^2S$	T^{-1}

For the stated assumptions, a drawdown is imposed on the reservoir at a constant rate, $dh/dt=C$, where dh/dt is the slope of the time hydrograph of reservoir elevation. Coordinates are oriented so that dh/dt and C are positive for a rising stage and negative for a falling stage.

For these conditions, ground water flows to the reservoir. At a section in the portion of the reservoir downstream from head of pool where ponded conditions still prevail, the equation of flow per unit length of reservoir from one side is (Rorabaugh, 1964, p. 435, eq 5)

$$q_d = -T\left[\frac{dh}{dx}\right]_{x=0} = CaS\left[1-\frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{e^{-(2n-1)^2\alpha t}}{(2n-1)^2}\right], \quad (1)$$

where q_d is the rate of flow across the boundary between the aquifer and the reservoir for a unit length and for one side of the ponded reach of the reservoir; a is the distance from the reservoir to valley wall; S is the coefficient of storage of the aquifer; t is time from beginning of change in reservoir level; α, which equals $\pi^2T/4a^2S$, is a descriptor of the aquifer shape and its hydrologic characteristics; T, the transmissivity of the aquifer; and dh/dx is the hydraulic gradient at the aquifer-reservoir boundary. In this equation and those following, flow is positive for movement from the reservoir to the aquifer and negative for ground-water discharge to the reservoir.

It should be noted that equation 1 was originally derived using a heat-flow equation as a starting point and that the analogy between heat flow and ground-water movement is used in some of the derivations that follow. Corresponding items in the analogy are listed below.

Heat conduction		Ground-water movement	
Concept	Notation	Concept	Notation
Temperature	v	Head	h
Specific heat of material times its density.	$c\rho$	Specific storage	S_s
Thermal conductivity	K	Hydraulic conductivity.	k
Diffusivity	$K/c\rho$	Diffusivity	k/S_s
		For diffusivity of an aquifer, inclusion of aquifer thickness results in the ratio transmissivity divided by storage coefficient.	T/S
One dimensional equation of conduction of heat.	$\frac{\partial^2 v}{\partial x^2} = \frac{c\rho}{K}\frac{\partial v}{\partial t}$	One dimensional equation of ground-water movement.	$\frac{\partial^2 h}{\partial x^2} = \frac{S}{T}\frac{\partial h}{\partial t}$

Since the basic differential equations are of the same form, the solution for a problem in one field will be the same as in the other field for similar boundary conditions, the only difference being notation.

At a section in the upstream part of the reservoir between the original head of pool and the new head of pool, ponded water has been depleted and stream level prevents any additional drawdown. The flow per unit unponded length of reservoir for one side is (Rorabaugh, 1964, p. 435, eq 7)

$$q_u = \frac{8CaS}{\pi^2}\sum_{n=1}^{\infty}\frac{e^{-(2n-1)^2\alpha t'} - e^{-(2n-1)^2\alpha t}}{(2n-1)^2} \quad (2)$$

where q_u is the rate of flow across the boundary between the aquifer and the reservoir for a unit length and for one side of the unponded reach of the reservoir, and t' is the time since the cessation of change in reservoir level at a section in the unponded reach.

To obtain the flow for the total length of the reservoir, inflows from the ponded and unponded reaches are added and multiplied by two to account for both sides of the reservoir. For the ponded reach, equation 1 is multiplied by the ponded length at time t. Unponded length is drawdown, Ct, divided by bed slope, m. Ponded length is initial length, L, minus Ct/m. Flow for the unponded reach is obtained by integrating equation 2 with respect to length. Limits of integration are $L_v = 0$ at initial condition and $L_v = Ct/m$ at time t. Note that the variable unponded length, L_v, is equal to $C(t-t')/m$. From this relation, the variable t' in equation 2 is replaced by its equivalent, $t' = t - L_v m/C$. Total flow is

$$Q = 2\left\{(L - Ct/m)\,q_d + \int_0^{Ct/m} q_u\,dL_v\right\};$$

when this is integrated, we have

$$Q = 2LCaS\left\{\left[1-\frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{e^{-(2n-1)\ \alpha t}}{(2n-1)^2}\right] - \frac{Ct}{Lm}\left[1-\frac{\pi^2}{12\alpha t}\left(1-\frac{96}{\pi^4}\sum_{n=1}^{\infty}\frac{e^{-(2n-1)^2\alpha t}}{(2n-1)^4}\right)\right]\right\}. \quad (3)$$

Equation 3 was derived for the case of a falling reservoir stage. For a rising stage, total flow is the sum of the flows of the ponded and unponded reaches, doubled to account for both sides of the reservoir. Ponded length is initial length, L. Flow at a section is given by equation 1; thus, total flow in the ponded reach is $2Lq_d$. As the reservoir rises, the head of pool moves upstream into an unponded reach. At a section in this reach a distance L_v upstream, flow to the aquifer is expressed by equation 1, in which time begins when the moving head of pool reaches the section. This time for pool to arrive at the section is $L_v m/C$. Therefore, t in equation 1 is replaced by $(t - L_v m/C)$. The equation is then integrated with respect to length. Limits of integration, in the positive direction of length, are from Ct/m to zero. Results are multiplied by two to account for both sides of the reservoir. Thus

$$Q = 2\left(Lq_d + \int_{Ct/m}^{0} q_d\,dL_v\right).$$

Integration results in equation 3, which applies to either a lowering or a raising of the reservoir level. C is positive for a rising reservoir level and negative for a falling level. The sign of Q indicates the direction of flow, a positive Q for flow from the reservoir to the aquifer and a negative Q for flow of ground water to the reservoir.

Inspection of equation 3 shows that for large values of time, series terms become very small. When $\alpha t \geq \pi^2/20$ (or $Tt/a^2S \geq 0.2$), all but the first series terms may be neglected. Equation 3 is modified for $\alpha t \geq \pi^2/20$ as follows:

$$Q = 2LCaS\left[1 - \frac{Ct}{Lm} + \frac{Ct}{Lm}\cdot\frac{\pi^2}{12\alpha t} - \left(1 + \frac{Ct}{Lm}\cdot\frac{1}{\alpha t}\right)\frac{8e^{-\alpha t}}{\pi^2}\right]. \tag{3a}$$

When time is small enough that the aquifer response has not reached the valley wall, the system is behaving as semi-infinite. From the solution for head in a semi-infinite aquifer given by Hantush (1961, p. 1311, eq 24) or from translation of the heat-flow equation of Carslaw and Jaeger (1959, p. 63, eq 4), we find that for a section for one side of the ponded reach of the reservoir

$$q_d = -T\left[\frac{dh}{dx}\right]_{x=0} = \frac{2CaS}{\sqrt{\pi}}\sqrt{\frac{Tt}{a^2S}},$$

and, by superposition, for a section for one side of the unponded reach of the reservoir

$$q_u = \frac{2CaS}{\sqrt{\pi}}\left(\sqrt{\frac{Tt}{a^2S}} - \sqrt{\frac{Tt'}{a^2S}}\right).$$

Total flow, for $\alpha t < \pi^2/20$, is

$$Q = 2\left\{(L - Ct/m)\, q_d + \int_0^{Ct/m} q_u dL_v\right\};$$

when this is integrated, we find

$$Q = 2LCaS\cdot\frac{2}{\sqrt{\pi}}\cdot\sqrt{\frac{Tt}{a^2S}}\left(1 - \frac{2Ct}{3Lm}\right). \tag{3b}$$

Periods of drawdown or fill followed by constant levels are experienced in reservoir operation. Also in computing effects of a series of regulations on a future time, it is convenient to have expressions for the condition of a constant change in stage $dh/dt = C$ for time t_1 followed by a constant level from time t_1 to time t. Expressions are developed by superposition.

For constant rate of drawdown or fill followed by stationary levels,

$$Q_{t\geq t_1} = 2LCaS\,\frac{8}{\pi^2}\left\{\left(1 - \frac{Ct_1}{Lm}\right)\sum_{n=1}^{\infty}\frac{e^{-(2n-1)^2\alpha\,(t-t_1)}}{(2n-1)^2} - \sum_{n=1}^{\infty}\frac{e^{-(2n-1)^2\alpha t}}{(2n-1)^2} + \frac{C}{Lm}\cdot\frac{1}{\alpha}\left[\sum_{n=1}^{\infty}\frac{e^{-(2n-1)\ \alpha\ (t-t_1)}}{(2n-1)^4} - \sum_{n=1}^{\infty}\frac{e^{-(2n-1)^2\alpha t}}{(2n-1)^4}\right]\right\}. \tag{4}$$

For $Tt/a^2S \geq 0.2$ and $T(t-t_1)/a^2S \geq 0.1$,

$$Q_{t\geq t_1} = 2LCaS\cdot\frac{8}{\pi^2}\left[\left(1 - \frac{Ct_1}{Lm} + \frac{C}{Lm}\cdot\frac{1}{\alpha}\right)e^{+\alpha t_1} - \left(1 + \frac{C}{Lm}\cdot\frac{1}{\alpha}\right)\right]e^{-\alpha t}. \tag{4a}$$

For $Tt/a^2S < 0.2$,

$$Q_{t\geq t_1} = 2LCaS\cdot\frac{2}{\sqrt{\pi}}\left\{\left(1 - \frac{2Ct}{3Lm}\right)\sqrt{\frac{Tt}{a^2S}} - \left[1 - \left(\frac{2C(t-t_1)}{3Lm}\right)\right]\sqrt{\frac{T(t-t_1)}{a^2S}} + \frac{Ct_1}{Lm}\sqrt{\frac{T(t-t_1)}{a^2S}}\right\}. \tag{4b}$$

For $Tt/a^2S \geq 0.2$ and $T(t-t_1)/a^2S \leq 0.1$,

$$Q_{t\geq t_1} = 2LCaS\left\{\left[1 - \frac{Ct}{Lm} + \frac{Ct}{Lm}\cdot\frac{\pi^2}{12\alpha t} - \left(1 + \frac{Ct}{Lm}\cdot\frac{1}{\alpha t}\right)\frac{8e^{-\alpha t}}{\pi^2}\right] - \frac{2}{\sqrt{\pi}}\sqrt{\frac{T(t-t_1)}{a^2S}}\left[1 - \frac{2C(t-t_1)}{3Lm} - \frac{Ct_1}{Lm}\right]\right\}. \tag{4c}$$

VOLUMES

Equations 3–4c are useful in computing rates of movement to and from bank storage. For large increments of time, as in monthly values, it is more convenient to compute cumulative storage changes. Flow equations are integrated with respect to time to produce the following volume equations:

For constant rate of drawdown or fill,

$$\begin{aligned} V=2LCaSt\,\Biggl\{\Biggl[&1-\frac{a^2S}{3Tt}+\frac{1}{\alpha t}\,\frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{e^{-(2n-1)^2\alpha t}}{(2n-1)^4}\Biggr]\\ &-\frac{Ct}{Lm}\Biggl[\frac{1}{2}-\frac{a^2S}{3Tt}+\frac{2}{15}\left(\frac{a^2S}{Tt}\right)^2\\ &-\left(\frac{1}{\alpha t}\right)^2\frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{e^{-(2n-1)^2\alpha t}}{(2n-1)^6}\Biggr]\Biggr\}. \end{aligned}\tag{5}$$

For $Tt/a^2S\geq 0.2$,

$$\begin{aligned} V=2LCaSt\Biggl[&1-\frac{Ct}{2Lm}-\frac{a^2S}{3Tt}+\frac{Ct}{Lm}\cdot\frac{a^2S}{3Tt}\\ &-\frac{2}{15}\cdot\frac{Ct}{Lm}\left(\frac{a^2S}{Tt}\right)^2\\ &+\frac{1}{\alpha t}\left(1+\frac{Ct}{Lm}\cdot\frac{1}{\alpha t}\right)\frac{8}{\pi^2}e^{-\alpha t}\Biggr]. \end{aligned}\tag{5a}$$

For $Tt/a^2S<0.2$,

$$V=2LCaSt\cdot\frac{4}{3\sqrt{\pi}}\sqrt{\frac{Tt}{a^2S}}\left(1-\frac{2Ct}{5Lm}\right).\tag{5b}$$

For drawdown or fill followed by stationary level,

$$\begin{aligned} V_{t\geq t_1}=2LCaSt_1\Biggl\{&1-\frac{Ct_1}{2Lm}+\frac{1}{\alpha t_1}\cdot\frac{8}{\pi^2}\\ &\Biggl[\sum_{n=1}^{\infty}\frac{e^{-(2n-1)^2\alpha t}}{(2n-1)^4}-\left(1-\frac{Ct_1}{Lm}\right)\\ &\sum_{n=1}^{\infty}\frac{e^{-(2n-1)^2\alpha(t-t_1)}}{(2n-1)^4}+\frac{Ct_1}{Lm}\cdot\frac{1}{\alpha t_1}\\ &\sum_{n=1}^{\infty}\frac{e^{-(2n-1)^2\alpha t}-e^{-(2n-1)^2\alpha(t-t_1)}}{(2n-1)^6}\Biggr]\Biggr\}. \end{aligned}\tag{6}$$

For $Tt/a^2S\geq 0.2$ and $T(t-t_1)/a^2S\geq 0.1$,

$$\begin{aligned} V_{t\geq t_1}=2LCaSt_1\Biggl\{&1-\frac{Ct_1}{2Lm}+\Biggl[1+\frac{Ct_1}{Lm}\cdot\frac{1}{\alpha t_1}\\ &-\left(1-\frac{Ct_1}{Lm}+\frac{Ct_1}{Lm}\cdot\frac{1}{\alpha t_1}\right)e^{+\alpha t_1}\Biggr]\frac{1}{\alpha t_1}\cdot\frac{8}{\pi^2}e^{-\alpha t}\Biggr\}. \end{aligned}\tag{6a}$$

For $Tt/a^2S<0.2$,

$$\begin{aligned} V_{t\geq t_1}=2LCaS\cdot\frac{4}{3\sqrt{\pi}}\Biggl\{&t\sqrt{\frac{Tt}{a^2S}}\left(1-\frac{2Ct}{5Lm}\right)\\ &-(t-t_1)\sqrt{\frac{T(t-t_1)}{a^2S}}\left[1-\frac{2C(t-t_1)}{5Lm}\right]\\ &+(t-t_1)\sqrt{\frac{T(t-t_1)}{a^2S}}\left(\frac{Ct_1}{Lm}\right)\Biggr\}. \end{aligned}\tag{6b}$$

For $Tt/a^2S>0.2$ and $T(t-t_1)/a^2S<0.1$,

$$\begin{aligned} V_{t\geq t_1}=2LCaSt\Biggl[&1-\frac{Ct}{2Lm}-\frac{a^2S}{3Tt}+\frac{Ct}{Lm}\cdot\frac{a^2S}{3Tt}\\ &-\frac{2}{15}\cdot\frac{Ct}{Lm}\left(\frac{a^2S}{Tt}\right)^2+\frac{1}{\alpha t}\left(1+\frac{Ct}{Lm}\cdot\frac{1}{\alpha t}\right)\frac{8}{\pi^2}e^{-\alpha t}\Biggr]\\ &-2\mathrm{LCaS}\cdot\frac{4}{3\sqrt{\pi}}(\mathrm{t}-\mathrm{t}_1)\sqrt{\frac{T(t-t)_1}{a^2S}}\Biggl[1-\frac{2C(t-t_1)}{5Lm}\\ &-\frac{Ct_1}{Lm}\Biggr]. \end{aligned}\tag{6c}$$

Hand calculation of flow by equations 3 and 4 and volume by equations 5 and 6 is too cumbersome. These equations lend themselves to computer solution, and a computer would be used if daily calculations were required. For this problem the modified equations 3*a*, 3*b*, 4*a*, 4*b*, and 4*c* for discharge and 5*a*, 5*b*, 6*a*, 6*b*, and 6*c*) for volume are not too cumbersome for hand calculation on a monthly basis.

SELECTION OF DIMENSIONAL CONSTANTS

The length of the reservoir at full pool, at an elevation of 3,560.5 feet, was determined as 32.5 miles (171,600 feet). This is based on maps and sections by Bateman (unpub. data, 1952). It is somewhat shorter than river mileage because some of the minor meanders are not considered.

The average bed slope (from sections) is −15.48 feet per mile or a ratio of −0.00293. Note from the orientation sketch (fig. 14) that the origin is at head of pool (at any pool level) and that *m* is negative.

The length, *L* (feet), at the start of any fluctuation is determined from reservoir and full-pool elevations (feet above mean sea level), and slope.

$$L=171{,}600-\frac{\text{reservoir elevation}-3{,}560.5}{-0.00293}$$

or

$$L=\frac{3{,}057.5-\text{reservoir elevation}}{-0.00293}.$$

The term *Lm* (feet) is determined as follows:

$$\begin{aligned} Lm&=-503-(\text{reservoir elevation}-3{,}560.5)\\ &=3{,}057.5-\text{reservoir elevation}. \end{aligned}$$

The distance from reservoir to valley wall was computed as 851 feet on the basis of the geometry of the wedge and volume of material computed from the unpublished cross sections.

HYDROLOGIC CONSTANTS

OUTWASH, DRY PARK AREA

In August 1964, three observation wells were installed in a line perpendicular to the reservoir to sample conditions in outwash deposits. The location is near Dry Park Creek on a 1,500-foot-wide terrace on the east side of the reservoir and about 2 miles downstream from the head of pool. These wells were drilled using 6-inch steel casing without a screen. Well information is summarized below:

Dry Park well 1, located 195 feet east of reservoir at full pool

Material	*Deep interval (feet)*
Silt, tan, sandy	0–1
Sand and gravel, well-rounded, washed; silt and clay	1–15
Gravel and sand, clean, loose	15–41.5
Sand, fine; silt	41.5–50
Clay, silt, sand, some gravel; hole stood open	50–57

Casing was pulled back to 38 feet below land surface to place the end of the casing in clean gravel. After developing, well was pumped at 70 gpm (gallons per minute) for 15 minutes with a drawdown of 0.8 foot. Land surface is at an elevation of 3,561.0 feet, and bottom of casing is at 3,523.5 feet.

Dry Park well 2, located 410 feet east of reservoir at full pool

Material	*Depth interval (feet)*
Silt, sandy; top soil	0–3
Gravel and sand, very loose, well-washed; more sand and silt than in well 1.	3–59

Well was pumped at 40 gpm for 3 hours with a drawdown of 5 feet. Land surface is at an elevation of 3,561.9 feet, and bottom of casing is at 3,502.8 feet.

Dry Park well 3, located 800 feet east of reservoir at full pool

Material	*Depth interval (feet)*
Soil, cobbles, silt	0–3
Silt, clay, sand	3–6
Sand and gravel, some silt	6–18
Gravel, sand, some silt	18–30
Gravel, sand, some silt	30–46
Sand, silt	46–51

Casing was pulled back to 45 feet below land surface. Well was pumped at 70 gpm with a drawdown of less than 1.5 feet. Land surface is at an elevation of 3,563.6 feet, and bottom of casing is at 3,518.6 feet.

At this section the streambed is at an elevation of about 3,520 feet. When the reservoir is lowered, beds of clean boulders, gravel, and sand are exposed on the steep bank. Following a rapid drawdown, freely flowing discharge from the outwash deposits to the river was observed just above river level.

Waterlevel recorders were installed in each observation well and operated from October 1, 1964, to November 1966. Well 1 did not record below an elevation of 3.524 feet. Considerable records were lost during the winter months because of severe weather and inability to service the recorders.

Water levels in all three observation wells responded to changes in reservoir level. Seiches in the reservoir, frequently having an amplitude of about 0.2 foot and a period of 96 minutes, were recorded with small timelag at all three wells. During reservoir-drawdown periods, ground-water levels dropped at almost the same rate as the surface of the reservoir. During a reservoir recession of 0.7 foot per day, a ground-water profile with about 0.2 foot of head from well 3 to the reservoir was established and changed little during the first 30 feet of drawdown. Below an elevation of 3,530 feet and as the pool approached river-bed level, gradients steepened, reflecting effects of reduced transmissivity caused by unwatering of the highly permeable material at the higher elevations.

Theoretical analyses of the response of the aquifer to seiches and also of the ground-water profile during rapid drawdown produce very large values for diffusivity (T/S). Inasmuch as the values of head are very small, the results of this approach have a wide range of error. All the evidence leads to the conclusion that this outwash material is highly permeable and that drainage or filling response time is so rapid that timelag is negligible except when dealing with very small increments of time. On the basis of experience gained from outwash and river deposits of similar nature, the storage coefficient of this material would be expected to be 0.20 or perhaps somewhat larger.

TILL, CANYON CREEK AREA

A field inspection was made on May 11, 1966, when reservoir-pool level was about 3,525 feet and was rising at the rate of 1.5 feet per day. An area of the reservoir bed on the east side between Deep Creek and Canyon Creek and mapped as till was inspected in some detail. A small pond, perhaps 40 feet in diameter and at an elevation of about 3,550 feet, had a water level about 2 feet below its outlet. A small stream was flowing into the pond. Erosion at the outlet showed that there had been substantial overflow when the lower elevation snow had melted a few weeks earlier. The fact that pond level had receded 2 feet during a time when there was inflow shows that at this location vertical infiltration rates into the till, although not high, may be of some importance in the analysis. A small pit was dug about 1 foot from the pond and about 2 feet below pond level. Material was cobbles in a matrix of fine sand and silt. Inspection an hour later showed no water in the pit, a clear indication that the pond was perched, that unsaturated flow existed below the pond, and that the vertical hydraulic conductivity of the till was greater than that of the pond bed.

A small pit was dug adjacent to the reservoir pool. Material was cobbles and fine sand. When bailed the pit filled in a few minutes indicating that, locally, the horizontal hydraulic conductivity is considerably better than that of the till generally. When a small ditch was dug to connect the pit to the reservoir, flow from the pit to the reservoir was observed. At this location vertical recharge from snowmelt and rain in the exposed reservoir bed and areas adjacent to the reservoir was large enough to maintain ground-water head above reservoir level during a period of rising reservoir levels.

This is an example of "ground-water backwater." Rising reservoir stage reduced ground-water gradients and reduced flow from the aquifer to the reservoir. Water which originated as ground-water recharge was slowed on its way toward the reservoir and was accumulated as bank storage.

TILL, MCINERNIE-RIVERSIDE AREA

Three 6-inch observation wells were drilled (June 1966) in the till on the east side of the reservoir and about 10 miles upstream from the dam. Material penetrated was till, mainly clay with various mixes of boulders, cobbles, and gravel. During drilling the only place where permeability was high enough to permit ground-water to enter the well in noticeable amounts was at the Riverside site at an elevation of 3,512–16 feet.

As shown on figure 15, water levels in McInernie wells 1 and 2 rose very slowly during the year following drilling, demonstrating that the till at the location had very low hydraulic conductivity. Water levels in the Riverside well recovered slowly (fig. 15), requiring about a month to rise 78 feet. This slow rise demonstrates a very low hydraulic conductivity. During the following year, while reservoir

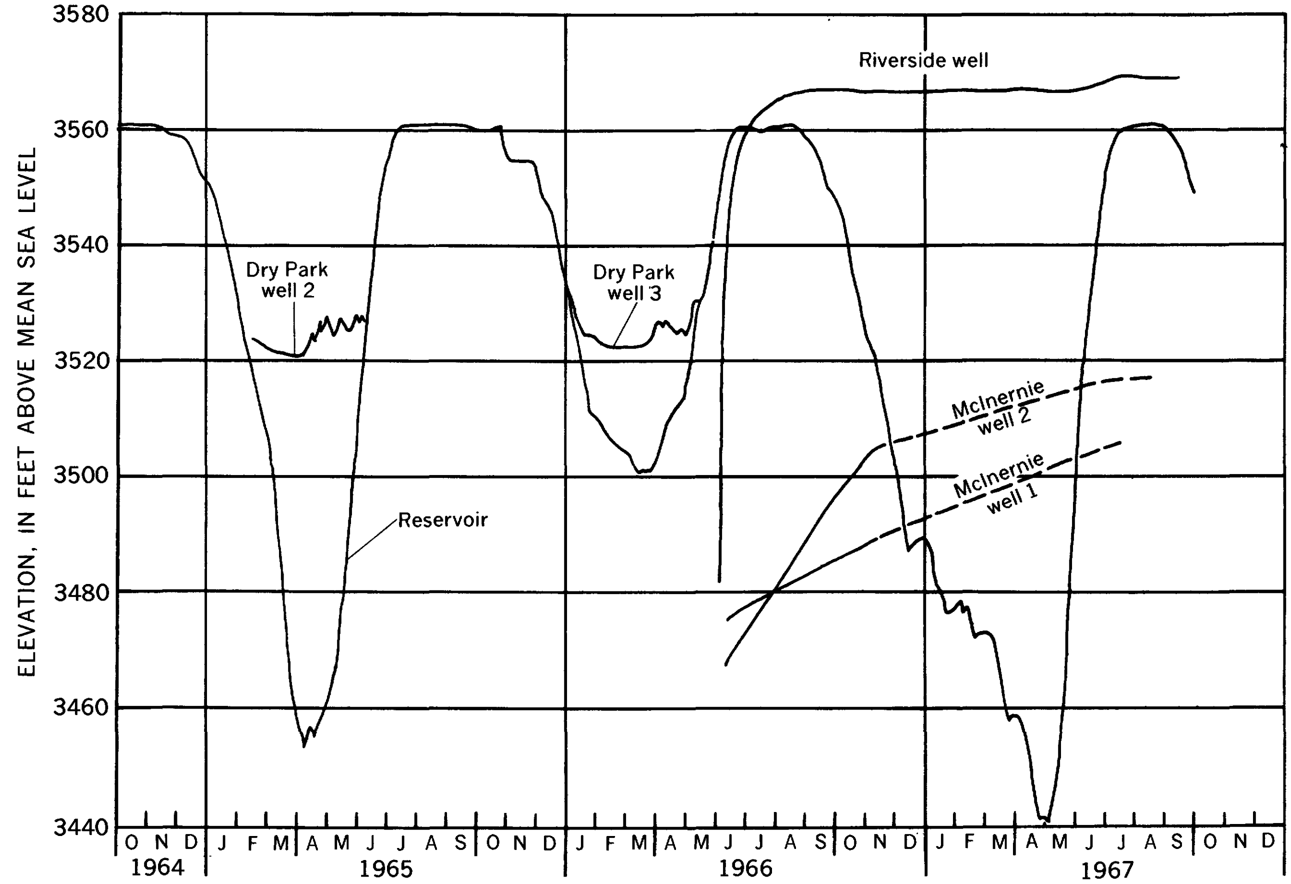

FIGURE 15.—Comparison of ground-water levels with stage of Hungry Horse Reservoir.

TABLE 21.—*Lineated stage of Hungry Horse Reservoir and input constants to theoretical model*

[Stage: Add 3,000 to obtain elevation, in feet above mean sea level]

Date	Stage (feet)	Change of stage (feet)	Duration, *t*, (days)	Rate of change of stage, *C* (ft per day)
1963				
Dec 8	560.5			
		−49	59	−0.8305
1964				
Feb 5	511.5			
		−25	93	−.2688
May 8	486.5			
		+74	43	+1.721
June 20	560.5			
		0	149	0
Nov 16	560.5			
		−1.5	9	−.1667
Nov 25	559.0			
		0	12	0
Dec 7	559.0			
		−10.5	33	−.3182
1965				
Jan 9	548.5			
		−42.7	55	−.7764
Mar 5	505.8			
		−40.9	20	−2.045
Mar 25	464.9			
		−11.5	15	−.7667
Apr 9	453.4			
		+9.6	29	+.3310
May 8	463.0			
		+87.0	48	+1.8125
June 25	550.0			
		+10.5	15	+.700
July 10	560.5			
		0	107	0
Oct 25	560.5			
		−6.0	8	−.750
Nov 2	554.5			
		0	27	0
Nov 29	554.5			
		−6.0	8	−.750
Dec 7	548.5			
		0	6	0
Dec 13	548.5			
		−36.5	45	−.8111
1966				
Jan 27	512.0			
		−11.8	48	−.2458
Mar 16	500.2			
		0	13	0
Mar 29	500.2			
		+13.0	26	+.500
Apr 24	513.2			
		0	9	0
May 3	513.2			
		+17.8	11	+1.618
May 14	531.0			
		0	10	0
May 24	531.0			
		+17.8	11	+1.618
June 4	548.8			
		+11.5	17	+.6765
June 21	560.3			
		+0.2	68	+.0029
Aug 28	560.5			
		−13.5	36	−.3750
Oct 3	547.0			
		−32.5	42	−.7738
Nov 14	514.5			
		0	4	0
Nov 18	514.5			
		−27.0	27	−1.000
Dec 15	487.5			
		+2.5	17	+.1471
1967				
Jan 1	490.0			
		−8.0	8	−1.000
Jan 9	482.0			
		−4.5	16	−.2813
Jan 25	477.5			
		0	20	0
Feb 14	477.5			
		−4.5	6	−.750
Feb 20	473.0			
		0	16	0
Mar 8	473.0			
		−14.5	14	−1.038
Mar 22	458.5			
		0	17	0
Apr 8	458.5			
		−17.5	20	−.875
Apr 28	441.0			

levels dropped 120 feet and then returned to full pool, water level in this well fluctuated about 2 feet. Ground-water level rose several feet above full-pool stage, indicating recharge. Movement of ground water toward the reservoir is very slow at this site.

From the foregoing evidence it is clear that hydraulic conductivity is highly variable from place to place, ranging from near zero in parts of the till to very high values in open-work gravels. The storage coefficients also appear to range from near zero to greater than 0.2. Frequently, when dealing with heterogeneous material, the problem can be adequately handled by treating in bulk—lumping segments of the problem into one or more groups and treating each group on an average basis. A number of theoretical solutions were computed and tested against observed data.

The unknown (or uncertain) constants appear in the equations in two groupings, aS *and* T/a^2S. An average value for a of 851 feet was determined from the volume and the geometry of the unconsolidated material. It must be kept in mind that this figure is approximate. Using the equations, assumed values for T, S, and a, and the reservoir-stage record, movement of water to and from its banks and volume of storage in the aquifer are calculated. The term S or aS appears as a multiplier in all the equations. Once a calculation is made for the period of record, the model solution obtained may be expanded into a family by multiplying by constants. If the multiplier is considered a change in storage coefficient, it also requires a similar change in transmissivity so that the term T/a^2S remains the same in the internal parts of the equation. If the multiplier is considered as a change in term a, then transmissivity has been altered by the square of the multiplier.

The reservoir-stage record, which is the boundary input to the model, was approximated as a sequence of straight lines each having a constant rate of change of stage, C. Table 21 lists the segments of the lineated hydrograph and the rate of change of stage constants.

THEORETICAL SOLUTIONS AND COMPARISONS WITH PRELIMINARY WATER BUDGET

Equations 3–6*c* constitute a general model for bank-storage relations for the assumed geometry. For this particular problem several trials were made using groups of selected constants. Subscripts are used to designate the trial groups of selected constants. For example, M_2 indicates that the model was used with the following constants: $a=851$ feet, $S=0.15$, and $T/a^2S=0.003$ per day.

The equations are in dimensionless form. In the calculations for this problem, all length and elevation values were expressed in feet; all time values, in days; changes of reservoir level, in feet per day; and transmissivity, in square feet per day. Storage coefficient and slope are dimensionless. Use of these units produces values of flow in cubic feet per day and volumes in cubic feet; division of these values by 86,400 seconds per day yields flow in cubic feet per second and volume in cfs-days.

TRIAL M_1

In the first trial very low values of diffusivity were assumed. A partial calculation yielded very small bank-storage values. The comparison with unadjusted water-budget residuals was so poor that this set of assumptions was abandoned.

TRIAL M_2

For M_2 the assumed constants were

$$a = 851 \text{ ft},$$
$$S = 0.15,$$
and $$T/a^2S = 0.003 \text{ per day}.$$

These constants define T as 326 square feet per day, or 2,444 gallons per day per foot. Calculations were made on a volume basis using equations 5*b* and 6*b* for intervals shorter than 67 days ($Tt/a^2S < 0.2$) and equations 5*a* and 6*a* for intervals equal to or greater than 67 days. It should be noted that the later equations tail as straight lines on semilog plots, and graphical methods may be used to shorten the calculations. For each recession segment (table 21) the cumulative ground-water storage gain or loss was computed at the end of each month from the beginning of the segment until the effect of the event became negligible. Total storage change at the end of any month is the algebraic sum of the effects at that time of all preceding changes in stage.

Water-budget calculations were computed so that negative residuals designate reservoir water going into bank storage, and positive, water moving from the aquifer to the reservoir. The equations were derived from the aquifer viewpoint, so negative signs in the theoretical model indicate ground-water outflow, and positive, flow the aquifer. For compatibility the signs of the model calculations were reversed. In addition, a constant was subtracted from the model in order to orient the model to the water-budget value of zero at midnight, September 30, 1964.

Accumulated gains to the reservoir for the unadjusted water budget and those from M_2 are shown in figure 16. Also shown are the accumulated differences of monthly water-budget residuals and calculated values from M_2. It is obvious that M_2 alone cannot be modified to satisfy the water-budget data. A large multiplier would be needed to satisfy the three periods of drawdown. This would imply a storage coefficient unreasonably large and would not improve the relation at times of full pool (July–Sept.). If M_2 were combined with another model solution using different constants, the combined solution would have to satisfy the difference in relationship in the lower graph. This is not possible. The water-budget data on this illustration and on the plot against elevation (fig. 13) are incompatible with theory and cannot be approximated by use of any reasonable combination of constants in the model. In 1965 a gain of 64,000 cfs-days occurred during a draft of 100 feet, but in 1966–67 only

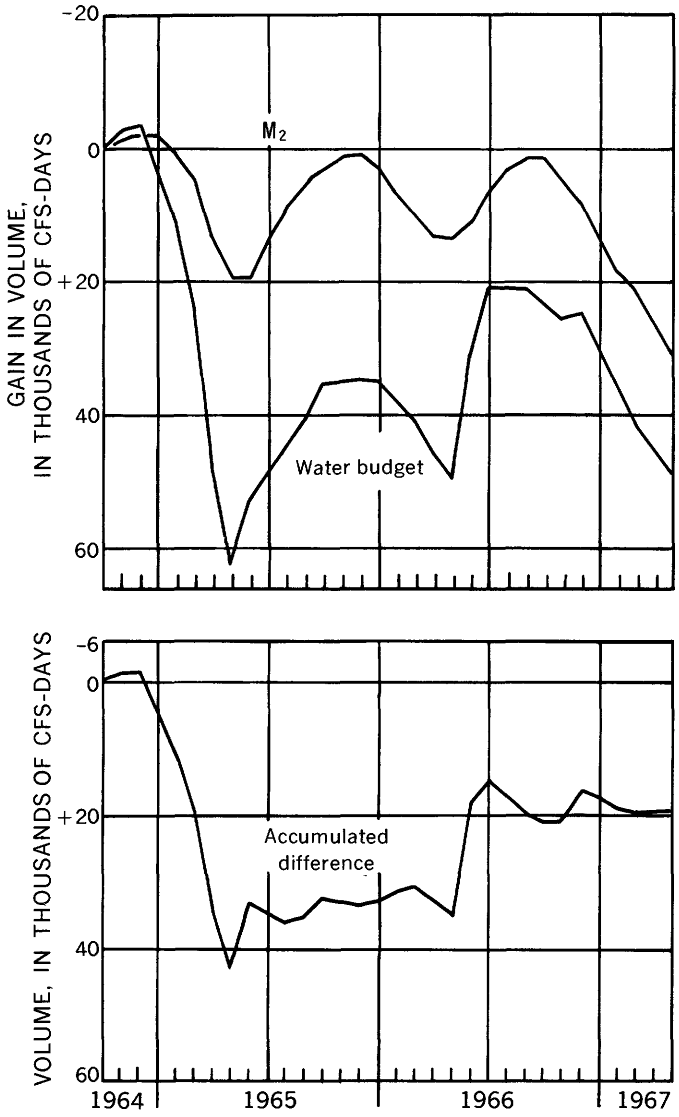

FIGURE 16.—Cumulative apparent gains to reservoir determined from unadjusted water budget and from M_2 and accumulated differences between water budget and M_2.

30,000 cfs-days was gained during a draft of 120 feet. In 1964–65, from full pool to full pool, return to ground-water storage was only 40 percent of the yield. For the 1965–66 pool-to-pool cycle, indicated return to the aquifer was double the yield. Thus the theoretical understanding points to the need to restudy the water budget for possible errors. The accumulated-difference graph indicates that a reduction of about 30,000 cfs-days in the period December 1964–March 1965 and an increase of about 10,000 cfs-days in May–June 1966 would be required to satisfy M_2 approximately. During the first period, total inflow to the reservoir was about 162,000 cfs-days; change in contents, about 930,000 cfs-days; and outflow, about 1,140,0000 cfs-days. The accumulation is about 20 percent of the inflow and about 3 percent of change in contents and outflow. For March the accumulation of 16,000 cfs-days is 50 percent of the inflow. The inflow records could not account for this item. The capacity table, which undoubtedly contains some error, cannot by itself be the source of difference. If it were adjusted, the other periods of rise and fall of reservoir levels would become incompatible. The outflow record for the period is within close limits of measurements and could not logically be shifted as much as 3 percent.

During March, which includes the large drawdown period March 6–24, 1965, the accumulation of 16,000 cfs-days is about 4 percent of the monthly flow. Four discharge measurements made during this period show that it is very unlikely that records could be 4 percent in error.

At this stage in the analysis, a reexamination was made of rating curves and record analyses used in the water-budget analysis. In order to avoid bias, results of the theoretical approach and the water-budget review were obtained independently.

WATER-BUDGET MODIFICATIONS

In the previous sections, it was pointed out that a considerable difference existed between the estimates of bank-storage effect made by the water-budget procedure and those made by the mathematical models. The results of the water-budget study did not conform in some aspects to mathematical theory or hydrologic reasoning. Therefore, all the basic data and computational procedures used in the water-budget study were reviewed in detail. The purpose of this review was to ascertain whether or not any modifications should be made in the various components of the water budget. This review revealed that minor modifications could be made in every item of the water budget. However, almost all such modifications would be of such a nature that they would not indicate superiority in either basic assumption or computational procedure.

There were three items that appeared to be worthy of further study: (1) the high-water rating for the gaging station South Fork Flathead River above Twin Creek near Hungry Horse (2) the high-water rating for the gaging station South Fork Flathead River near Columbia Falls, and (3) the estimate of reservoir inflow from the ungaged areas. A discussion of these items follows.

The upper end of the rating curve for the gaging station South Fork Flathead River above Twin Creek near Hungry Horse was reviewed in detail. Because this main inflow gaging station was newly established, some instability in the definition of the stage-discharge relationship might be expected. A review of the gage-height record did not reveal any periods where changes should be made. During the period of study, two rating tables had been used in the computation of daily discharges. These rating tables were identical up to a gage height of 8.7 feet, discharge 5,150 cfs. Above this stage, the two tables tended to diverge, and at a stage of 12.0 feet the difference amounted to about 7 percent. Three high-water measurements were made during each of the water years 1965, 1966, and 1967, and two were made during water year 1968. A slope-area measurement of the peak of the 1964 flood had also been made.

The channel characteristics at this gaging station suggest that a single stage-discharge relationship would be logical. Thus, the 12 measurements above a gage height of 8.7 feet were used to develop a mean high-water rating. Table 22 shows the percentage deviations of each of these measurements from the tentative rating table developed in this

TABLE 22.—*Percentage deviations of high-water discharge measurements from rating tables, South Fork Flathead River above Twin Creek near Hungry Horse*

Measurement	Date	Gage height (feet)	Discharge (cfs)	Percentage deviation from indicated rating table		
				1	2	Tentative
1	[1] 6–64	20.87	50,900	----	----	----
7	4–29–65	9.77	7,430	0	----	−2.9
8	5–14–65	11.55	13,000	+1.2	----	−0.8
9	6– 7–65	12.16	15,100	−1.2	----	−1.9
21	5– 6–66	11.15	11,900	----	−0.2	+2.2
23	5–26–66	9.83	8,160	----	+4.2	+4.5
24	5–30–66	12.03	15,500	----	0.0	+4.0
33	5–24–67	13.41	19,700	−4.8	----	−2.2
34	6–14–67	10.88	10,500	+1.0	----	−2.0
35	7– 7–67	9.35	6,450	−1.1	----	−2.4
46	5–21–68	10.57	9,730	+2.9	----	−0.3
47	6–19–68	11.17	11,700	+3.4	----	−0.1

[1] Slope-area measurement taken.

review and the tables used in the computation of the published discharge record.

The overall balance of the 12 discharge measurements is very good; the total plus deviation from the tentative rating table is 10.7 percent, and the total minus deviation is 12.6 percent. The individual deviations ranged from +4.5 percent to −2.9 percent, the average deviation being 2.1 percent. If these are considered algebraically, the weighted average deviation amounts to −0.2 percent. There is some tendency for the measurements to cluster by years, but the total percentage deviations are well within the limits that characterize a good stage-discharge rating of a natural stream. The balance of these groups of measurements, by stage, is good; and in each range the plus and minus deviation approximately balance each other. The tentative rating table developed in this analysis was adopted for use in computing the 1968 discharge records. The use of this mean table was assumed to be appropriate for the entire period of record available at this station.

This rating table would be applicable during the period April–July 1965 and May–June 1966. It would modify the computed runoff by +16,750 cfs-days in water year 1965 and −6,050 cfs-days in water year 1966. These changes are in the right direction to improve the estimate of bank-storage effect on the reservoir-refill periods and were judged to be a better evaluation of runoff during the high-water periods. This alternative computation of runoff was adopted for use in the revised water-budget part of this analysis, and computed values of monthly runoff are shown in table 23.

TABLE 23.—*Monthly runoff, South Fork Flathead River above Twin Creek near Hungry Horse*

Month	Monthly runoff for indicated water year (cfs-days)		
	1965	1966	1967
Oct	25,968	30,939	10,783
Nov	18,596	18,811	11,390
Dec	25,932	16,374	12,327
Jan	18,751	12,773	11,903
Feb	14,160	9,657	11,737
Mar	16,794	15,642	11,896
Apr	[1] 88,356	75,620	28,389
May	[1] 273,410	[1] 249,900	-----
June	[1] 353,290	[1] 201,110	-----
July	[1] 118,390	66,592	-----
Aug	35,559	20,119	-----
Sept	47,496	12,703	-----

[1] Revised.

The inflow to Hungry Horse Reservoir from the ungaged drainage area was reviewed for consistency with the inflow from other parts of the drainage basin. For the area on the east side of the reservoir, the inflow was assumed to be 0.75 times the sum of the inflow derived from the east-side secondary gaging-station network. The drainage-area ratio of the east-side ungaged drainage area and secondary gaging-station drainage areas is 0.775. Since the original coefficient is so very close to the ratio of the drainage areas, there is sufficient justification to recompute the reservoir inflow from the ungaged area using the coefficient of 0.775. This in effect would give the same runoff per square mile as for the secondary-network drainage area. An inspection of figure 9 shows that the two areas are intermingled to such an extent that this assumption appears to have hydrologic justification. In a similar manner, the reservoir inflow from the west-side ungaged area was recomputed using a coefficient of 0.946 in place of 0.90. The revised estimates of inflow for the ungaged drainage areas on the east and west banks of the reservoir are shown in table 24. The revised estimate is 14,158 cfs-days more than was estimated for the preliminary water-budget and has been used in the reevaluation of the water budget.

TABLE 24.—*Revised estimate of reservoir inflow from ungaged drainage area*

Month	Monthly runoff for indicated water year (cfs-days)		
	1965	1966	1967
Oct	5,382	4,373	2,049
Nov	4,998	4,189	2,482
Dec	8,151	3,492	4,056
Jan	4,187	2,452	3,387
Feb	3,615	1,716	3,262
Mar	3,744	3,725	2,751
Apr	19,925	15,480	7,622
May	44,941	41,238	----
June	52,123	34,127	----
July	13,841	10,256	----
Aug	5,362	3,326	----
Sept	6,863	2,042	----

The records for the main outflow station South Fork Flathead River near Columbia Falls were also reviewed in detail. The high-water discharge occurs during periods of heavy drawdown which normally occur from September through April but most consistently from November through February. The gage height record for the period of this study was reviewed, and no further changes appeared to be justified. Review of the flows during the drawdown periods for water years 1965, 1966, and 1967 showed that two rating tables had been used, one for water year 1965 and the second for water years 1966 and 1967. These were virtually the same at a discharge of 9,000 cfs and below, but above that point they tended to spread until the variation was about 3 percent.

An examination of these two rating tables and all the high-water discharge measurements that were made since 1954 suggests that a single rating for the entire period of record could be developed which would be an approximate mean of the two tables used. The deviations of the high-water discharge measurements from a tentative table are between +2.5 percent and −2.8 percent; the average deviation is 1.24 percent. Thus it appears that the use of a single rating is justified.

The deviations from the tentative rating table are shown in table 25. The stage-discharge relationship at this station, as judged by the 36 high-water measurements, appears to be extremely stable. The high flows that occurred during the period March 10–23, 1965, were the highest flows since 1960. Thus, if there were to be any major changes they would have occurred during this period.

TABLE 25.—*Percentage deviations of high-water discharge measurements from tentative rating table, South Fork Flathead River near Columbia Falls*

Measurement	Date	Gage height (feet)	Discharge (cfs)	Deviations (percent)
270	2–23–54	9.82	9,140	+1.0
274	4–16–54	11.29	12,600	0
275	4–19–54	11.40	13,000	+.8
278	7–13–54	14.55	21,400	+1.9
289	4–20–55	10.50	10,300	−2.8
292	7– 8–55	9.80	9,070	+.7
312	11–20–56	9.96	9,470	+1.2
313	12–28–56	10.12	9,820	+.9
322	11–12–57	10.06	9,690	+1.0
323	12–10–57	10.25	10,200	+2.0
338	3–24–59	12.68	16,500	+2.5
339	4–24–59	11.04	12,200	+1.7
341	6–22–59	14.09	19,500	−1.5
348	1–15–60	12.20	14,600	−2.0
349	2– 1–60	14.69	21,400	0
353	4–14–60	11.08	12,100	0
365	2–24–61	9.86	9,160	+.2
366	3–27–61	11.60	13,500	+.7
367	4–18–61	12.31	15,400	+1.3
376	1–25–62	10.16	9,960	+1.4
397	12–17–63	9.96	9,370	+.1
398	1–17–64	10.11	9,460	−2.5
407	6–29–64	10.94	11,500	−1.8
412	1–11–65	9.96	9,570	+2.2
413	2–10–65	9.96	9,390	+.3
414	3– 8–65	13.14	17,200	−.6
415	3– 8–65	13.14	17,000	−1.7
416	3–10–65	14.05	19,400	−1.5
417	3–15–65	14.06	20,200	+2.5
424	10–29–65	9.96	9,360	0
426	12–20–65	10.00	9,280	−1.8
432	9–15–66	9.91	9,000	−2.7
433	11– 9–67	10.13	9,500	−2.6
443	12–19–67	10.20	9,970	+.6
444	1–24–68	10.50	10,600	0
448	6–13–68	11.24	12,500	0

For purposes of this analysis, all measurements made prior to water year 1965 were in one group and those made during and after 1965 were in a second group. A summary of these percentage deviations for different gage-height ranges and time periods is shown in table 26. There is a slight tendency for the measurements for the two time periods to cluster. However, in long-term perspective it is felt that a single rating is satisfactory for use in this study.

A review was also made of the relationship of power-generation, head, and turbine discharge for periods of full load (300 megawatts or more) and no flow through the spillway or river outlets. This review lends support to the contention that a single rating table might be applicable during the entire period of this study.

This mean rating table was used in the subsequent water-budget computations. Changes in the computed runoff for South Fork Flathead River near Columbia Falls were made for December 1964–May 1965, October 1965–January, 1966, and July 1966–April 1967. These revisions indicate an increase in monthly outflow of 28,520 cfs-days for the entire

TABLE 27.—*Monthly runoff, South Fork Flathead River near Columbia Falls*

Month	Monthly runoff for indicated water year (cfs-days)		
	1965	1966	1967
Oct	44,530	[1] 90,639	[1] 277,160
Nov	59,430	[1] 68,774	[1] 236,207
Dec	[1] 162,234	[1] 260,630	[1] 156,342
Jan	[1] 253,510	[1] 264,741	[1] 132,047
Feb	[1] 262,710	74,835	[1] 70,044
Mar	[1] 456,210	66,636	[1] 126,326
Apr	[1] 183,225	29,526	[1] 177,789
May	[1] 79,930	85,460	--------
June	6,144	130,670	--------
July	84,793	[1] 103,123	--------
Aug	51,144	[1] 48,757	--------
Sept	75,190	[1] 148,356	--------

[1] Revised.

TABLE 26.—*Summary of percentage deviations of high-water discharge measurements from tentative rating table, South Fork Flathead River near Columbia Falls*

Gage-height range	1954–1968					1954–1963					1964–1968				
		Deviation (percent) [1]					Deviation (percent) [2]					Deviation (percent) [3]			
	No.	Plus	Minus	Weighted	Avg	No.	Plus	Minus	Weighted	Avg	No.	Plus	Minus	Weighted	Avg
9.82–10.00	10	5.7	4.5	+1.2	+0.1	5	3.2	0	+3.2	+0.6	5	2.5	4.5	−2.0	−0.4
10.11–10.50	9	5.9	7.9	−2.0	−.2	5	5.3	2.8	+2.5	+.5	4	.6	5.1	−4.5	−1.1
10.94–11.60	7	3.2	1.8	+1.4	+.2	5	3.2	0	+3.2	+.6	2	0	1.8	−1.8	−.9
12.20–13.14	5	3.8	4.3	−.5	−.1	3	3.8	2.0	+1.8	+.6	2	0	2.3	−2.3	−1.2
14.05–14.69	5	4.4	3.0	+1.4	+.3	3	1.9	1.5	+1.4	+.1	2	2.5	1.5	+1.0	+.5
9.82–14.69	36	23.0	21.5	+1.5	<+.05	3	1.9	1.5	+.4	+.1	15	5.6	15.2	−9.6	−.6
Max deviation	--	2.5	2.8	----	----	--	2.5	2.8	----	----	--	2.5	2.7	----	----

[1] Avg deviation, 1.24.

[2] Avg deviation, 1.13.

[3] Avg deviation, 1.38.

period of study and are in a direction which would make the residuals of the water-budget study conform in general shape to those computed by the mathematical model. These revised flows are summarized in table 27.

REVISED WATER-BUDGET COMPUTATIONS

The water-budget computations were revised and are shown in table 28, which incorporates the modifications to reservoir inflow and outflow discussed in the previous sections. A mass curve of these revised monthly residuals from the water budget and month-end reservoir elevations was prepared and is shown in figure 17. The computations cited above correct many of the questionable periods which were discussed previously. The magnitudes of the residuals approximately balance each other for the two complete cycles of drawdown and refill. In fact, there is a slightly larger residual in the 1966 refill period than during the drawdown period. The slopes of the various mass-curve segments for drawdown and refill periods are about the same. The average water-budget residuals, in cfs-days per foot of change in reservoir stage, are shown in the following tabulation:

TABLE 28.—*Revised components of water-budget computations, Hungry Horse Reservoir*

[Values in cfs-days, except as indicated]

Month	Outflow	Inflow	Change in contents	Residual	Accumulated residual	Residual (cfs–days × 10^{-3})
1964						
Oct	46,452	49,444	+242	−2,750	−2,750	−2.8
Nov	59,156	42,477	−17,904	−1,225	−3,975	−1.2
Dec	161,748	64,352	−92,385	+5,011	+1,036	+5.0
1965						
Jan	253,284	37,835	−207,478	+7,971	+9,007	+8.0
Feb	262,533	30,056	−222,067	+10,410	+19,417	+10.4
Mar	456,028	30,826	−404,940	+20,262	+39,679	+20.3
Apr	182,556	168,204	−1,650	+12,702	+52,387	+12.7
May	78,737	443,003	+343,213	−21,053	+31,328	−21.1
June	5,760	544,904	+525,733	−13,411	+17,917	−13.4
July	87,792	169,882	+76,867	−5,223	+12,694	−5.2
Aug	55,283	59,468	0	−4,185	+8,509	−4.2
Sept	77,692	78,119	−5,082	−5,509	+3,000	−5.5
Oct	92,422	48,118	−44,492	−188	+2,812	−0.2
Nov	68,496	38,134	−30,190	+172	+2,984	+0.2
Dec	260,455	31,313	−223,280	+5,862	+8,846	+5.8
1966						
Jan	264,598	24,820	−231,186	+8,592	+17,438	+8.6
Feb	74,731	17,320	−54,849	+2,562	+20,000	+2.6
Mar	66,506	32,020	−29,309	+5,177	+25,177	+5.2
Apr	29,056	140,127	+113,568	+2,497	+27,674	+2.5
May	85,607	406,779	+306,131	−15,041	+12,633	−15.1
June	130,265	335,846	+195,939	−9,642	+2,991	−9.6
July	107,662	106,587	−1,452	−377	+2,614	−0.4
Aug	53,919	34,235	−19,704	−20	+2,594	0.0
Sept	152,050	20,670	−128,279	+3,100	+5,695	+3.1
Oct	279,225	21,994	−250,807	+6,424	+12,119	+6.4
Nov	235,996	26,683	−204,089	+5,224	+17,343	+5.2
Dec	156,044	31,202	−113,305	+11,537	+28,880	+11.6
1967						
Jan	131,793	28,912	−93,920	+8,961	+37,841	+8.9
Feb	69,840	24,855	−39,946	+5,039	+42,880	+5.1
Mar	126,173	23,324	−98,202	+4,647	+47,527	+4.6
Apr	177,572	62,238	−109,866	+5,468	+52,995	+5.5
Total	4,289,431	3,173,747	−1,062,689	+52,995	--------	------

Year	*Drawdown*	*Refill*
1965	559	492
1966	422	427
1967	424	-----

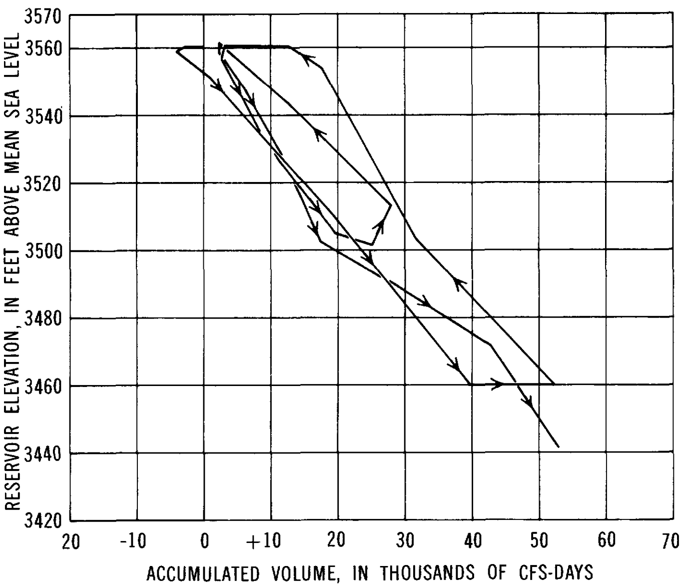

FIGURE 17.—Revised mass curve of accumulated water-budget residuals and month-end reservoir elevations.

These estimates are more consistent than those from the preliminary water budget and for all practical purposes are about as consistent as can be achieved by water-budget analysis. Further testing by mathematical model will be discussed in the succeeding sections.

SELECTION OF MODEL CONSTANTS

Water-budget data resulting from the reanalysis of records were adopted as a basis for trial solutions for constants in the equations. The field model was calculated on a systematic basis, and although application of some judgment and experience was necessary, the results are considered to be unbiased.

SINGLE SOLUTIONS

Although conditions are highly variable, the possibility that a single solution of the model could be used was studied. A double mass plot of cumulative residual volumes from the water budget and from M_2 has a mean slope of about one-half. If M_2 were to be used alone, all values would be multiplied by 2. This would imply an average storage coefficient of 0.3, which would be unreasonably large.

Two additional model computations were made with assumptions as follows:

	a (feet)	S	T/a^2S (day^{-1})	T (ft^2 per day)
M_3	851	0.2	0.0064	927
M_4	851	.2	.0256	3,710

Monthly and cumulative volumes calculated from M_2, M_3, and M_4 are given in table 29.

TABLE 29.—*Volumes of bank storage computed from* M_2, M_3, *and* M_4

[Plus, to reservoir; minus, from reservoir]

	Volumes of bank storage (1000 cfs-days)					
	M_2		M_3		M_4	
Month	Cumulative	Monthly	Cumulative	Monthly	Cumulative	Monthly
1964						
Oct	−1.3	−1.3	−1.7	−1.7	0	0
Nov	−2.2	−.9	−2.5	−.8	+.6	+.6
Dec	−2.0	+.2	−1.3	+1.2	+4.0	+3.4
1965						
Jan	+.3	+2.3	+3.9	+5.2	+13.7	+9.7
Feb	+4.5	+4.2	+12.3	+8.4	+26.5	+12.8
Mar	+13.1	+8.6	+27.5	+15.2	+51.3	+24.8
Apr	+19.6	+6.5	+40.1	+12.6	+60.5	+9.2
May	+19.8	+.2	+38.9	−1.2	+46.0	−14.5
June	+13.6	−6.2	+24.2	−14.7	+16.4	−29.6
July	+8.5	−5.1	+12.7	−11.5	+2.3	−14.1
Aug	+5.4	−3.1	+6.1	−6.6	+.3	−2.0
Sept	+3.2	−2.2	+2.1	−4.0	0	−.3
Oct	+1.6	−1.6	0	−2.1	+.9	+.9
Nov	+1.0	−.6	+.1	+.1	+3.7	+2.8
Dec	+2.6	+1.6	+4.2	+4.1	+12.3	+8.6
1966						
Jan	+6.7	+4.1	+13.0	+8.8	+25.8	+13.5
Feb	+10.0	+3.3	+20.0	+7.0	+33.3	+7.5
Mar	+13.1	+3.1	+25.6	+5.6	+37.4	+4.1
Apr	+13.7	+.6	+25.4	−.2	+32.3	−5.1
May	+11.2	−2.5	+19.9	−5.5	+19.5	−12.8
June	+6.5	−4.7	+10.0	−9.9	+4.0	−15.5
July	+3.7	−2.8	+4.4	−5.6	+.7	−3.3
Aug	+1.8	−1.9	+1.1	−3.3	+.4	−.3
Sept	+1.8	0	+1.9	+.8	+5.5	+5.1
Oct	+4.3	+2.5	+7.6	+5.7	+17.3	+11.8
Nov	+8.5	+4.2	+16.3	+8.7	+30.5	+13.2
Dec	+13.7	+5.2	+26.4	+10.1	+42.5	+12.0
1967						
Jan	+18.4	+4.7	+34.5	+8.1	+49.7	+7.2
Feb	+21.7	+3.3	+40.0	+5.5	+52.7	+3.0
Mar	+26.2	+4.5	+46.4	+6.4	+59.4	+6.7
Apr	+31.0	+4.8	+53.4	+7.0	+66.9	+7.5

Model M_3, because of higher transmissivity, permits a more rapid drainage than M_2. This solution would require a multiplier of about 1.2 for an average fit to the water budget. The inferred storage coefficient is 0.24, which is unreasonably large if it represents only the aquifer.

M_4, with a transmissivity greater than those for M_2 and M_3, permits very rapid drainage. The match with field data requires that the model solution be multiplied by about 0.8 and that the storage coefficient be about 0.16. If we assume that the storage coefficient for the 20 percent of the material classified as open gravel and sand is 0.2, the remaining 80 percent of the material consisting mostly of till would have a coefficient of about 0.15. Although not impossible in view of the fact that more fine sand than anticipated was found in the till, the value is higher than would be expected. The rapid drainage feature of this solution minimizes timelag and narrows the loop effect. The solution produces a better fit to the water budget than M_2 or M_3 in the lower part of the draft periods but a much poorer fit during the late stages of filling and following return to full pool.

Study of the characteristics of bank-storage responses calculated by use of several sets of constants in the model indicates the following:

1. No single application of the theoretical model is completely accurate.
2. Large inferred storage coefficients point to the need to consider other segments of the problem such as errors in the storage table and errors in the water budget.

The conclusion that a single model solution would not be adequate became evident when comparing computed results from M_2, M_3, M_4 with the field water budget. On a seasonal basis a slow lag such as is contained in M_2 is needed; on a short-time basis quick response such as is contained in M_4 is needed. Because of the wide range of hydrologic characteristics of the aquifer, it would seem appropriate to subdivide the aquifer into several or many units and assign T, S, and a values to each. Calculations for such a system would become very lengthy, and a more refined solution might result. In view of all the uncertainties, there is very little justification for over-refinement of the computations. In the following sections, the problem has been lumped into two groupings of characteristics.

RESERVOIR STAGE AS A PARAMETER

Solutions were computed on the basis of a mathematical model solution plus an increment for change in reservoir stage. The stage increment is determined from the slope of a plot of reservoir stage versus the cumulated differences of the water-budget and the model results. This procedure lumps errors from the capacity table with the yield of highly permeable parts of the aquifer which respond with a small timelag.

Each of the three model solutions was expanded into a family of curves by multiplying by constants (thus varying storage coefficient and transmissivity). Cumulative differences of water-budget and model volumes when plotted against stage produced a sequence of graphs for each of the three cases. The graphs in each of the three sequences had similar characteristics. As the multiplier was varied, loops varied from positive through zero to negative. However, timing was different at different stages. A best solution was selected on the basis of mean monthly error. The plot for this solution is shown in figure 18.

This analysis indicates that bank storage can be calculated or predicted by the relation

Bank-storage volume = Volume computed from M_2 + 230 cfs-days per foot of change of stage in the reservoir.

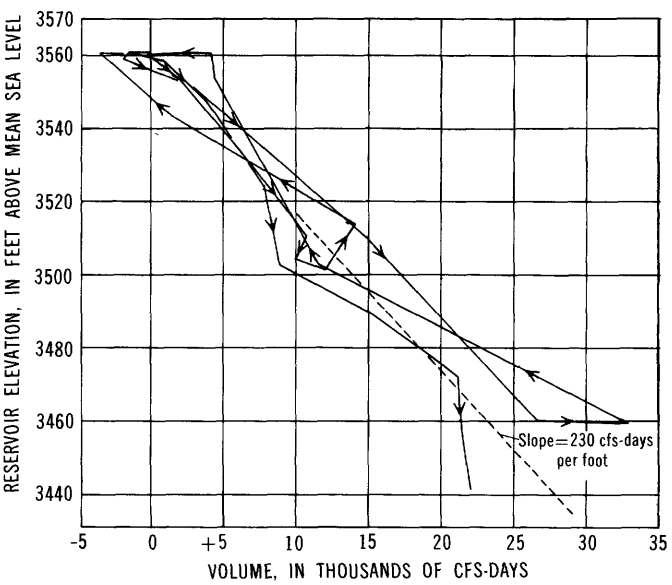

FIGURE 18.—Reservoir elevation versus cumulative difference of water-budget volumes and those computed by M_2.

Using stage record as input, the relation was computed for the period of study. Comparison of computed and water-budget results is shown in figure 19.

The overall agreement of computed and observed results is good. Monthly differences are within limits of ±5,000 cfs-days for 28 of the 31 months and within limits of ±3,000 cfs-days for 21 of the 31 months. The mean deviation of monthly differences is 2,400 cfs-days. The cumulative-difference graph shows fluctuations which are balanced in relation to the zero baseline and which deviate more than 5,000 cfs-days only twice in the 31-month period. For yearly cyclic periods, from full pool to full pool, differences are very small.

Some of the larger monthly differences are to be expected. During the smowmelt and reservoir-filling periods, problems of timing should be evident. The theory assumes horizontal flow from the reservoir to the aquifer. During rapid filling, terraces are covered and some recharge takes place downward. This would make observed movement to bank storage larger than that predicted. Also during snowmelt, water from snow on the exposed reservoir bed and on the adjacent areas enters the aquifer. This volume of water was included in the value for precipitation on the reservoir bed and in the estimates for the ungaged areas. Estimates were based on gaged areas, and while the quantity is probably closed approximated, the timing is delayed by routing through the aquifer. At least part of the monthly differences in May 1965 and 1966 is related to these effects. Further, excessive recharge in May leaves less storage capacity to be filled in later months, and field observations should be smaller than values computed from the model. Data for June–July 1965 and July–September 1966 are consistent with this expectation.

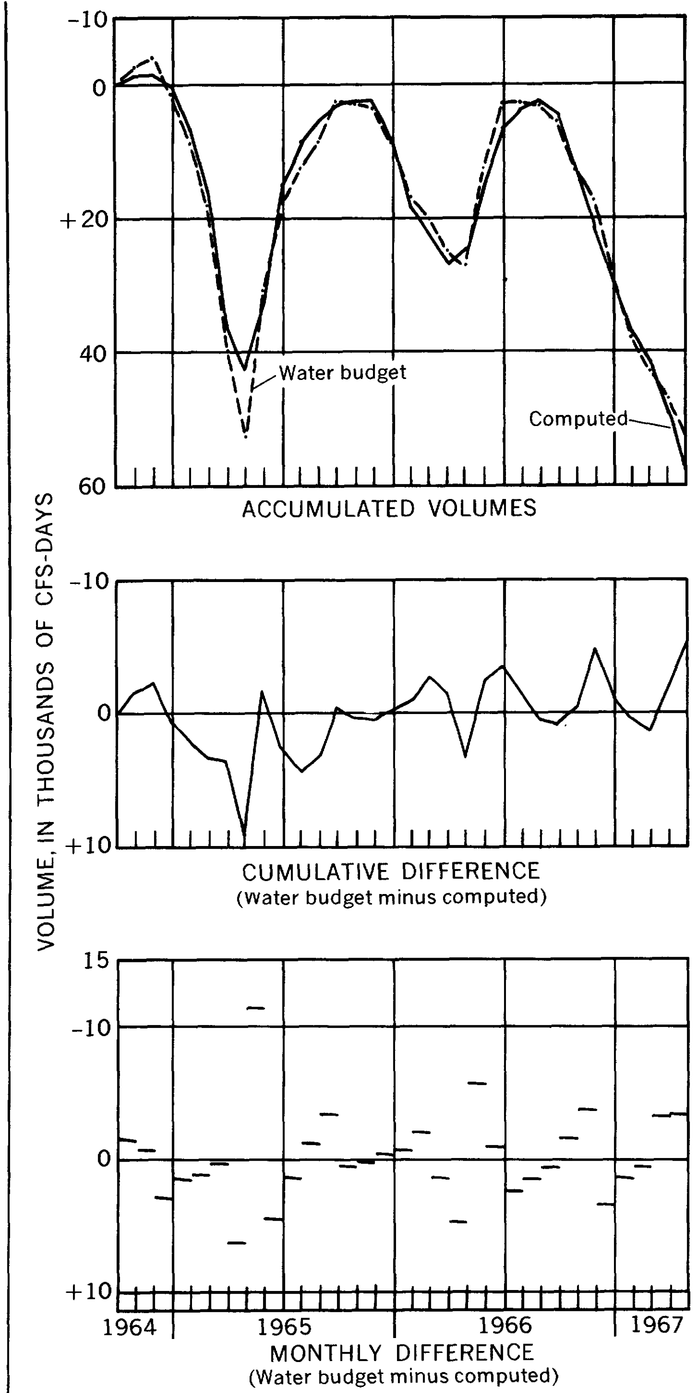

FIGURE 19.—Comparison of volumes of water from water-budget residuals and those computed by M_2+230 cfs-days per foot of stage change.

Channel storage between the main inflow station and head of pool was neglected. This item is estimated to be about 1,000 cfs-days in May 1965 and contributes to the deviation for that month.

During May, the model calls for flow to bank storage downstream from head of pool and drainage in the reach upstream from head of pool. In May 1965 the river rose about 7 feet in the reach upstream from head of pool, and movement to bank storage occurred. This is confirmed by the rise in observation wells at Dry Park. Here again, the model is deficient. However, although this segment could be calculated, its magnitude is about 2,000 cfs-days (May 1965) and is small enough to be neglected. Problems related to filling periods have been discussed to explain major deviations.

The difference of 6,000 cfs-days in April 1965 might be an indication that the mix of parameters is deficient. Reservoir stages at the beginning and end of April were nearly the same so that the portion of the model related to stage was not operating. This parameter lumps errors from the capacity table and part of the aquifer component. For April, only M_2 is effective. The data suggest that M_2 is inadequate and that we need to consider a mix of model solutions.

SIGNIFICANCE OF MODEL CHARACTERISTICS

An estimate of the model components is as follows:

1. The sand and gravel part of the aquifer (fig. 12) has a volume of about 1,150 acre-ft per foot of elevation. For an estimated storage coefficient of 0.2, this accounts for about 115 cfs-days per ft.
2. The remainder of the 230 cfs-days per ft in the model equals about 115 cfs-days per ft chargeable to error in the capacity table. In the top 100 feet of storage, capacity would average 1.2 percent greater than table values.
3. M_2 has a storage coefficient of 0.15. For this interpretation the value 0.15 is applicable to 80 percent of the volume of the aquifer, and the inferred coefficient is about 0.19. This is higher than expected for this type of material.

The accumulated volume of ground-water outflow computed from the model is plotted against reservoir stages in fig. 20. In general, the plot compares favorably with the similar plot from the water budget (fig. 17).

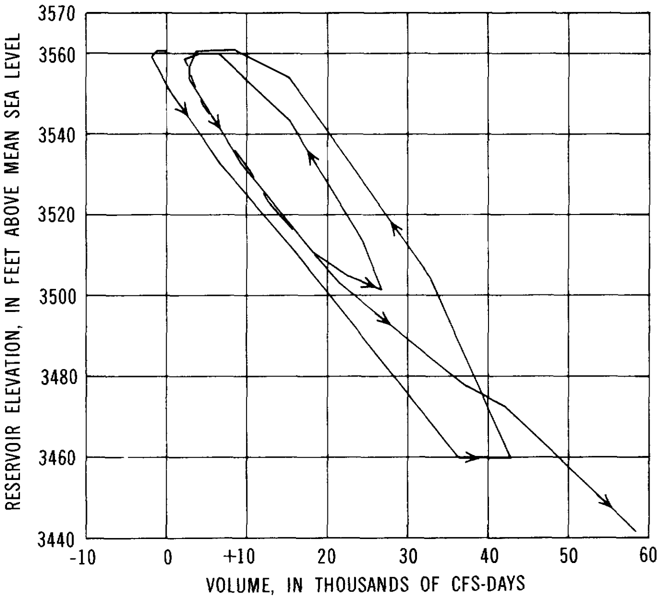

FIGURE 20.—Accumulated volume of ground-water outflow computed using M_2+230 cfs-days per foot of stage change.

MODEL SOLUTIONS WITH TWO SETS OF CONSTANTS

Using two sets of constants in the model, a systematic analysis was made to seek the best combination to fit the field data.

One solution is

$$\text{Volume} = 0.6M_2 + 0.4M_4.$$

Comparison of values computed from this relation with those of the water budget is given in figure 21. Mean monthly deviation is about 2,800 cfs-days. Monthly differences are within limits of ±5,000 cfs-days for 26 months and are within ±3,000 cfs-days for 22 months. Cumulative-difference values deviate by more than 5,000 cfs-days five times during the 31-month period.

Another solution is

$$\text{Volume} = M_2 + 0.4M_4.$$

Results of this solution are compared with the water-budget results in figure 22. Mean monthly deviation is about 2,600 cfs-days. Monthly differences are within limits of ±5,000 cfs-days for 28 months and within ±3,000 cfs-days for 21 months. Cumulative difference values deviation by more than 5,000 cfs-days five times during the 31-month period. This solution is somewhat better than the previous one.

The solution implies a storage coefficient for the till of about 0.19, and for the gravel and sand, about

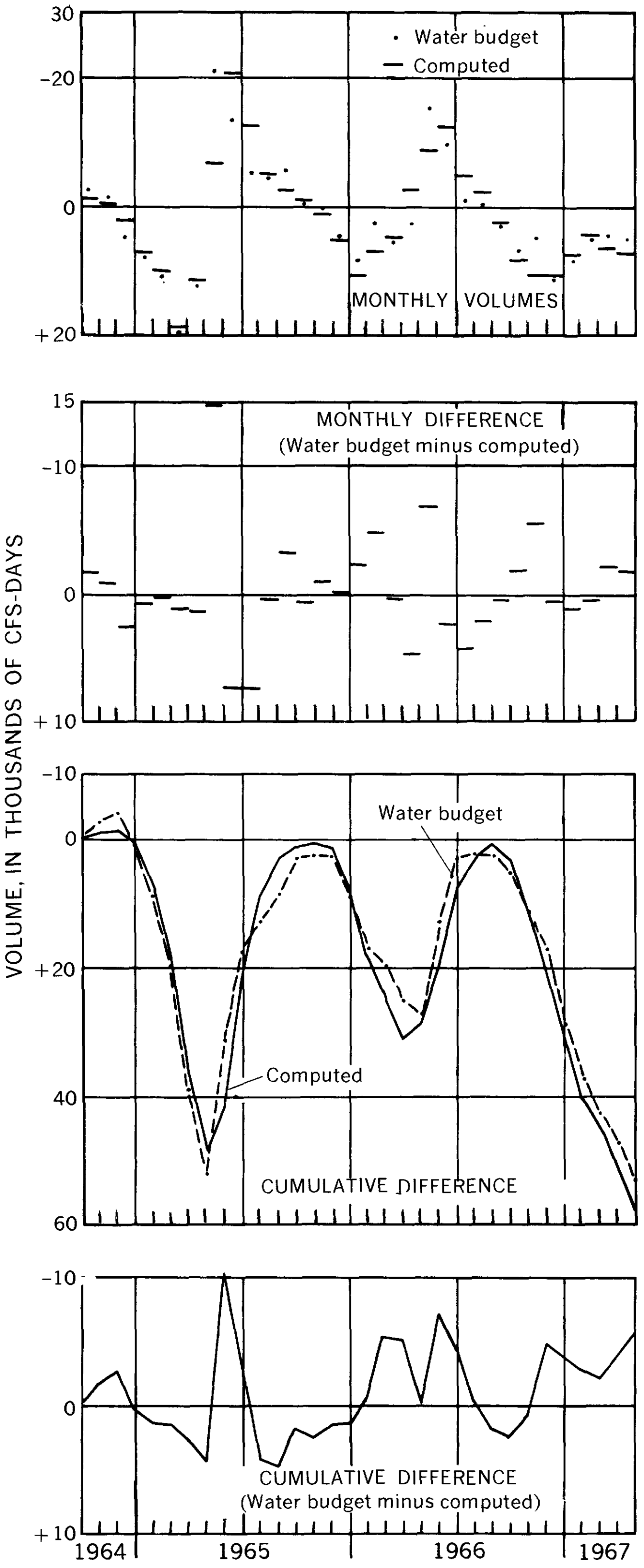

Figure 21.—Comparison of volumes of water from water-budget residuals and those computed using $0.6M_3+0.4M_4$.

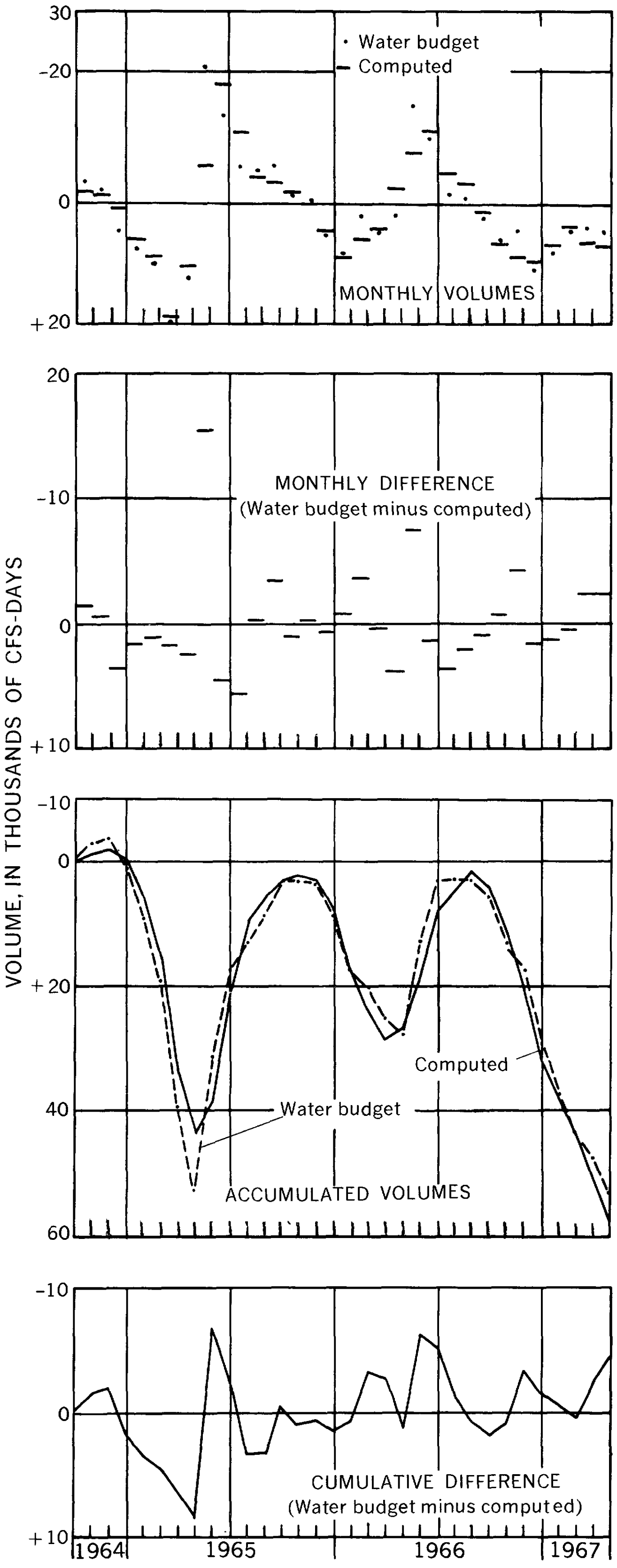

Figure 22.—Comparison of volumes of water from water-budget residuals and those computed using $M_2+0.4M_4$.

0.4. Although these storage coefficients are larger than expected for these materials, the values are regarded as reasonable because of the following considerations: The assumption that the capacity table has no errors is probably too rigid, and computation of the aquifer width a from geologic cross sections was based on limited data. Errors introduced by these two items plus the errors in elements of the water budget are all reflected in the implied storage coefficients.

Accumulated volume for the solution $M_2+0.4\,M_4$ is plotted against reservoir stage in figure 23.

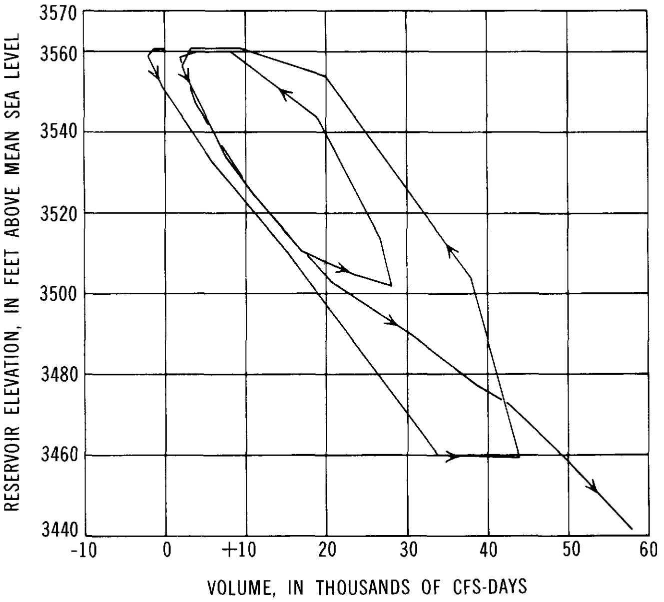

Figure 23.—Accumulated volume of ground-water outflow computed using $M_2+0.4M_4$.

This curve has a wider loop than that for M_2+230 cfs-days per ft (fig. 19) or for the water budget (fig. 17). The water-budget curve is short circuited on the rising-stage part because of vertical recharge discussed previously. The curve based on $M_2+0.4M_4$ is statistically not as good as that for M_2+230 cfs-days per ft. However, the statistics are distorted because of comparison to conditions in the field that differ from those of the model. The solution $M_2+0.4\,M_4$ fits better in April and June 1965. This solution is considered superior because of the likelihood that it will give better results when projected to lower elevations for which data are not available. Such a projection based on the solution $M_2+0.4M_4$ will have a diminishing characteristic related to the wedge shape of the aquifer. In the solution M_2+230 cfs-days per ft, the first term has the wedge effect but the second term does not. Use of the second term would depict a condition of an increasing error in capacity as the reservoir became smaller.

INHERENT ERRORS IN DISCHARGE RECORDS

All the relations to this point in the analysis are based on the assumption that the reworked station records are without error. Solutions developed are well within the limitations of the data. However, the implied storage coefficient for the till and associated deposits appears to be larger than that to be expected on the basis of experience.

The fact that the yearly (full pool to full pool) values correlate extremely well verifies that the records are generally of high quality. The yearly figures provide only a broad look at the overall quality of records. Many errors affecting individual months are eliminated in this comparison. Those related to the capacity table and to the reservoir-stage readings self-compensate, and those related to vertical recharge of the aquifer, channel storage, stage effect on bank storage in the reach upstream from head of pool, and snow and ice storage on the unwatered bed of the reservoir and on the lake are nearly balanced out by midsummer.

Stream-flow measurements at all stations were made by standard Geological Survey methods. Personnel and equipment were rotated so that the records should be consistent and unbiased. If there were an inherent error in the procedure, it would balance out on an annual basis. On a seasonal basis, it could be significant since large inflows occur in spring and large withdrawals occur in the fall and winter. Since annual figures are in balance, any inherent error should be considered as being the same at all stations and also should be applied to ungaged estimates based on records. By judgment based on a large implied storage coefficient, it is concluded that solutions thus far obtained are probably high; that is, their use for predicting additional water for power would have more chance of overpredicting than underpredicting. Accordingly, in studying the sensitivity of the model to inherent errors in gaging it was assumed that measured flows might be too large. The water budget was recalculated for a sequence of assumed errors. For each member of the sequence, a constant percentage reduction was made in all measured flows and in all estimated flows derived from measured flows. Four water-budgets were calculated by this procedure for assumed flow reductions of 0, 1, 2, and 5 percent. Slopes from double mass plots of cumulated water-budget residuals versus cumulative volumes determined from $M_2+0.4M_4$ yield multipliers to be applied to the model values.

Model solutions corresponding to each of the water budgets calculated to include inherent errors are listed below:

	Reduction of flow (percent)	Model solutions
A	0	$M_2+0.4M_4$
B	1	$0.8(M_2+0.4M_4)$
C	2	$0.6(M_2+0.4M_4)$
D	5	------------

Cumulative differences of water-budget residuals calculated to include the listed assumed errors minus the volumes calculated by the corresponding model solution are plotted in figure 24. The graph shows that individual loops at middle and lower elevations open up as the assumed error increases and also that the spread of points increases at full-pool level. At lower elevations, data for the two drawdown periods move closer together, then spread. At midrange, points for different years move closer together and then spread.

Results for these assumed conditions for 31 months are summarized below:

	Number of months for which monthly difference was within the range indicated		Number of times during period that cumulative difference was within ±5,000 cfs-days	Mean monthly deviation cfs-days
	±5,000 cfs-days	±3,000 cfs-days		
A	28	21	26	2,600
B	28	23	28	2,500
C	27	22	26	2,600

Trial *B* appears to be the best solution, although trials *A* and *C* are acceptable. Trial *A*, based on $M_2+0.4M_4$, was discussed previously and, although based on a reasonable match to field data, it was judged to be high because of high implied storage coefficients. Trial *C*, based on an assumed inherent

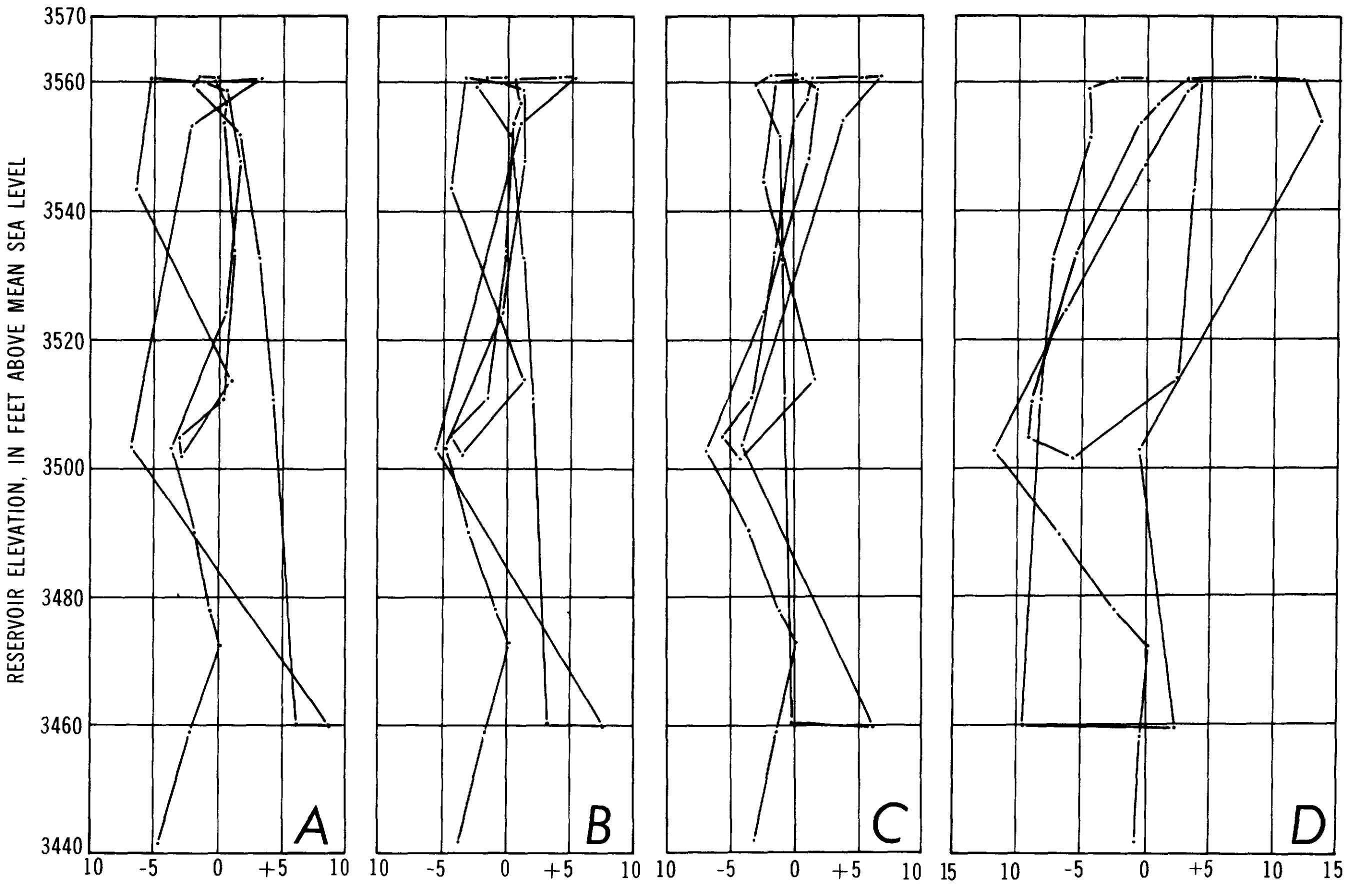

Figure 24.—Cumulative residuals for a sequence of assumed inherent errors. Diagrams are cumulative differences: (water-budget residuals minus indicated assumed error) minus (multiples of $M_2+0.4M_4$). *A*, No inherent error and $M_2+0.4M_4$; *B*, 1 percent error and $0.8(M_2+0.4M_4)$; *C*, 2 percent error and 0.6 $(M_2+0.4M_4)$; and *D*, 5 percent error alone.

error of 2 percent and using $0.6(M_2+0.4M_4)$, fits the data about as well as Trial *A*. Calculated storage coefficients are about 0.12 for 75 percent of the material (till) and 0.20 for 25 percent of the material (sand and gravel). Trial *B*, using 1 percent assumed error and $0.8(M_2+0.4M_4)$, fits field data somewhat better than *A* or *C*. The storage coefficients are about 0.15 for 80 percent of the material (till) and 0.32 for 20 percent of the material (sand and gravel), or 0.18 for 68 percent of the material and 0.2 for 32 percent. If an allowance were made for error in the capacity table, these coefficients would be smaller.

SENSITIVITY

A complete sensitivity analysis is not possible because range-of-error values cannot be determined for many of the items in the problem. The spread from diagrams *A* to *D* in figure 24 is 5 percent, while the corresponding effect on bank-storage values is from about 50,000 cfs-days to zero. Thus each 1 percent assumed inherent error causes a 20-percent change in the bank-storage results.

The same relation (1 percent assumed error causes 20-percent change in bank-storage results) would be approximated if the errors were assumed to be in the capacity table. However, a 5-percent adjustment to the table will produce a graph very nearly like *D*. This graph shows a pronounced loop related to the aquifer response. Expressing bank storage as a percentage adjustment to the capacity table can modify only the slope of the loop, not the loop itself. On an average basis, solutions *A*, *B*, and *C*, give results approximately equivalent to 5, 4, and 3 percent, respectively, of the capacity table.

CHOICE OF MODEL CONSTANTS

While solution *B* appears to be the best fit, the implied coefficients seem high. Part of the determination relates to the distance from reservoir to valley wall. The value used (851 ft) is an average value computed from the volume of valley fill which was determined from poorly controlled geologic sections. The opportunity for error in the width is substantial, and it is very possible that the volume of material is larger than estimated. Another item which was neglected is storage in the hard rocks flanking the unconsolidated fill. Storage space in these rocks is probably less than 1 percent by volume; however, as there is no way of arriving at a reasonable volume of material involved, quantitative evaluation was not attempted. The effect of omitting this item is to make the apparent storage coefficients slightly larger than the true coefficients for the unconsolidated material.

In view of all the uncertainties, a final selection of model constants must be determined on the basis of judgment. Solution *B* is recommended as representing a reasonable approximation of true conditions. Solutions *A* and *C* which represent solution *B* ±25 percent are considered reasonable limits bracketing the zone within which the true solution probably lies.

Solution *B* is recommended for use in general studies where adjustment for bank storage needs to be used. For predicting water volume for power generation, solution *B* is recommended.

AQUIFER STORAGE

Aquifer storage capacity at any reservoir level is equivalent to ground-water storage for the condition of constant level for a long enough time either to drain or to fill the aquifer to that level. It can be computed from the geometry of the aquifer and the storage coefficient.

$$V=\frac{aSh^2}{-m}$$

where h = reservoir elevation − 3,057.5 feet,
a = 851 feet,
and $m = -0.00293$.

For combined models a weighted *S* value is used.

Curves of aquifer storage capacity were computed using constants for recommended solution *B* and for ±25 percent bracketing solutions *A* and *C*. Under normal operating conditions the reservoir

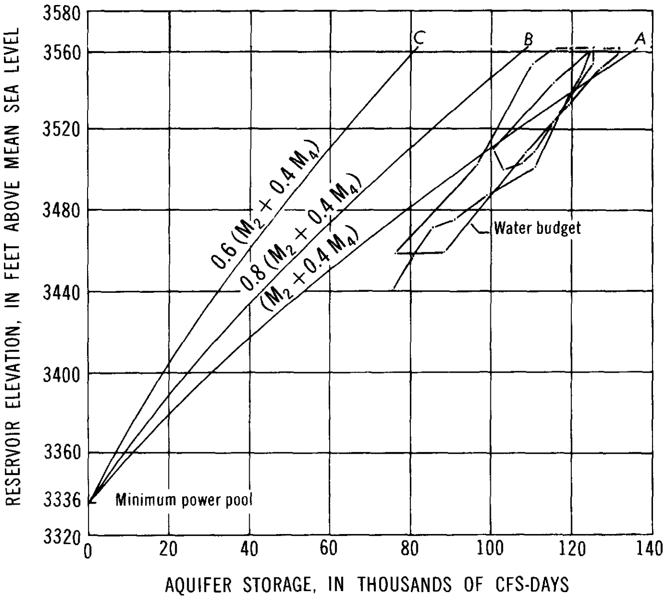

Figure 25.—Aquifer storage-capacity curves for solutions *A*, *B*, and *C*.

will not be drawn down below an elevation of 3,336 feet (bottom of power pool). Ground-water storage in the part of the aquifer below this elevation includes dead storage below the lowest outlet at elevation 3,196 feet, and inactive storage between elevations 3,196 and 3,336 feet (not available under normal operating conditions). Curves of aquifer storage capacity for reservoir stages between 3,336 feet and 3560.5 feet are shown in figure 25. These curves are for "active" aquifer storage capacity inasmuch as they define the aquifer storage capacity in which water may be stored or withdrawn for beneficial use. The weighted storage coefficient, the dead and inactive aquifer storage capacity, and the active aquifer storage capacity are listed below:

	Weighted *S*	Aquifer storage capacity (cfs-days)		
		Dead and inactive	Active	Total
A	0.23	60,100	135,400	195,500
B	.184	48,100	108,300	156,400
C	.138	36,100	81,200	117,300

Figure 25 also shows a plot of the cumulative water-budget residuals oriented to the aquifer storage-capacity curve for solution *A*, the solution which best matched field data. The starting point for this loop was calculated on the basis of the model. The average slope of the field loop is steeper than that of the capacity curve. The fit is very much in accordance with that to be expected. During drawdown, loops cross the capacity curve and reflect the lag in movement of ground water to the reservoir. If drawdown stops and stage is held constant, the loop curve should move to the left at a decreasing rate and approach the capacity curve as a limit. On a rising stage loops cross left of the curve, reflecting lag in filling of the aquifer. After reaching pool level, water continues to move to ground-water storage at a diminishing rate and the loop approaches the capacity curve as a limit. Thus, a very simple seasonal cycle consisting of (1) a constant rate of drawdown, (2) a stationary stage for several months, (3) a constant rate of fill, and (4) a stationary stage for several months, would lie inside a diamond-shaped limiting "box." The capacity curve would be the diagonal of the box, and rising and falling limbs would have slopes related to the rate of change of reservoir stage.

The aquifer storage-capacity curve for the recommended solution (*B*) and the storage loop calculated from this solution, $0.8(M_2+0.4M_4)$, are shown in figure 26. The loop on the rising-stage positions is wider than the observed loop in the preceding figure because the theoretical loop does not include the effect of vertical recharge which flattens the observed loop. The deviations of the storage loops from the aquifer storage-capacity curves in figures 25 and 26 clearly demonstrate the transient nature of ground-water storage and demonstrate that bank storage cannot be accurately defined by a single curve.

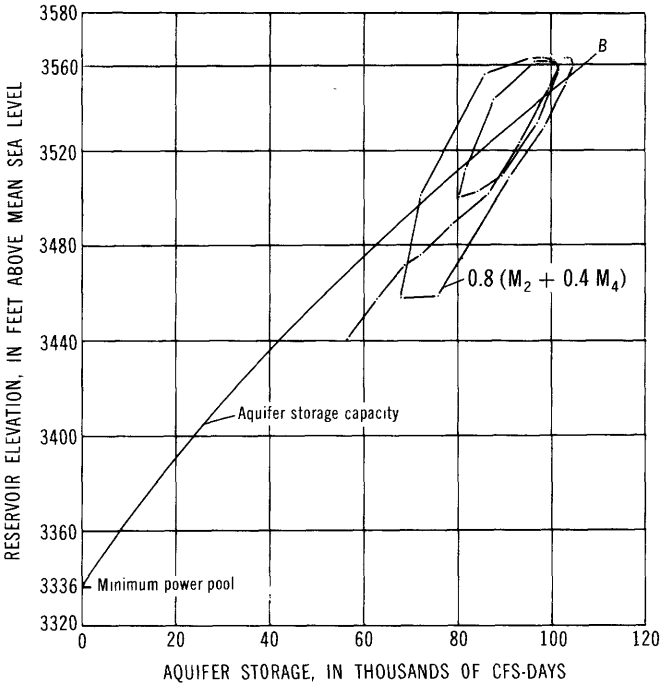

FIGURE 26.—Aquifer storage and storage capacity computed from solution *B*, $0.8(M_2+0.4M_4)$.

USE OF THE MODEL

The solution $0.8(M_2+0.4M_4)$, can be used to evaluate changes in ground-water movement or storage changes occurring in response to stage changes of the reservoir. Inspection of the equations shows that there are too many variables to permit drawing a simple working curve or family of curves. As shown by the analysis, simple relations attempting to use stage or a flat percentage of the capacity table can only approximate the average slope of the loop curve and cannot account for the time-dependent effects which control the spread of the loop.

Computations in this report were made on a monthly basis by desk calculator. Time was reduced by using mathematical and graphical shortcuts. The equations lend themselves to computer solution; if used to any great extent, they should be programmed for the computer.

LOW-FLOW FORECASTS

As previously indicated, the primary objectives of the Hungry Horse Project are to provide at-site and downstream power generation and local and downstream flood control. The power operations are based on bringing Hungry Horse Reservoir to its highest stage during July of each year and withdrawing water during the period August–April as needed. The amount of drawdown will depend upon the loads to be met and the stage of development of the power system. The flood-control operations are based on having the reservoir drawn down to a stage on May 1 which will provide for storing most of the inflow to Hungry Horse Reservoir during May, June, and July. During years of high-runoff potential, the flood-control parameters may indicate the need for withdrawing more water from storage than is needed for power generation.

The efficient operation of this reservoir to meet these dual objectives requires careful planning because the storage may be used on a "cyclic" or multiyear basis, as well as on a seasonal basis. The accurate evaluation of future inflows to the reservoir plays an important part in this planning procedure. A method for forecasting the inflow to Hungry Horse Reservoir for use during the period January–July was developed under the auspices of the Water Management Subcommittee of CBIAC in November 1964. This forecast is used as a parameter in the operation of this reservoir, primarily during the refill period. An accurate evaluation of potential reservoir inflows during the low-flow period would improve the seasonal operations during the reservoir-drawdown period. The second phase of this investigation reviews the July–April runoff data for both natural and regulated conditions and develops a method of forecasting the reservoir inflows during the low-flow period.

NATURAL CONDITIONS

The initial storage of water in Hungry Horse Reservoir occurred in September 1951. Prior to this date the observed runoff records for South Fork Flathead River near Columbia Falls are assumed to be the inflow to the reservoir. Summaries of these data for the months of July–April for power years 1929–51 are listed in table 30. (A power year ends June 30 of the year indicated). The accumulated monthly runoff through April of each power year is shown in table 31. Frequency diagrams for the time periods listed in table 31 are shown in figure 27. Power year 1937 had the lowest runoff during power years 1929–51 for all time periods except for the month of April when it had the second lowest.

Evaluations of "assured" runoff for some of these periods had previously been made utilizing recession curves developed from discharge records of the gaging station South Fork Flathead River near Columbia Falls. Frequency curves of increments of flow derived from concurrent weather conditions were used for other levels of flow probabilities. Dependable flow curves (Sachs, 1957) are also available for use in evaluating the potential runoff during the fall and winter months.

TABLE 30.—*Monthly runoff, South Fork Flathead River near Columbia Falls*

Power year	Monthly runoff (cfs-days)									
	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr
1929	172,960	46,090	21,461	28,365	22,200	16,368	14,043	12,040	18,786	63,256
1930	77,190	25,141	14,790	13,795	11,760	11,532	9,579	15,064	14,570	254,610
1931	57,660	21,390	16,740	28,582	30,000	23,498	21,514	21,140	37,200	99,150
1932	42,470	19,158	20,730	19,065	24,600	24,428	17,112	41,760	66,030	165,540
1933	107,880	35,340	21,570	25,792	68,700	59,210	36,270	25,480	27,218	119,225
1934	167,400	44,330	26,100	89,869	123,840	108,624	84,519	57,176	91,295	353,050
1935	59,117	24,025	16,170	27,258	61,920	30,902	28,633	28,804	39,695	91,726
1936	99,610	29,892	17,214	13,991	11,873	9,716	10,725	10,125	14,683	216,657
1937	48,364	20,952	14,934	13,402	10,844	12,720	8,244	8,444	12,457	60,606
1938	71,190	27,065	15,110	17,066	24,717	29,798	29,663	26,493	29,109	159,345
1939	81,290	27,688	17,032	17,747	16,872	24,219	23,370	14,430	40,365	228,550
1940	84,530	25,791	16,205	14,477	14,310	21,607	17,236	16,791	42,718	136,820
1941	41,106	18,817	14,970	15,748	14,730	14,787	14,415	13,916	29,543	97,660
1942	35,712	17,267	23,550	47,180	35,755	73,070	29,710	16,920	19,311	163,810
1943	109,530	31,436	20,534	16,211	32,505	34,050	23,270	20,680	28,900	294,160
1944	256,700	51,760	24,991	23,025	19,162	19,107	13,960	11,090	13,960	77,729
1945	51,696	23,376	20,247	19,524	17,933	18,292	25,190	20,200	23,105	55,068
1946	102,160	28,259	20,005	28,587	57,480	35,040	27,195	20,172	41,094	215,290
1947	108,640	35,024	21,464	47,715	51,750	60,040	45,700	49,000	58,060	195,480
1948	115,560	38,080	29,343	77,320	42,870	29,436	28,905	20,100	19,650	119,167
1949	93,560	38,707	19,126	14,948	14,023	13,602	11,040	9,990	17,936	168,595
1950	57,340	23,628	18,646	21,780	41,805	45,770	29,980	24,150	34,000	104,700
1951	301,240	70,730	28,122	60,302	70,991	82,790	50,672	61,916	34,316	161,600
Avg	101,692	31,476	19,959	29,641	35,680	34,722	26,131	23,734	32,783	156,600
Max	301,240	70,730	29,343	89,869	123,840	108,624	84,579	61,916	91,295	353,050
Min	35,712	17,267	14,790	13,402	10,844	9,716	8,244	8,444	12,457	55,068

TABLE 31.—*Accumulated monthly runoff through April, South Fork Flathead River near Columbia Falls*

Power year	Accumulated monthly runoff (cfs-days)									
	July–Apr	Aug–Apr	Sept–Apr	Oct–Apr	Nov–Apr	Dec–Apr	Jan–Apr	Feb–Apr	Mar–Apr	Apr
1929	415,569	242,609	196,519	175,058	146,693	124,493	108,125	94,082	82,042	63,256
1930	448,031	370,841	345,700	330,910	317,115	305,355	293,823	284,244	269,180	251,610
1931	356,874	299,214	277,824	261,034	232,502	202,502	179,004	157,490	136,350	99,150
1932	440,893	398,423	379,265	353,535	339,470	314,870	290,442	237,330	231,570	165,540
1933	526,685	418,305	383,465	361,895	336,103	267,403	208,193	171,923	146,443	119,225
1934	1,146,263	978,863	934,533	908,433	318,564	694,724	586,100	501,521	444,345	353,050
1935	408,250	349,133	325,103	308,933	281,680	219,760	183,858	160,225	131,421	91,726
1936	434,486	334,876	304,984	287,770	273,779	261,906	252,190	241,465	231,340	216,657
1937	210,967	162,603	141,651	126,717	113,315	102,471	89,751	81,507	73,063	60,606
1938	429,556	358,366	331,301	316,191	299,125	274,408	244,610	214,947	188,454	159,345
1939	491,563	410,273	382,585	365,553	347,806	330,934	306,715	283,345	268,915	228,550
1940	390,485	305,955	280,164	263,959	249,482	235,172	213,565	196,329	179,538	136,820
1941	275,692	234,586	215,769	200,799	185,051	170,321	155,534	141,119	127,203	97,660
1942	462,285	426,573	409,306	385,756	338,576	302,821	229,751	200,041	183,121	163,810
1943	611,276	501,746	470,310	449,776	433,565	401,060	367,010	343,740	323,060	294,160
1944	507,484	254,784	203,024	178,033	155,008	135,846	116,739	102,779	91,689	77,729
1945	274,631	222,935	199,559	179,312	159,788	141,855	123,563	98,373	78,173	55,068
1946	575,282	473,122	444,863	424,858	396,271	338,791	303,751	276,556	256,384	215,290
1947	672,873	564,233	529,209	507,745	460,030	408,280	348,240	302,540	253,540	195,480
1948	520,431	404,871	366,791	337,448	260,128	217,258	187,822	158,917	138,817	119,167
1949	401,527	307,967	269,260	250,134	235,186	221,163	207,561	196,521	186,531	168,595
1950	401,799	344,459	320,831	302,185	280,405	238,600	192,830	162,850	138,700	104,700
1951	922,679	621,439	550,709	522,587	462,285	391,294	308,504	257,832	195,916	161,600
Avg	492,417	391,160	359,249	339,290	309,649	273,969	239,247	211,551	189,382	156,600
Max	1,146,263	978,863	934,533	908,433	318,564	694,724	586,100	501,521	444,345	353,050
Min	210,967	162,603	141,651	126,717	113,315	102,471	89,751	81,507	73,063	55,068

REGULATED CONDITIONS

Subsequent to September 1951, the amount of water available for project use includes the net inflow to the reservoir plus or minus the change in storage. The net inflow includes runoff from the land area tributary to the reservoir plus precipitation falling on the reservoir area minus evaporation from the reservoir surface. The change in system storage includes the water stored within the limits of the topographic reservoir and the component stored in the aquifers adjacent to the reservoir. Each of these factors must be evaluated in order to arrive at the actual volume of water available for project use.

Initially the inflow to Hungry Horse Reservoir was estimated by adjusting the measured outflow for change in reservoir contents. The hydrographs of daily inflows computed in this manner are very irregular during months of low inflow and during periods of rapid drawdown. The potential reservoir inflows were evaluated by selecting a base-flow value for the beginning of each forecast period and using the recession curve previously developed for the outflow gaging station. The resulting flow projections were highly irregular primarily because of the difficulty in selecting the proper base-flow value. Theoretically, the recession curves developed for the downstream station should not be used with the reservoir inflow computed in this manner since they are not completely compatible. The characteristics of the natural hydrologic system were greatly modified because of the construction of Hungry Horse Reservoir. The index of inflow developed by the 1959 studies was not completely satisfactory, and daily reporting facilities were never installed.

INFLOW TO HUNGRY HORSE RESERVOIR

In the water-budget studies, the reservoir inflow from the land area was in effect a measured quantity. But for other periods of time, it can be computed by an index based on records from upstream gaging stations.

A step-regression analysis was made using the water-budget data to derive an index of reservoir inflow from the land area for use after April 1967. In this analysis the reservoir inflow, except for precipitation, was the dependent variable. The independent variables included the runoffs from following upstream stations:

South Fork Flathead River above Twin Creek near Hungry Horse
Sullivan Creek near Hungry Horse
Twin Creek near Hungry Horse
Soldier Creek near Hungry Horse
Graves Creek near Hungry Horse
Canyon Creek near Hungry Horse
Goldie Creek near Hungry Horse
Wounded Buck Creek near Hungry Horse
Emery Creek near Hungry Horse
Hungry Horse Creek near Hungry Horse

Reservoir-inflow volumes and runoff from the above gaging stations were expressed as total cfs-

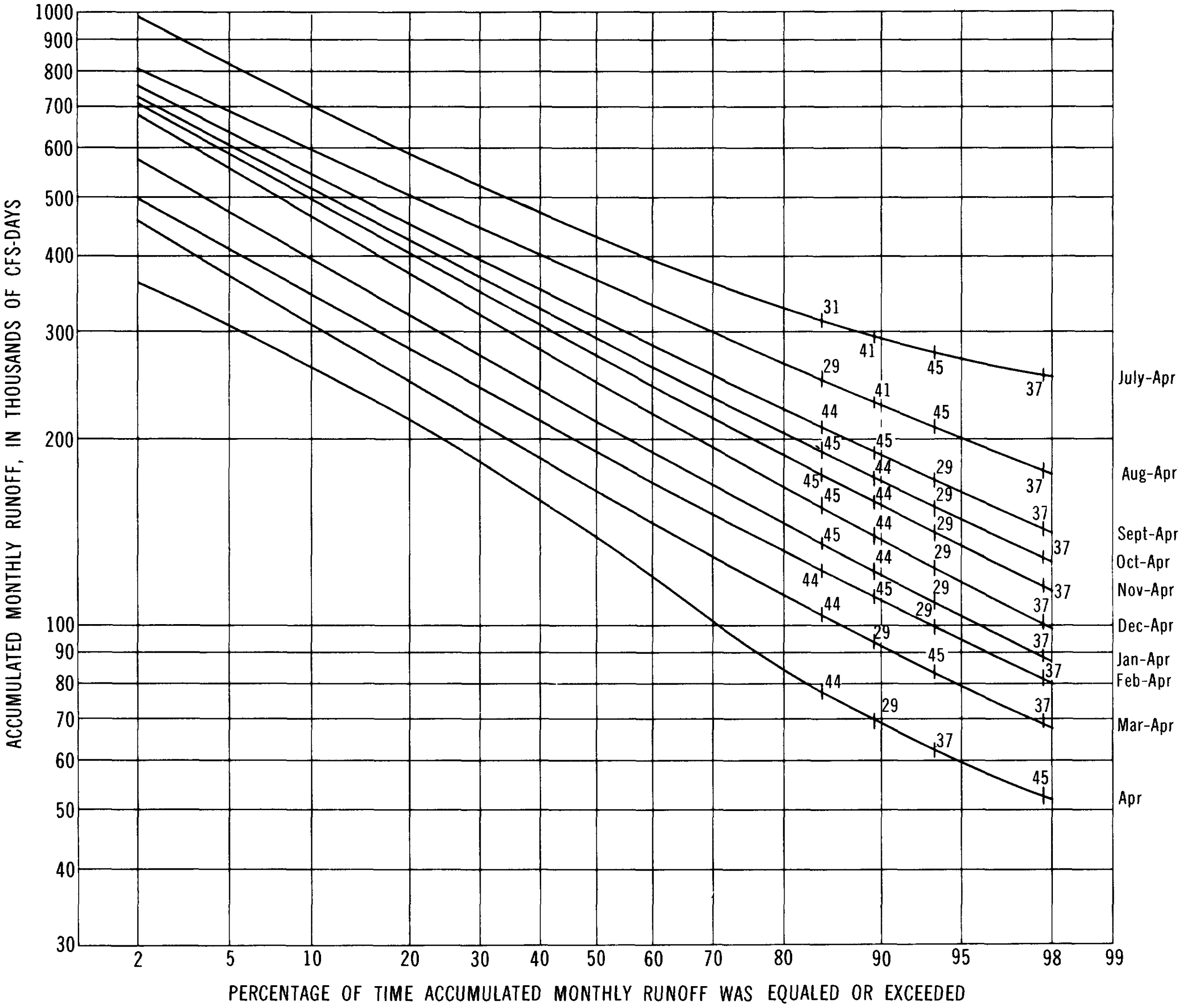

FIGURE 27.—Frequency diagrams of accumulated monthly runoff for various time periods, South Fork Flathead River near Columbia Falls, 1929–51. The plotting positions of the lowest 4 power years are indicated on the curve for each time period.

days for each of the 31 months used in this analysis. Both linear and logarithmic relationships were examined. The linear equations were slightly better than the logarithmic equations in their ability to reproduce the original data for the dependent variable.

The equation selected on the basis of the analysis is

$$X_1 = 1.18X_2 + 4.47X_3 + 1{,}246,$$

where X_1 = monthly reservoir inflow except for precipitation, in cfs-days,

X_2 = monthly runoff at South Fork Flathead River above Twin Creek near Hungry Horse, in cfs-days,

and X_3 = monthly runoff of Sullivan Creek near Hungry Horse, in cfs-days.

This equation has a correlation coefficient of 0.9999 and a standard error of estimate of 2,230 cfs-days. When the reservoir inflows computed by the above equation were compared with the water-budget data, the differences ranged from −6,740 to +5,310 cfs-days and had an average deviation of 1,470 cfs-days.

The addition of the other independent variables listed above did not increase the correlation coefficient but did tend to reduce slightly the standard error of estimate. This is to be expected because the dependent variable is composed primarily of the sum of the independent variables selected for this step-regression analysis. However, in view of the accuracy indicated by the two-station index, it is recommended that no more components be included in the index. The use of this index is judged to be a practical and economical method of evaluating the reservoir inflow from the tributary land area.

Another step-regression analysis was made for computation of reservoir inflow from the land area prior to October 1964. In this analysis the dependent variable was the same reservoir inflow used previously but the independent variables included runoffs from the following stations:

South Fork Flathead River at Spotted Bear Ranger Station near Hungry Horse
Sullivan Creek near Hungry Horse
Twin Creek near Hungry Horse
Graves Creek near Hungry Horse

These gaging stations were in operation for part of the period between 1951 and 1964 and during the period of the present study.

The equation selected from this analysis was

$$X_1 = 1.20X_2 + 6.94X_3 - 777,$$

where X_1 = monthly reservoir inflow except for precipitation, in cfs-days,

X_2 = monthly runoff, South Fork Flathead River at Spotted Bear Ranger Station near Hungry Horse, in cfs-days,

and X_3 = monthly runoff, Sullivan Creek near Hungry Horse, in cfs-days.

The correlation coefficient of this equation is 0.9994, and the standard error of estimate is 4,747 cfs-days. This equation has almost the same correlation coefficient as the index based on South Fork Flathead River above Twin Creek near Hungry Horse, but it has about double the standard error of estimate. The average deviation is 2,830 cfs-days, and deviations range from +13,730 to −11,590 cfs-days.

Both of these index procedures were able to duplicate the water-budget data very well. For the 31 months the accumulated differences were +1,380 and +1,840 cfs-days, respectively, for the above Twin Creek and Spotted Bear indexes.

An estimate of the monthly inflow to Hungry Horse Reservoir was developed by use of these two index procedures for the period 1949–68 when data for the indexes were available. In the period prior to the start of intensive data collection, October 1964, the reservoir inflow was based on the index equation for South Fork Flathead River at Spotted Bear Ranger Station near Hungry Horse and Sullivan Creek near Hungry Horse. For the period after April 1967, the index developed on the combination of the values for South Fork Flathead River above Twin Creek near Hungry Horse and Sullivan Creek near Hungry Horse was used. During the period of the study, October 1964–April 1967, the water-budget data were used. These inflows are shown in tables 32 and 33.

RECESSION CHARACTERISTICS

The recession characteristics of the inflow to Hungry Horse Reservoir from the land area were determined, using the recession characteristics previously developed for the stations South Fork Flathead River at Spotted Bear Ranger Station near Hungry Horse and South Fork Flathead River above Twin Creek near Hungry Horse as guides. These characteristics indicate that one curve could be used throughout the year. The inflow follows

TABLE 32.—*Estimated monthly inflow to Hungry Horse Reservoir*

[Excluding precipitation on reservoir surface]

Water year	Estiimated monthly inflow (1,000 cfs-days)											
	October	November	December	January	February	March	April	May	June	July	August	September
1949	15.1	15.1	13.3	10.8	10.5	18.0	149.8	512.6	248.5	54.7	21.6	16.8
1950	19.9	44.7	34.4	20.1	20.2	34.4	95.6	383.2	612.2	309.4	75.8	27.3
1951	66.2	76.9	87.6	46.1	57.9	30.0	154.4	475.5	332.6	183.0	46.9	35.0
1952	70.8	43.7	32.7	21.5	18.3	18.8	215.2	462.0	267.8	80.8	29.8	17.9
1953	12.5	10.0	10.5	25.7	24.9	22.5	102.0	341.1	513.1	166.1	37.8	19.0
1954	13.6	15.5	16.6	13.7	16.8	27.2	85.5	545.7	462.0	267.0	51.6	33.4
1955	46.9	43.7	29.5	18.0	13.1	14.6	44.2	294.7	489.5	166.8	40.0	19.9
1956	52.5	51.5	47.5	30.1	17.7	26.6	160.8	540.9	460.0	103.8	34.8	21.1
1959												58.7
1960	159.4	95.0	57.7	31.6	21.9	57.3	172.6	300.1	468.4	124.9	38.8	21.6
1961	21.8	26.9	20.6	18.6	44.3	45.2	112.1	484.1	478.3	72.8	25.7	21.6
1962	48.3	29.4	20.0	18.2	20.6	26.0	227.8	453.8	426.2	111.9	36.0	21.7
1963	43.0	47.0	44.4	25.4	57.8	38.9	96.2	333.7	281.7	95.7	28.8	19.0
1964	15.2	14.5	11.7	13.7	11.3	11.0	54.0	377.7	643.3	150.9	39.8	55.6
1965	46.5	37.6	56.4	34.4	27.4	30.6	163.1	441.1	541.1	168.6	55.1	74.6
1966	47.2	34.9	29.8	21.9	16.0	29.7	136.2	404.6	329.3	105.0	32.1	20.0
1967	18.6	21.3	28.3	24.8	24.0	22.1	56.2	437.2	655.1	180.6	37.6	20.1
1968	26.5	52.7	27.9	29.0	37.1	62.0	60.3	334.7	425.6	122.7	43.2	77.3
Avg	42.6	38.8	33.5	23.7	25.9	30.3	122.7	419.0	450.1	145.0	39.7	32.4
Max	159.4	95.0	87.6	46.1	57.9	62.0	227.8	545.7	655.0	309.4	75.8	58.7
Min	12.5	10.0	10.5	10.8	10.5	11.0	44.2	294.7	284.5	54.7	21.6	16.8

TABLE 33.—*Accumulated monthly inflow through April to Hungry Horse Reservoir*

Power year	Accumulated monthly inflow (1,000 cfs-days)									
	July–April	August–April	September–April	October–April	November–April	December–April	January–April	February–April	March–	April
1949				232.6	217.5	202.4	189.1	178.3	167.8	149.8
1950	362.4	307.7	286.1	269.3	249.4	204.6	170.2	150.1	130.0	95.6
1951	931.5	622.1	546.3	519.0	452.9	375.9	288.4	242.3	184.4	154.4
1952	686.0	502.9	456.0	421.0	350.2	306.5	273.8	252.3	234.0	215.2
1953	336.4	255.7	225.9	208.0	195.6	185.6	175.1	149.5	124.5	102.0
1954	411.7	245.7	207.9	188.9	175.3	159.8	143.2	129.5	112.7	85.5
1955	562.0	295.0	243.5	210.0	163.1	119.5	90.0	72.0	58.8	44.2
1956	613.4	446.6	406.6	386.7	334.2	282.7	235.2	205.0	187.3	160.8
1960			654.2	595.5	436.1	341.1	283.4	251.8	229.9	172.6
1961	474.9	350.0	311.1	289.6	267.7	240.8	220.2	201.6	157.4	112.1
1962	512.1	439.3	413.6	390.3	342.0	312.6	292.6	274.4	253.8	227.8
1963	530.2	410.3	374.3	352.6	309.6	262.6	218.3	192.9	135.1	96.2
1964	274.8	179.1	150.2	131.3	116.1	101.6	89.9	76.2	65.0	53.9
1965	642.4	491.5	451.6	396.1	349.6	312.0	255.5	221.2	193.8	163.1
1966	614.0	445.4	390.3	315.7	268.3	233.6	203.8	181.9	165.9	136.2
1967	352.4	247.4	215.3	195.3	176.6	155.4	127.1	102.3	78.3	56.2
1968	533.8	353.2	315.7	295.5	269.0	216.3	188.5	159.5	122.3	60.3
Avg	522.5	372.8	353.0	317.5	274.9	236.1	202.6	178.9	153.0	122.7
Max	931.5	622.1	654.2	595.5	452.9	375.9	292.6	274.4	253.8	227.8
Min	274.8	245.7	150.2	131.3	116.1	101.6	89.9	72.0	58.8	44.2

this curve for periods of a few days to several weeks at a time.

This curve is steeper than the recession curves developed for the station South Fork Flathead River near Columbia Falls and is not defined over as large a range in discharge. This is as would be expected because the reservoir flooded much of the land area that previously had contributed much of the base flow at the downstream station. The period of record prior to the construction of the reservoir covered a wider range in discharge conditions. The recession characteristics of the reservoir inflow were considered satisfactory for a preliminary evaluation of its utility as a forecasting parameter for the low-water season.

During the period of study, October 1964–April 1967, a recession index was determined for the first day of each month from the water-budget data. For other months during power years 1949–68, a recession index was developed from data for South Fork Flathead River at Spotted Bear Ranger Station near Hungry Horse and (or) above Twin Creek near Hungry Horse and for Sullivan Creek near Hungry Horse. These values are shown in table 34.

INFLOW FORECASTS

The July–April flows for power year 1937 were assumed to be indicative of the minimum flows for natural (unregulated) conditions. As a means of comparing "assured" flows for the period of regulated flows with flows for power year 1937, an equivalent recession index for the critical year was determined for the beginning of each month. It was assumed that the flows for each month resulted entirely from the recession index for that month.

TABLE 34.—*Recession index for the inflow to Hungry Horse Reservoir*

Power year	Recession index (cfs)										
	July	August	September	October	November	December	January	February	March	April
1949				560	500	500	450	370	590	610
1950	2,720	1,040	680	550	1,030	1,500	830	550	790	830
1951	16,900	3,610	1,330	780	2,870	1,980	2,500	880	1,180	1,020
1952	7,800	2,500	1,350	1,510	1,900	1,050	750	720	630	690
1953	4,400	1,370	730	490	450	360	380	720	540	1,120
1954	8,830	2,020	840	600	470	580	530	530	610	740
1955	12,700	2,440	1,330	1,070	1,440	1,200	690	530	440	560
1956	8,970	2,150	800	690	1,420	790	1,200	610	630	1,220
1957	6,030	1,620	930							
1960			1,260	2,360	3,730	2,740	1,030	950	590	3,530
1961	8,700	1,580	980	610	830	740	600	600	1,120	1,790
1962	4,450	1,180	740	890	1,140	850	680	590	670	880
1963	8,440	1,780	900	720	1,240	1,340	1,220	630	1,200	2,020
1964	5,890	1,350	710	580	490	490	490	480	380	620
1965	10,100	1,880	1,250	1,340	1,370	1,080	1,680	970	1,070	770
1966	7,370	2,170	1,920	2,390	1,040	1,000	730	660	560	3,740
1967	6,310	1,380	870	560	650	680	720	900	580	710
1968	12,900	1,910	740	570	1,450	1,090	690	1,140	1,520	2,080
1969	6,100	1,500	1,040							
Avg	8,160	1,860	1,020	960	1,300	1,060	890	700	770	1,350
Max	16,900	3,610	1,920	2,390	3,730	2,740	2,500	1,140	1,520	3,740
Min	2,720	1,040	680	490	450	360	380	370	380	560

Thus, if the recession index for the flow during a regulated period was lower than the equivalent 1937 index, then its assured flows would be less than flows for power year 1937. This equivalent index and the number of times that the recession indexes during the period of regulated flows were less than indexes for power year 1937 are shown in the following tabulation:

	Equivalent 1937 index (cfs)	Number of times less than 1937		Equivalent 1937 index (cfs)	Number of times less than 1937
July	3,800	1	Dec	610	3
Aug	1,200	2	Jan	355	0
Sept	800	5	Feb	400	1
Oct	680	9	March	700	7
Nov	505	4	April	5,400	17

This is an extreme test because concurrent weather conditions during each month had some modifying effect, particularly the fall rainstorms. Even with these severe restrictions, the recession index by itself indicates the probability that the flows for about two-thirds of the fall and winter months would equal or be greater than those for power year 1937.

In order to evaluate the relative significance of the various factors that affect the reservoir inflow during the fall and winter periods, a linear step-regression analysis was made of the following basic relationship:

TABLE 35.—*Monthly precipitation, Hungry Horse Dam*

Power year	Monthly precipitation (inches)									
	July	August	September	October	November	December	January	February	March	April
1948	0.49	3.78	1.94	4.04	3.00	1.49	2.03	2.86	1.98	3.92
1949	3.90	1.24	.55	1.15	2.79	1.79	1.30	3.49	2.16	1.50
1950	1.53	.79	1.95	2.96	2.71	2.53	7.02	2.07	2.82	1.72
1951	2.26	1.43	1.19	6.80	1.53	3.41	2.80	2.49	1.60	.81
1952	1.68	2.97	3.79	6.56	1.41	4.67	2.06	.91	1.12	.57
1953	1.84	.94	.49	.29	.72	1.45	5.27	2.07	2.23	2.17
1954	.10	1.52	.97	.56	2.46	4.50	6.94	2.48	2.33	2.12
1955	2.81	5.21	1.19	1.98	2.43	1.81	1.65	3.50	1.69	2.02
1956	3.49	0	3.67	6.30	6.42	5.94	3.71	3.02	2.03	2.22
1957	1.90	3.31	2.69	2.85	1.17	3.44	2.01	3.64	1.75	1.79
1958	.77	.98	.28	3.74	1.57	3.13	3.08	4.48	1.20	3.50
1959	1.05	.73	4.47	1.73	6.56	4.89	6.85	2.60	1.61	2.38
1960	.20	2.11	5.48	4.54	7.37	1.03	2.88	1.70	2.58	1.59
1961	.14	3.74	1.10	3.15	5.94	2.22	1.94	5.11	2.80	5.16
1962	1.47	1.53	4.02	3.17	3.16	4.94	1.53	1.75	2.98	3.06
1963	.29	2.04	2.15	5.00	4.74	2.40	2.41	3.22	2.94	2.38
1964	1.02	.87	2.42	1.98	2.64	2.31	3.19	.97	2.74	1.82
1965	3.29	2.31	3.48	2.92	4.92	8.21	3.83	3.23	.36	3.76
1966	1.24	4.31	3.52	.90	3.26	1.72	3.44	1.69	3.17	2.01
1967	1.57	2.13	.65	3.35	5.46	4.30	6.22	1.33	2.12	1.18
1968	.22	.11	.97	5.78	2.88	3.37	3.13	3.21	2.85	1.37
Avg	1.49	2.15	2.24	3.32	3.48	3.31	3.44	2.66	2.00	2.24
Max	3.90	5.21	5.48	6.80	7.37	8.21	6.94	5.11	3.17	5.16
Min	.10	0	.28	.29	.72	1.03	.13	.91	.36	.57

TABLE 36.—*Accumulated monthly precipitation through April, Hungry Horse Dam*

Power year	Accumulated monthly precipitation (inches)									
	July–April	August–April	September–April	October–April	November–April	December–April	January–April	February–April	March–April	April
1948	25.53	25.04	21.26	19.32	15.28	12.28	10.79	8.76	5.90	3.92
1949	19.87	15.97	14.73	14.18	13.03	10.24	8.45	7.15	3.66	1.50
1950	26.10	24.57	23.78	21.83	18.87	16.16	13.63	6.61	4.54	1.72
1951	18.32	16.06	14.63	13.44	12.64	11.11	7.70	4.90	2.41	.81
1952	25.74	24.06	21.09	17.30	10.74	9.33	4.66	2.60	1.12	.57
1953	17.47	15.63	14.69	14.20	13.91	13.19	11.74	6.47	4.40	2.17
1954	23.98	23.88	22.36	21.39	20.83	18.37	13.87	6.93	4.45	2.12
1955	24.29	21.48	16.27	15.08	13.10	10.67	8.86	7.21	3.71	2.02
1956	36.80	33.31	33.31	29.64	23.34	16.92	10.98	7.27	4.25	2.22
1957	24.55	22.65	19.34	16.65	13.80	12.63	9.19	7.18	3.54	1.79
1958	22.73	21.96	20.98	20.70	16.96	15.39	12.26	9.18	4.70	3.50
1959	32.87	31.82	31.09	26.62	24.89	18.33	13.44	6.59	3.99	2.38
1960	29.48	29.28	27.17	21.69	17.15	9.78	8.75	5.87	4.17	1.59
1961	31.30	31.16	27.42	26.32	23.17	17.23	15.01	13.07	7.96	5.16
1962	27.61	26.14	24.61	20.59	17.42	14.26	9.32	7.79	6.04	3.06
1963	27.57	27.28	25.24	23.09	18.09	13.35	10.95	8.54	5.32	2.38
1964	19.96	18.94	18.07	15.65	13.67	11.03	8.72	5.53	4.56	1.82
1965	36.31	33.02	30.71	27.23	24.31	19.29	11.18	7.35	4.12	3.76
1966	25.26	24.02	19.71	16.19	15.29	12.03	10.31	6.87	5.18	2.01
1967	28.31	26.74	24.61	23.96	20.61	15.15	10.85	4.63	3.30	1.18
1968	23.89	23.67	23.56	22.59	16.81	13.93	10.56	7.43	4.22	1.37
Avg	26.09	24.60	22.60	20.36	17.33	13.85	10.53	7.04	4.36	2.24
Max	36.80	33.31	33.31	29.64	24.31	19.39	15.01	13.07	7.96	5.16
Min	17.47	15.63	14.63	13.44	10.74	9.33	4.66	2.60	1.12	.57

$$X_1 = aX_2 + bX_3 + cX_4 + d,$$

where X_1 = reservoir inflow, in 1,000 cfs-days,
X_2 = recession index for the first of each month, in cubic feet per second,
X_3 = precipitation at Hungry Horse Dam, in inches,
and X_4 = degree days (65°F.) at Hungry Horse Dam.

The data for X_1 and X_2 are shown in tables 32–34. The data for X_3 and X_4 are shown in tables 35–38.

The analysis was made for each month July–April and for each group of months ending in April (July–Apr. and Aug.–Apr. for example). The results of this analysis are shown in table 39. The best equation was selected on the basis of the lowest standard error of estimate. The significance level of each component was based on the *t* test.

The recession index appears to be the most useful variable of those tested. However, under some circumstances the addition of precipitation and (or)

TABLE 37.—*Monthly degree days (65° F), Hungry Horse Dam, Montana*

[Values through November of 1954 are estimated]

Power year	Monthly degree days												
	July	August	September	October	November	December	January	February	March	April	May	June	Total
1949	160	135	320	710	980	1,480	1,930	1,350	1,150	600	350	230	9,395
1950	125	100	360	790	830	1,320	1,895	1,130	1,095	775	515	280	9,215
1951	75	90	335	640	1,040	1,100	1,430	1,160	1,290	720	460	330	8,670
1952	95	150	470	765	1,050	1,530	1,500	1,090	1,100	625	400	250	9,025
1953	135	100	280	570	1,030	1,200	900	920	840	770	520	280	7,545
1954	70	90	250	560	845	1,036	1,347	913	1,179	818	434	339	7,881
1955	78	132	346	736	805	1,111	1,197	1,202	1,247	815	558	184	8,411
1956	142	37	362	622	1,259	1,295	1,298	1,265	996	711	389	188	8,564
1957	65	82	267	667	1,023	1,149	1,686	1,127	1,007	705	293	159	8,230
1958	33	85	241	782	999	989	1,117	978	995	675	165	132	7,191
1959	62	21	317	650	984	1,127	1,260	1,204	916	684	546	221	7,992
1960	79	130	337	691	1,209	1,196	1,404	1,171	1,017	703	480	184	8,651
1961	11	144	272	615	963	1,238	1,120	819	876	657	390	79	7,184
1962	8	9	471	718	1,113	1,285	1,438	1,139	1,054	608	485	202	8,530
1963	88	98	312	642	828	1,015	1,618	901	895	678	423	200	7,698
1964	67	64	186	557	885	1,257	1,106	1,033	1,071	733	452	251	7,662
1965	58	180	407	662	961	1,321	1,076	1,014	1,213	659	468	202	8,221
1966	37	102	573	525	908	1,089	1,230	1,025	972	713	321	264	7,759
1967	51	96	158	660	974	1,070	1,083	902	1,057	763	429	180	7,423
1968	9	4	123	626	952	1,260	1,276	1,001	786	741	477	252	7,507
1969	112	159	364	729	965	1,416	1,625	----	----	----	----	----	----
Avg	74	96	324	663	981	1,214	1,359	1,067	1,038	708	428	220	----
Max	160	180	573	790	1,209	1,530	1,930	1,350	1,290	818	558	339	----
Min	8	4	123	525	805	989	900	819	786	600	165	79	----

TABLE 38.—*Accumulated monthly degree days (65°F) through April, Hungry Horse Dam, Montana*

Power year	Accumulated monthly degree days									
	July–April	August–April	September–April	October–April	November–April	December–April	January–April	February–April	March–April	April
1949	3,815	8,655	8,520	8,200	7,490	6,510	5,030	3,100	1,750	600
1950	8,420	8,295	8,195	7,835	7,045	6,215	4,895	3,000	1,870	775
1951	7,880	7,805	7,715	7,380	6,740	5,700	4,600	3,170	2,010	720
1952	8,375	8,280	8,130	7,660	6,895	5,845	4,315	2,815	1,725	625
1953	6,745	6,610	6,510	6,230	5,660	4,630	3,430	2,530	1,610	770
1954	7,108	7,038	6,948	6,698	6,138	5,293	4,257	2,910	1,997	818
1955	7,669	7,591	7,459	7,113	6,377	5,572	4,461	3,264	2,062	815
1956	8,946	8,804	8,442	7,820	6,561	5,266	3,968	2,703	1,707	711
1957	7,778	7,713	7,631	7,364	6,697	5,674	4,525	2,839	1,712	705
1958	6,894	6,861	6,776	6,535	5,753	4,754	3,765	2,648	1,670	675
1959	7,225	7,163	7,142	6,825	6,175	5,191	4,064	2,804	1,600	684
1960	7,987	7,908	7,778	7,391	6,700	5,491	4,295	2,891	1,720	703
1961	6,715	6,704	6,560	6,288	5,673	4,710	3,472	2,352	1,533	657
1962	7,843	7,835	7,826	7,355	6,637	5,524	4,239	2,801	1,662	608
1963	7,075	6,987	6,889	6,577	5,935	5,107	4,092	2,474	1,573	678
1964	6,959	6,892	6,828	6,642	6,085	5,200	3,943	2,837	1,804	733
1965	7,551	7,493	7,313	6,906	6,244	5,283	3,962	2,886	1,872	659
1966	7,174	7,137	7,035	6,462	5,937	5,029	3,940	2,710	1,685	713
1967	6,764	6,713	6,617	6,459	5,799	4,825	3,755	2,672	1,770	763
1968	6,777	6,769	6,765	6,642	6,016	5,064	3,804	2,528	1,527	741
Avg	7,535	7,463	7,354	7,019	6,328	5,344	4,141	2,797	1,743	708
Max	8,946	8,804	8,520	8,200	7,490	6,510	5,030	3,264	2,062	818
Min	6,715	6,610	6,510	6,230	5,660	4,630	3,430	2,352	1,527	600

TABLE 39.—*Summary of step-regression analysis, reservoir inflow versus recession index, precipitation, and degree days (65°F)*

Period	Best expression for X_1	Correlation coefficient	Standard error of estimate	Significance level (percent)			Reservoir inflow	
				X_2	X_3	X_4	Mean	Standard deviation
July	$0.017X_2+9.76X_3 \quad -2.7$	0.92	26.9	<1	$\sim$15	>50	148.1	65.7
Aug	$0.019X_2+1.80X_3 \quad +1.1$	.96	3.6	<1	$\sim$1	>50	39.7	12.7
Sept	$0.043X_2+7.77X_3-0.046X_4 \quad +16.9$	.91	8.9	<1	<1	$\sim$20	32.4	20.0
Oct	$0.043X_2+7.19X_3 \quad -22.6$	.87	19.1	<1	<1	>50	42.6	35.6
Nov	$0.025X_2+1.47X_3-0.023X_4 \quad +23.0$	.97	6.6	<1	$\sim$30	$\sim$20	38.8	22.6
Dec	$0.028X_2+4.77X_3-0.020X_4 \quad +13.2$	.88	10.7	<1	<1	$\sim$30	33.5	20.1
Jan	$0.015X_2 \quad -0.008X_4 \quad +21.7$	.90	4.1	<1	>50	$\sim$5	23.7	8.8
Feb	$0.027X_2+5.50X_3-0.029X_4 \quad +24.0$	.66	12.4	$\sim$10	<10	$\sim$20	25.9	14.8
Mar	$0.025X_2 \quad -0.034X_4 \quad +46.8$	.76	9.6	<1	>50	<10	30.3	14.0
Apr	$-0.700X_4+616.0$	.77	42.0	>50	>50	<1	117.3	61.9
July–Apr	$0.033X_2 \quad +0.103X_4-530.6$	.86	93.3	<1	>50	<1	522.5	167.3
Aug–Apr	$0.120X_2+6.16X_3+0.047X_4-353.0$	.79	84.2	<1	10	$\sim$10	372.8	120.7
Sept–Apr	$0.189X_2+6.78X_3+0.089X_4-645.2$	.73	102.5	$\sim$5	$\sim$20	$\sim$3	353.0	135.0
Oct–Apr	$0.116X_2+6.20X_3+0.070X_4-436.2$	.71	97.5	1	<20	$\sim$10	317.5	124.2
Nov–Apr	$0.088X_2+5.66X_3+0.029X_4-120.4$	.86	54.7	<1	$\sim$20	<30	274.9	95.5
Dec–Apr	$0.078X_2 \quad +153.0$	.59	65.3	$\sim$1	>50	>50	236.0	78.7
Jan–Apr	$0.067X_2 \quad +142.9$	.54	56.7	$\sim$2	>50	>50	202.6	65.3
Feb–Apr	$0.082X_2 \quad +121.7$	.28	60.5	$\sim$30	>50	>50	178.9	60.9
Mar–Apr	$-0.090X_4+310.4$	.25	57.7	$\sim$50	>50	$\sim$30	153.0	57.7

temperature variables can make significant improvement in the reliability of the regression equations. This analysis indicates that if the actual values of the variables—recession index, precipitation, and temperature—are known for each time period, then the reservoir inflows could be computed with a smaller standard error of estimate than the standard deviation of the original reservoir inflows.

It is assumed that sufficient current hydrologic data would be available so that the recession index could be determined at the beginning of each time period. Future values of precipitation and temperatures cannot, with our present knowledge, be reliably forecast for a month or more in advance. Thus the basic use of equations such as those shown previously is to evaluate the probable range of reservoir inflows that can occur with different levels of precipitation and temperature. If average values of precipitation and (or) temperature are inserted into one of the equations above, then the resulting inflows should have an average chance of occurring. On the other hand, if the minimum values of precipitation and (or) temperature were used, then the resulting inflows would have a minimum chance of occurring. These two values could provide a measure of the potential range in reservoir inflows that could be used as a guide in reservoir operations.

There are indications based on the above summary that useful forecasting of reservoir inflow during the low-flow period may be developed. The examination of the low-flow forecasting technique outlined above is by no means complete. There are other combinations of time-period variables and internal relations that should be examined and evaluated. The prospects are encouraging for the development of a level of inflow forecasting during the drawdown period that would greatly enhance the operation of Hungry Horse Reservoir.

PRECIPITATION

Precipitation on the surface of Hungry Horse Reservoir is another item of inflow. The amount of inflow from assumed precipitation during the forecast period would be added to the reservoir inflow from the land area. In these studies the precipitation at Hungry Horse Dam was assumed to be representative of the precipitation over the entire surface of the reservoir. Some inherent variation is known to exist, but there are not enough data to justify any refinements. For forecasting the reservoir inflow, the use of average or minimum amounts selected from tables 35 and 36 probably will supply the range in values needed as guides in reservoir operation.

One inch of precipitation represents about 1,000 cfs-days when the reservoir is at full-pool elevation. For amounts other than 1 inch or reservoir areas other than those at a stage of 3,560 feet, inflow values can be obtained by simple ratios. Monthly precipitation values have ranged from 0 to 8.21 inches; thus the range of inflow would be from 0 to 8,210 cfs-days at full-pool level. If the 8.21 inches of precipitation had occurred when the area of the reservoir was 21,000 acres, then it would have resulted in (21,000/24,000) × 8,210, or 7,184 cfs-days. Likewise seasonal values for the period July–April could have ranged from 17,470 to 36,800 cfs-days.

EVAPORATION

Evaporation from the surface of Hungry Horse Reservoir is a loss as far as usable water for the project is concerned. Like precipitation, this is an unknown for each forecast period and its potential magnitude would have to be evaluated from past records.

Records for a class A evaporation pan have been collected since 1948. The normal evaporation period is considered to extend from May through October, with perhaps minor amounts occurring at other times. The data for periods not covered by observations were estimated and are included along with the observed readings in table 40. The energy-budget study of evaporation made in connection with this study provided a measure of the actual evaporation from the surface of the reservoir. The energy-budget values are shown in table 16.

TABLE 40.—*Monthly and seasonal evaporation, class A pan, Hungry Horse Dam*

	Evaporation (inches)						
Year	May	June	July	August	September	October	Season total
1948	3.72	5.55	6.76	5.21	4.51	[1]1.1	26.85
1949	5.03	6.73	7.27	7.54	3.72	[1]1.0	31.29
1950	4.86	4.95	7.28	5.41	3.94	[1]1.4	27.84
1951	5.07	4.88	7.36	5.89	[1]2.5	[1]4.0	29.70
1952	4.59	5.00	7.10	7.29	4.02	2.27	30.27
1953	4.32	4.68	8.99	6.71	4.49	[1]1.7	30.89
1954	[1]5.00	4.78	8.10	5.93	2.33	[1]1.0	27.14
1955	5.03	7.38	[1]7.3	10.35	4.03	1.06	35.15
1956	5.41	6.64	7.63	6.17	3.70	[1]1.3	30.85
1957	5.51	5.65	9.61	6.74	4.17	[1].7	31.75
1958	8.10	6.47	8.00	9.14	4.32	[1]1.4	37.43
1959	4.21	5.96	8.90	7.17	2.86	[1]1.2	30.30
1960	4.74	6.70	11.28	5.53	3.72	[1]1.6	33.57
1961	4.98	7.62	8.60	7.74	2.90	[1]1.8	33.64
1962	3.68	6.26	8.06	6.03	3.34	[1]1.8	29.17
1963	5.37	4.99	7.62	7.06	3.40	1.35	29.79
1964	4.54	5.20	7.37	5.00	2.66	1.26	26.03
1965	4.62	6.24	7.75	5.24	1.97	1.68	27.50
1966	6.35	5.06	8.10	6.82	3.73	1.39	31.45
1967	4.78	6.13	9.90	9.39	5.29	2.06	37.55
1968	4.68	5.29	7.75	4.96	2.65	.98	26.31
Avg	4.98	5.82	8.13	6.73	3.54	1.53	30.69
Max	8.10	7.62	11.28	10.35	5.29	[1]4.00	37.55
Min	3.68	4.68	6.76	4.96	1.97	[1].7	26.03

[1] Estimated or partially estimated.

A comparison was made of the energy-budget evaporation data and the class-A-pan data. Ratios of the energy-budget amounts to the class-A-pan amounts were calculated for the periods used in the energy-budget study and are shown graphically in figure 28.

Monthly coefficients were selected to be used to convert the class-A-pan data to equivalent energy-budget data. These are shown in the following tabulation:

May	0.4	Aug.	0.9
June	.5	Sept.	1.3
July	.6	Oct.	1.6

If the average amounts of evaporation from the class A pans were modified by these coefficients, the equivalent energy-budget evaporation amounts, in inches, would be the following:

May	1.99	Aug.	6.06
June	2.91	Sept.	4.60
July	4.88	Oct.	2.45

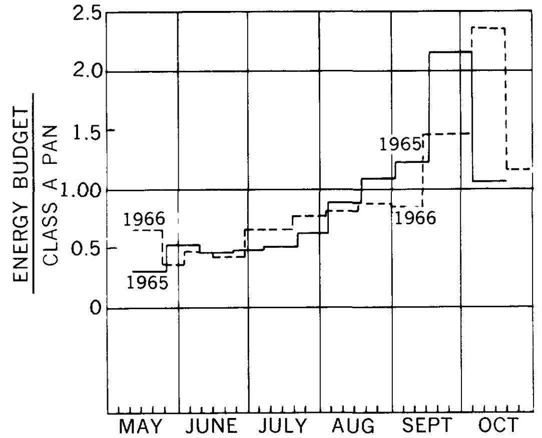

FIGURE 28.—Ratio of evaporation amounts calculated by energy budget and by class A pan, Hungry Horse Reservoir, 1965 and 1966.

The loss for these amounts would be 1,000 cfs-days per inch at full reservoir pool.

The evaporation during July–October is of prime concern in this study. The amounts of evaporation and precipitation are in opposite directions, and the average values of each are compared below:

	Evaporation (inches)	Precipitation (inches)	Net precipitation (inches)
July	4.88	1.49	−3.4
August	6.06	2.15	−3.9
September	4.60	2.24	−2.4
October	2.45	3.32	+.9

Thus evaporation losses are, on the average, greater than gains from precipitation during July, August, and September.

STORAGE CHANGES

The total storage change is composed of that within the topographic limits of the reservoir and that within aquifers adjacent to the reservoir. Each of these must be evaluated in order to compute the amount of water available for project use. The stage record at Hungry Horse Dam and the capacity table can be used to evaluate the changes in reservoir storage. The model solution 0.8 ($M_2+0.4M_4$) can be used to evaluate ground-water storage changes occurring in response to changes in stage of the reservoir.

WATER AVAILABLE

The water available at Hungry Horse Reservoir can be evaluated by considering each of the following components: Inflow from the land area (+), precipitation on reservoir area (+), evaporation from reservoir surface (−), changes in reservoir storage (±), and changes in ground-water storage (±).

Of these, the inflow from the land area and changes in reservoir storage are the largest. But each of the other three components is large enough to be considered in project operations.

SUMMARY AND CONCLUSIONS

The Hungry Horse Project is a major element in the Federal Columbia River Power System. It furnishes important at-site and downstream power benefits and local and downstream flood control. Certain operating problems have been intensified because of an apparent imbalance between inflows and outflows. The multipurpose operation of Hungry Horse Reservoir can be enhanced by resolving this difference. The basic objective of this study was to determine more accurately the water available for project use, including bank storage, and to improve the methods of forecasting the inflows to the reservoir during the low-flow period. In its simplest form, the water available for project use can be expressed as follows:

$$\text{Outflow} = \text{inflow} \pm \text{changes in storage.}$$

Each of these items is composed of many factors, often interrelated. The accurate measurement or evaluation of each of the various components of outflow, inflow, and changes in storage is essential to the solution of this problem.

The least known or understood factor in this study is the ground-water storage in the aquifers adjacent to the reservoir. This bank-storage effect has received emphasis in the first phase of this study. The alluvium adjacent to Hungry Horse Reservoir has been evaluated as a ground-water reservoir, its hydraulic characteristics have been inferred, and a mathematical model has been developed for computing gains to and losses from the reservoir in response to changes of stage of Hungry Horse Reservoir.

Two approaches were used: (1) a comprehensive water budget based on field data collected over a 31-month period and (2) a theoretical model of the response of the aquifer to changes in stage of Hungry Horse Reservoir. Residuals in the water budget represent ground-water storage changes which are masked by the accumulation of all the errors in field measurements. The mathematical model is poorly defined because rigid assumptions may not truly represent the field prototype and because the hydrologic properties of the aquifer material lack definition. However, by using the two methods jointly, improved water-budget balances were obtained and a "best fit" set of hydrologic constants was derived for the model. The model was studied relative to possible errors and a final set of constants selected. This solution is probably within ±25 percent of the true solution of the gains to and losses from ground-water storage in response to changes in the stage of Hungry Horse Reservoir.

The recommended solution is a combination of two applications of the mathematical model. Each part is computed by equations 5 and 6, or by use of the simplified equations 5a, 5b, 6a, 6b, and 6c. In the model where hydrologic constants are designated by 0.8 $(M_2+0.4M_4)$, segment M_2 is calculated using $a=851$ feet, $S=0.15$, and $T/a^2S=0.003$ per day. The second segment, M_4, is 0.4 times the calculation using $a=851$ feet, $S=0.20$, and $T/a^2S=0.0256$ per day. The sum of the two segments is then multiplied by 0.8.

From the model, the inactive and dead ground-water storage below an elevation of 3,336 feet is calculated as 48,100 cfs-days and probably lies between the limiting curve values of 36,000 and 60,000 cfs-days.

Ground-water storage capacity between elevations of 3,336 and 3,560 feet is computed as 108,300 cfs-days, with probable limits of 81,200 and 135,400 cfs-days. All this storage would be available for use only if the stage of Hungry Horse Reservoir were lowered to an elevation of 3,336 feet and held at that level for approximately 1 year.

The release of water from the aquifer in response to stage changes of Hungry Horse Reservoir forms a loop curve over each seasonal cycle of drawdown and fill. The volume of water to be gained by Hungry Horse Reservoir during a drawdown period is controlled by the aquifer characteristics, the rate of change of stage, the antecedent changes in stage, the time since they occurred, and the time sequence during draft. Because of the time-lag and loop effects, a simple relation of yield per foot of draft, or a percentage of the capacity table, cannot be expected to produce valid estimates.

Calculations of potential ground-water storage—the maximum to be expected if Hungry Horse Reservoir were held full for a long time (1 year), were drafted and then were held at that level for about a year—are shown below for the three drawdown periods. Also shown are the ground-water storage releases for these periods derived from the model.

Draft season	Draft (feet)	Potential storage (1,000 cfs-days)	Storage release (1,000 cfs-days)	Ratio of released storage to potential storage
1964–65	100	56.0	34.0	0.61
1965–66	59	35.0	19.9	.57
1966–67	119	65.2	43.0	.66

Antecedent conditions were more favorable for filling the ground-water reservoir in 1964–65 when pool level was held constant for 6 months in contrast to 2 months in 1966–67. This condition was more than offset by the earlier and longer draft period of 8 months in 1966–67 compared to 4 months in 1964–65. Thus, even though there was greater aquifer storage in the first year, the yield to the reservoir was proportionally less, because the time for drainage was small compared to the 1966–67 season.

The second phase of this study was devoted to improving the methods of forecasting the reservoir inflow during the low-flow periods, July–April. In the period of natural flow prior to September 1951, forecasts of "assured" flows were based on the data and characteristics for the outflow gaging station South Fork Flathead River near Columbia Falls.

In the period of regulated flows subsequent to September 1951, the inflow to the reservoir was not measured directly but was indirectly computed. Prior to the present study this was done by adjusting the measured outflow for changes in reservoir contents. Forecasts of reservoir inflow were made by the technique developed for natural conditions. This proved to be unsatisfactory because of the erratic nature of the computed inflow. The index equation for computing reservoir inflow developed in the 1959 studies was not considered adequate for present use.

During the period of this study the reservoir inflow, except for precipitation, was in effect a measured quantity. Index equations were developed from these data which could be used to evaluate the inflow to the reservoir for other periods of time. The water-budget data for the inflow to Hungry Horse Reservoir were analyzed by step-regression analysis, and an index of reservoir inflow, except for precipitation, was developed. This equation is

$$X_1 = 1.18X_2 + 4.47X_3 + 1{,}246,$$

where X_1 = monthly reservoir inflow except precipitation, in cfs-days,

X_2 = monthly runoff, South Fork Flathead River above Twin Creek near Hungry Horse, in cfs-days,

and X_3 = monthly runoff, Sullivan Creek near Hungry Horse, in cfs-days.

This equation has a correlation coefficient of 0.9999, a standard error of estimate of 2,230 cfs-days, and an average deviation of 1,470 cfs-days. This equation was used for computation of reservoir inflows after April 1967.

A similar index for use prior to October 1964 was developed. It is

$$X_1 = 1.20X_2 + 6.94X_3 - 777,$$

where X_1 = monthly reservoir inflow except precipitation, in cfs-days,

X_2 = monthly runoff, South Fork Flathead River at Spotted Bear Ranger Station near Hungry Horse, in cfs-days,

and X_3 = monthly runoff, Sullivan Creek near Hungry Horse, in cfs-days.

The correlation coefficient is 0.9994, standard error of estimate is 4,747 cfs-days, and average deviation is 2,830 cfs-days.

These two index equations and the water-budget data were used to estimate the inflow to Hungry Horse Reservoir except for precipitation for power years 1949–68 where data were available.

The recession characteristics of the reservoir inflow were analyzed and recession indexes were computed for periods when data were available. The "assured" flows from these indexes are larger than those from an equivalent index for the period 1936–37 in more than two-thirds of the fall and winter months.

A preliminary step-regression analysis of the monthly reservoir inflow versus the recession index, precipitation, and degree days (65°F) indicated that the recession index was the most significant factor in forecasting reservoir inflows during the period July–April. Further study of other time periods and meteorological data for stations other than Hungry Horse Dam are needed to fully develop the potential indicated by the above analysis.

Forecasts of water available for project use must include reservoir inflow (+), precipitation on the reservoir (+), evaporation from surface of reservoir (−), changes in reservoir storage (±), and changes in ground-water storage adjacent to the reservoir (±). The reservoir inflow and changes in reservoir storage are the largest components, but precipitation, evaporation, and changes in ground-water storage should be evaluated in order to enhance the efficient operation of Hungry Horse Reservoir.

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