ABSTRACT OF THESIS

Colorado Agricultural and
Mechanical College
Fort Collins, Colorado

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May, 1949

FORECASTING SEASONAL WATER YIELD
IN THE
UPPER SNAKE RIVER BASIN
IDAHO-WYOMING.

STATEMENT:

The value of forecasts of the volume of the spring season's water-yield is well recognized. Efficient and intelligent management of the annual resources of water for irrigation, electrical energy generation, flood control, navigation, fish and wildlife, recreation, and for industrial and urban use is founded upon seasonal water-yield forecasts.

The Problem.--

Water utilization in the Upper Snake River in Idaho-Wyoming has reached almost the ultimate. There is, moreover, an ever-growing need for flood control. As it is not possible to satisfy exclusively each interest by so-called "inviolate" storage allocation, the justification of the Palisades Dam rests upon the derivation of an acceptable method of seasonal water-yield forecasting on the basis of which reservoir allocations and operation schedules can be selected for each irrigation and flood control season in the light of forecasted total flows. T n deals with the development of an improved method of seasonal water-yield forecasting for the Upper Snake River in Idaho-Wyoming.

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Delimitation.--

This investigation is limited to the Upper Snake River in Idaho-Wyoming above Heise, Idaho, which is very near to the site of the proposed Palisades Dam. It is limited to methods of forecasting based upon snow surveys, as the Upper Snake River is a distinctly snowfed stream. It, also, is limited to forecasting of total flows for a forecast period; it does not deal with rate-of-runoff forecasts. The Snake River drainage basin is treated in two subdivisions. The term: "Snake River above Jackson Lake, Wyoming," refers to that portion of the drainage basin which flows into Jackson Lake; seasonal water volumes, expressed in acre-feet, have been corrected for changes in storage at Jackson Lake, and express, therefore, the yield from the melting of the accumulated winter season's precipitation. The term: "Jackson Lake, Wyoming, to Heise, Idaho" refers to that part of the drainage basin above Heise, Idaho (but exclusive of the drainage area above Jackson Lake). The runoff totals given for this part of the Snake River drainage basin do not include the water yield of the Jackson Lake drainage basin.

Definition of Terms:--

Seasonal water yield is defined as the volume of water expressed in acre-feet which is measured at a definite point along a stream channel, for a selected time interval, such as April to July, inclusive.

A water year is the year beginning with October 1 and ending with September 30 of the following calendar year.

Because of the seasonal nature of precipitation in the West, the water year is taken as the natural sequence of the autumn and winter season's precipitation followed by the spring season's runoff and the spring and summer irrigation usage.

Snow water equivalent, expressed in inches of water, refers to the water equivalent of the snow and ice crystals and any capillary water which might be retained in the snow mass. The term: water content, on the other hand, refers only to the liquid water which may be held in the interstices of the snow and ice crystals. Snow water equivalents are used throughout this thesis.

Altitudinal Adjustments:--

One of the basic physiographic characteristics of a watershed is that of the range of elevations above sea level and of the distribution of fractions of the total area at various elevations. This characteristic of a watershed exerts profound effects upon the meteorology and hydrology of the watershed. The idea of elevation-weighting of snow courses is based upon the common observation that the amount of snow accumulation increases with altitude. This is mainly a result of two climatological processes. First, precipitation tends to fall as snow at the higher altitudes because of the cooling effect on air masses of uplifts induced by mountain ranges. This cooling process is known as the orographic effect. Second, the lower air temperatures prevailing at higher altitudes tend to preserve the snow blanket until spring. It is recognized that the depth of snowfall and of snow accumulation is influenced by factors other than elevation. Among these are differences in precipitation caused by geographic size of the drainage basin, by local orographic and barrier effects and by prevailing storm paths. Also, the accumulation of snow on the ground at given points may be influenced considerably by prevalence and type of forest growth.

The method of elevation-weighting of snow survey data presented in this thesis introduces into the forecast computation one of the most individualistic and important watershed characteristics affecting seasonal water yield. Until an exhaustive study has been made of the interaction of all of the various factors affecting the accuracy of a seasonal water yield forecast, it will not be known which of the factors or what combination of them may produce the best results. Such an exhaustive study cannot be made for most drainage basins, either because of non-existence of data, or because of the shortness of records. On the other hand, the topography of drainage basins can be ascertained from maps of the Civil Aeronautics Administration, even for areas not mapped by any other agency, either governmental or private.

METHODS AND MATERIALS:

Sources of the Basic Data:--

Materials used in this investigation consisted of snow surveys, runoff records, and maps of the drainage basins. Geological Survey topographic sheets, State maps, and Forest Service maps were consulted, but , for the most part the maps used were those prepared as Aeronautical Charts by the Civil Aeronautics Administration, as these maps show thousand-foot contours for portions of the drainage basin not otherwise topographically mapped. Nine snow courses, the surveys of which began in 1919, were used for the drainage basin above Jackson Lake; fifteen snow courses, the surveys of which began in 1936 with one exception, were used for the drainage basin between Jackson Lake and Heise. The following runoff and lake level records were used: Snake River at Moran, Wyoming, drainage area 816 square miles, records beginning in September 1903; Jackson Lake at Moran, Wyoming, records begining with July 1908 (1908-1910 fragmentary); Snake River near Heise, Idaho records begin September, 1019, and are complete except for the winters of 1914 to 1924, inclusive, drainage area is 5,740 square miles.

This study is based upon published and publicly available records. For this reason there is no tabulation of the raw data included with this presentation.

Preparation of Data for Analysis:--

The initial step consisted of the tabulation of the records of all snow courses used for each year of record. Averages were calculated for each snow course for each of the two drainage basins used in this investigation. Arithmetic averages of snow water equivalents for all snow courses for each year for each drainage basin were also calculated. Similarly, runoff records were secured from Water Supply Papers, together with information about the changes in content of Jackson Lake for each snow-melt season. Runoff records of the Snake River at Moran, Wyoming, were corrected for changes in storage at Jackson Lake to produce computed volumes of water-yield from the drainage basin above Jackson Lake.

The Elevation-weighting Procedure:--

This method of elevation-weighting of snow course data differs from others in that it introduces into the forecasting computation the use of individual snow courses only to establish the curve of snow storage on a watershed in relation to elevation. Water equivalent values are derived from the curves plotted for each forecast date for each year of record and used in connection with area-elevation distribution fractions to compute the elevation-weighted snow-water equivalent for the drainage basin. This use of snow survey data takes into account portions of the drainage basin not sampled by snow surveys. It provides for the extrapolation of snow storage curves into higher elevations of a drainage basin which have not been sampled by snow surveys, or which are so remote or inaccessable as to render surveying of courses impractical.

SUMMARY:

A method is presented for seasonal water-yield forecast derivation based upon snow survey data. The method takes into account snow water equivalent by area-elevation zones, and interpolates derived snow-water equivalents for higher altitudes and for other portions of a watershed not actually sampled by snow courses. The seasonal water yield forecast derived by this method for the Upper Snake River in Wyoming, above Jackson Lake reservoir, has a correlation coefficient r of 0.824 ± 0.066, whereas the arithmetic-average-of-snow-courses based forecast has a correlation coefficient r of 0.760 ± 0.086. This increase in the numerical value of the correlation coefficient r and reduction in the numerical value of the standard deviation expresses the improvement attained in the snow-survey based forecast for Jackson Lake through the application of the elevation-weighting procedure.

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The thesis consists of the text, two illustrations, eleven tables, and thirteen figures.

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Walter U. Garstka

T H E S I S

FORECASTING SEASONAL WATER YIELD
IN THE
UPPER SNAKE RIVER BASIN
IDAHO-WYOMING.

Submitted by

Walter Urban Garstka

In partial fulfillment of the requirements
for the Degree of Master of Science
in Irrigation Engineering
Colorado
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MAY 24 1949

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR

SUPERVISION BY WALTER URBAN GARSTKA

ENTITLED FORECASTING SEASONAL WATER YIELD IN THE

UPPER SNAKE RIVER BASIN, IDAHO-WYOMING.

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE.

CREDITS 8

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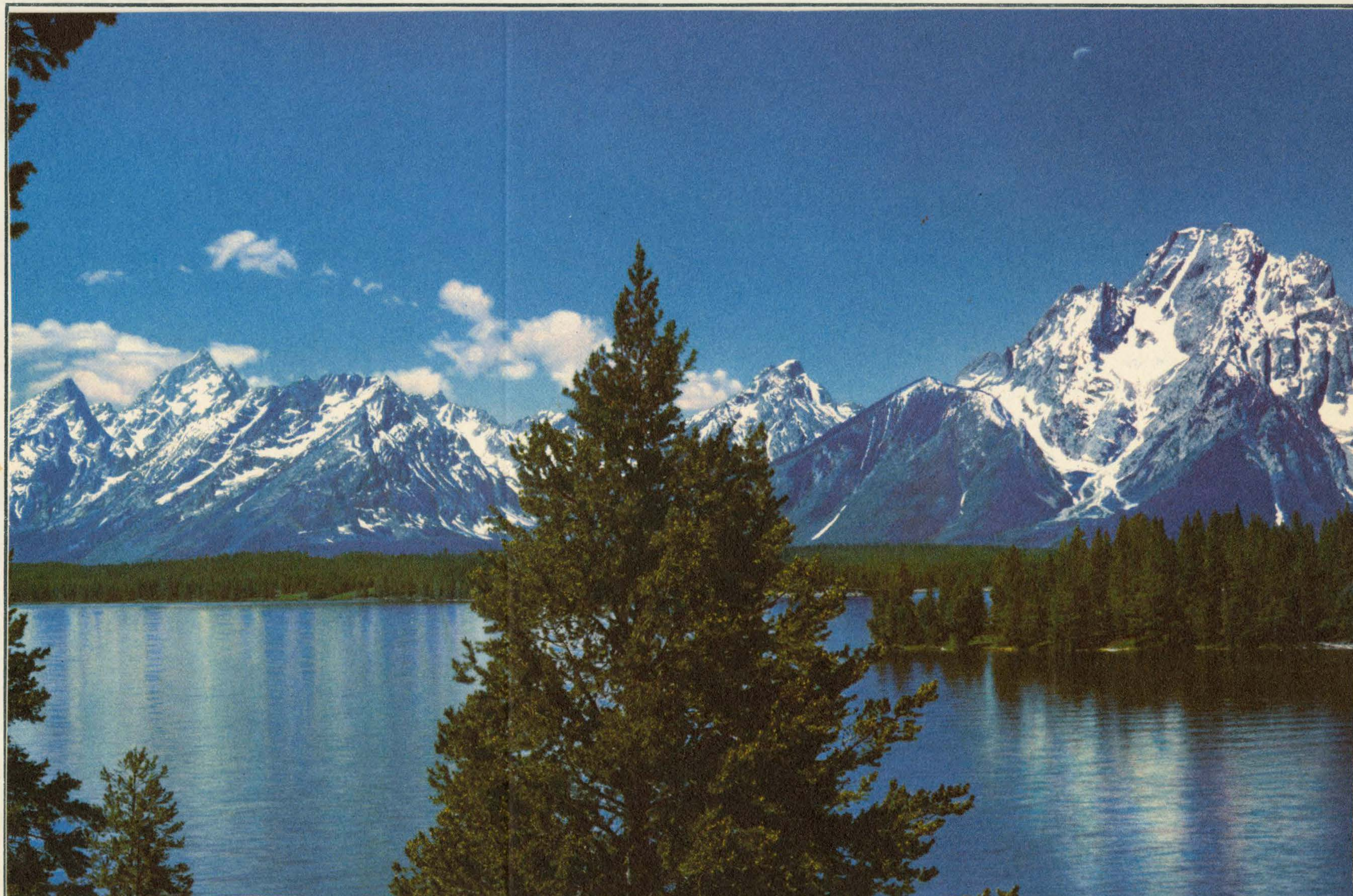
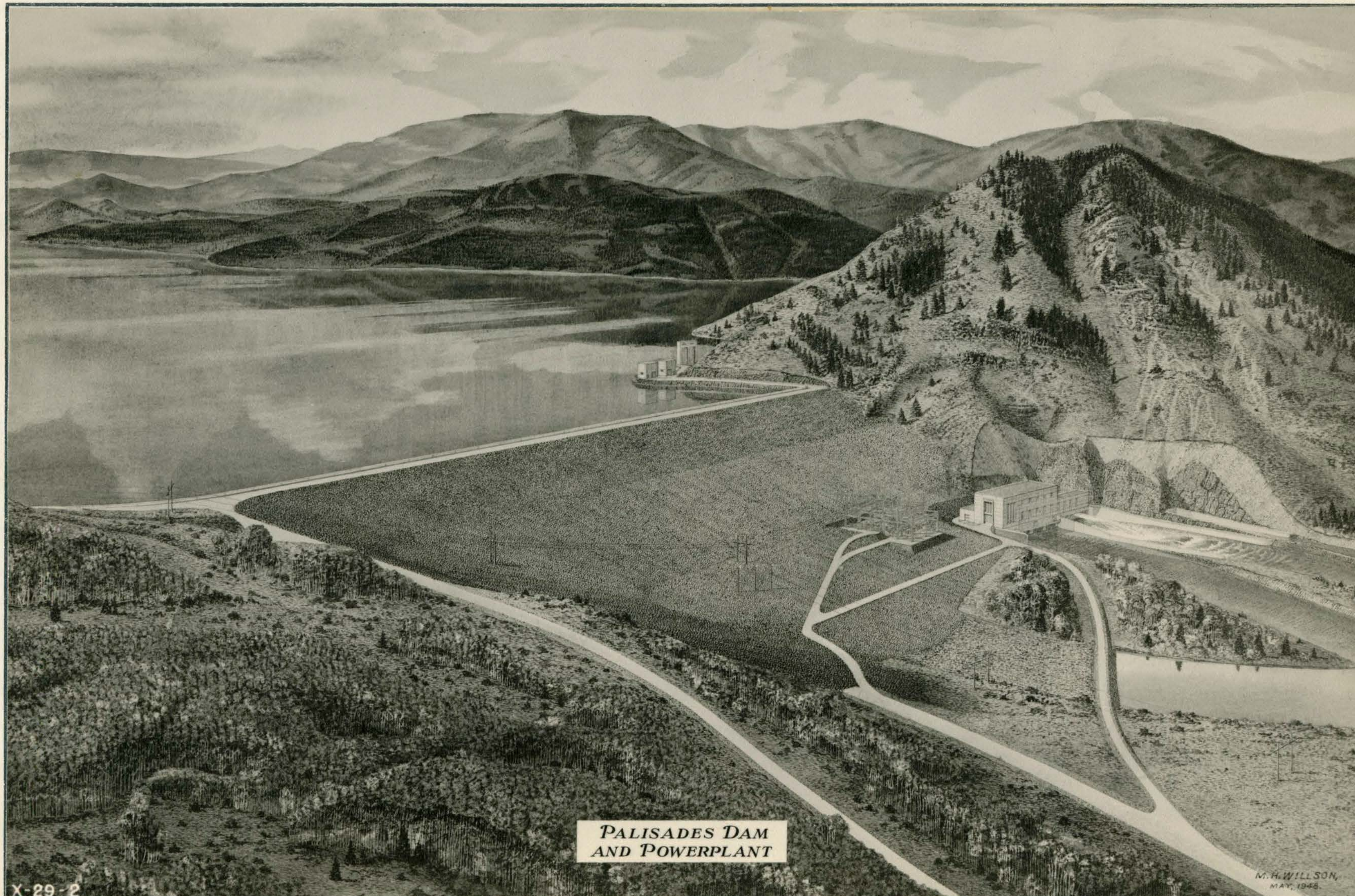
<u>The reproduction in color</u>

The Grand Tetons in Wyoming, as seen across Jackson Lake, a printing-press reproduction of a natural color photograph taken by an unknown photographer. This reproduction depicts the rugged character of a part of the drainage basin of the Upper Snake River and shows, in general terms, an area-elevation distribution discussed in detail in the thesis.

<u>The black and white drawing</u>

Artist M. H. Willson's conception of the Palisades Dam, now authorized for construction on the Upper Snake River near Heise, Idaho. This dam is to be of zoned-earth construction. Its height is to be 260 feet above the stream-bed. It will contain 10,500,000 cubic yards of earth and 2,000,000 cubic yards of rock. It will be the largest earth dam ever built by the Bureau of Reclamation, although it will not be as large as Fort Peck Dam in Montana, which was built by the Corps of Engineers. The power plant is being designed for an ultimate capacity of 54,000-kw. The forecast derivation method which is the subject of this thesis was performed to ascertain the possibilities of multiple-purpose operation of Palisades Dam on forecast basis.





PALISADES DAM
AND POWERPLANT

Chapter I

INTRODUCTION

The value of forecasts of the volume of the spring season's water-yield is well recognized. Efficient and intelligent management of the annual water resources for irrigation, electrical energy generation, flood control, navigation, fish and wild-life, recreation and for industrial and urban use is founded upon seasonal water-yield forecasts.

The problem

Water utilization in the Upper Snake River in Idaho-Wyoming has reached almost the ultimate. There is, moreover, an ever-growing need for flood control. Since it is not possible to satisfy exclusively each interest by so-called "inviolate" storage allocation, the justification of the Palisades Dam rests upon the derivation of an acceptable method of seasonal water-yield forecasting on the basis of which reservoir allocations and operation schedules can be selected for each irrigation and flood control season in the light of forecasted total flows. This specific problem deals with the development of an improved method of seasonal water-yield forecasting for the Upper Snake River in Idaho-Wyoming.

Delimitation

This investigation is limited to the Upper Snake River in Idaho-Wyoming above Heise, Idaho, which is very near the site of the proposed Palisades Dam. It is limited to methods of forecasting based upon snow surveys, as the Upper Snake River is a distinctly snow-fed Stream. It, also, is limited to forecasting of total flows for a forecast period; it does not deal with rate-of-runoff forecasts. The Snake River drainage basin, as shown in Figure 1, is considered to be in two subdivisions. The term: "Snake River above Jackson Lake, Wyoming," refers to that portion of the drainage basin which flows into Jackson Lake; seasonal water volume, expressed in acre-feet, have been corrected for changes in storage at Jackson Lake, and express, therefore the yield from the melting of the accumulated winter season's precipitation. The term: "Jackson Lake, Wyoming to Heise, Idaho" refers to that part of the drainage basin above Heise, Idaho, (but exclusive of the drainage area above Jackson Lake). The runoff totals given for this part of the Snake River drainage basin do not include the water yield of the Jackson Lake drainage basin.

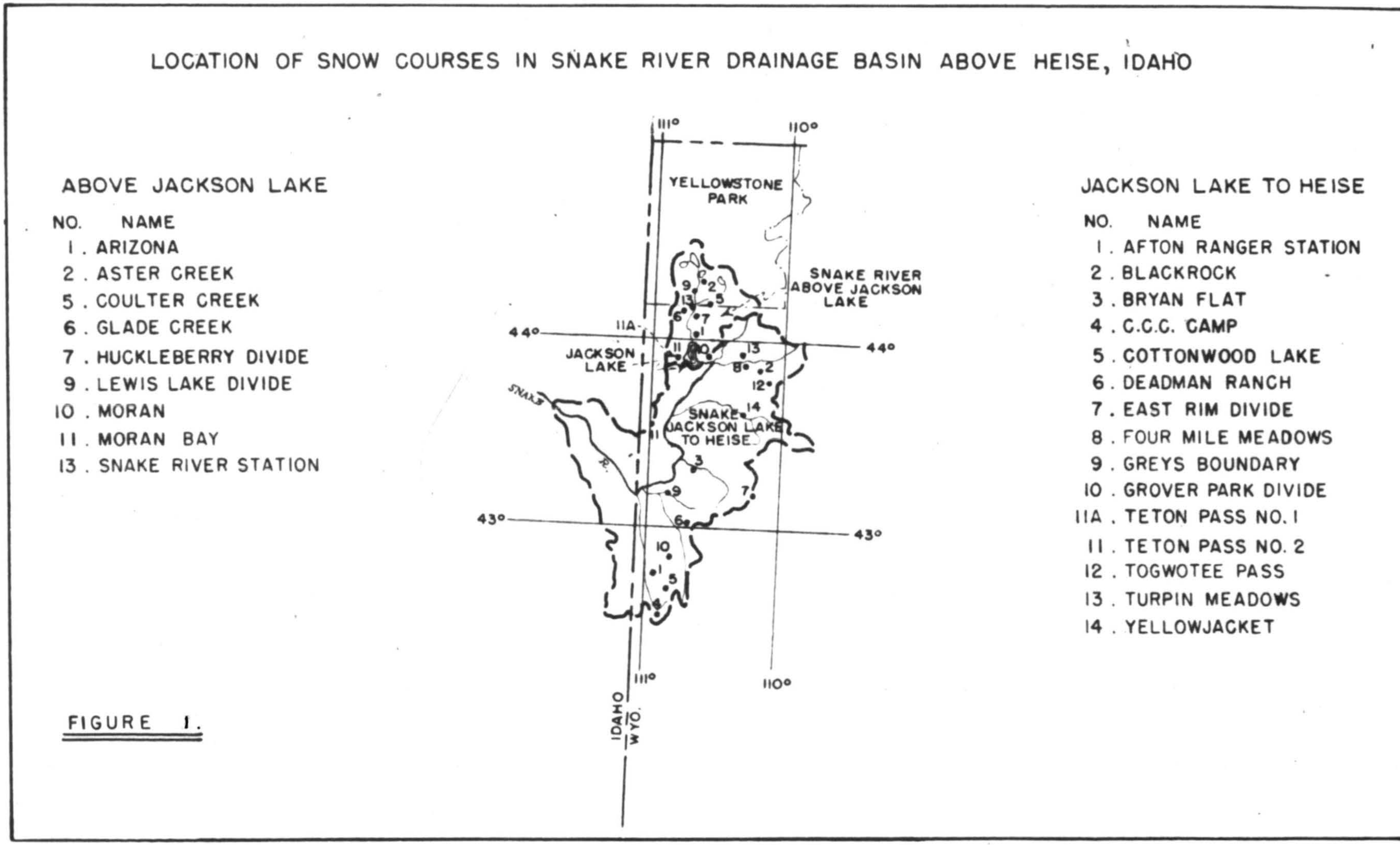


FIG. 1.-Location of snow courses in Snake River drainage basin above Heise, Idaho.

Definition of terms

Seasonal water yield is defined as the volume of water expressed in acre-feet which is measured at a definite point along a stream channel, for a selected time interval, such as April to July, inclusive.

A water year is the year beginning with October 1 and ending with September 30 of the following calendar year. Because of the seasonal nature of precipitation in most of the West, the water year is taken as the natural sequence of the autumn and winter seasons' precipitation followed by the spring season's runoff and the spring and summer irrigation usage.

Snow-water equivalent, expressed in inches of water, refers to the water equivalent of the snow and ice crystals and any capillary water which might be retained in the snow mass. The term, water content, on the other hand, refers only to the liquid water which may be held in the interstices of the snow and ice crystals. Snow-water equivalents are used throughout this thesis.

Chapter II

REVIEW OF THE LITERATURE

Development of snow survey systems

It is not known exactly when the first snow-water equivalent determination was made. The earliest reference to such a determination found in the literature to date is given by Horton (25), in which he mentions Prussian research (17) dealing with snow-water equivalents beginning on January 1, 1896, and extending to March 23, 1900. Although the original reference is given in the Bibliography, it was not seen in the course of this investigation.

The first reference to snow-water equivalent determination in the United States is given by Mixer (34), who made a snow survey in the Androscoggin River Basin in Maine on March 17, 1900. Horton (23) measured the water equivalent of snow on the ground at Utica, New York, in 1903 and 1904, using a cylindrical snow sampler which he devised for the purpose. Church evolved a snow sampler adapted to the taking of samples of deep snows about 1909, and embarked upon systematic snow surveying in the Lake Tahoe drainage basin, in Nevada and California at the request of the Sierra Pacific Power Company. Records of the Mount Rose, Nevada, snow course begin in 1910. J. Cecil Alter likewise invented a snow sampler and made determinations of snow-water equivalents in the Wasatch Mountains near Salt Lake City, Utah, about 1910.

The author discussed the subject of prior development of snow surveying with Robert E. Horton, James E. Church, and J. Cecil Alter during the Central Snow Conference of December 11, 1941, at the Michigan State College at East Lansing, Michigan. It developed at that time that each of these men had proceeded with snow-water equivalent determinations without knowing of parallel efforts of the others. It was agreed that, insofar as the United States is concerned, the credit for initiation of snow surveying belongs to Charles A. Mixer.

<u>The "snow-stake"</u>.--

At the time pioneering developments were under way with reference to snow surveying, the United States Weather Bureau and the United States Forest Service were cooperating in a project for securing observations of the depth of snow on the ground at so-called "snow-stakes". Monthly climatological data bulletins (1) of that period for the Western states contain the records of the snow-stake observations. As records accumulated, it became evident that snow depths did not provide the required information about the winter's precipitation and the system was abandoned.

Development of forecast methods

With the realization of the importance of snow-water equivalent determination, the indicativeness of a series of snow samples required consideration. In the early days, various diameters and types of snow sampling tubes were used. There was at that time little standardization of snow course layouts. With expansions of systems it became evident that more precise procedures were necessary. Connaughton (13) reported upon a study of the number of samples which should be taken along a snow course in order to measure the snow-water equivalent of the course within ten percent. His study showed that, for the Berthoud Pass, Colorado, snow course as of 1937, 23 snow samples were required. At that time, actually, 21 samples were being taken.

About 1933, the staking-out of snow course lines was begun. In the early days, a snow surveyor went into the mountains and, upon reaching a certain locality, took a number of samples. Too much was left to the decision of the surveyor. This system was suspected of introducing errors into forecast correlations, since no two surveyors sampled the same area. At present, snow courses are surveyed and mapped, and the ends of the lines of samples are witnessed by metal or masonite shields affixed to trees or posts. Detailed specifications for the taking of samples, for example, at 50-foot intervals along a line, remove the personal element. All of the snow courses now reporting to the centers of the Federal-State Cooperative Snow Survey Systems, coordinated by the Division of Irrigation of the Soil Conservation Service, are either staked out, or are scheduled for early staking and mapping.

The accuracy of samples of snow as taken by samplers of different diameters was subjected to considerable study. Some of the early samplers took cores eight inches in diameter. Goodell and Roberts (22) reported in 1941 upon their tests of snow sampling tubes of large and small diameters. Their statistical analyses disclosed that the standard 1.485 inches inside-diameter tube was just as accurate as larger tubes, and much more practical for snow surveying in the mountains.

The forecasting of seasonal water yield is accomplished by ascertaining the extent and trend of correlation between snow-water equivalent, usually plotted along the x-axis, and measured seasonal water yield, usually plotted along the y-axis, for all previous years of record. An actual forecast is then made by determining, from the trends established by previous years' records, what seasonal water yield would correlate with the snow-water equivalent as measured at the date of the forecast.

As each watershed possesses individual characteristics, the literature of the development of seasonal water yield forecasting based upon snow surveys consists for the most part of reports of various investigators who have used certain methods of calculating the correlation of certain combinations of selected factors for specific watersheds. An excellent treatment of the subject is given by Church (11). Detailed reports upon experiences with seasonal water yield forecasting in certain watersheds are to be found in many of the publications listed in the bibliography.

<u>Altitudinal adjustments</u>

One of the basic physiographic characteristics of a watershed is that of the range of elevations above sea level and of the distribution of fractions of the total area at various elevations. This characteristic of a watershed exerts profound effects upon the meteorology and hydrology of the watershed, as will be discussed in Chapter III. Work, in discussing the factors which may account for failures of the forecasted yield to agree closely with the measured volumes, states:

> (F) Relatively greater or lesser snowfall at other watershed-levels than reflected by a high or low elevation snow-course alone--Relatively less snowfall at lower levels occurs in warm winters and relatively greater snowfall at lower levels occurs in cold winters. Therefore, snow-distribution according to elevations of watershed is not always comparable from year to year. (45:127)

Various efforts have been made to introduce into a forecast computation the elevation characteristic of a watershed.

Church (11:107) applied altitudinal zoning to the Lake Tahoe snow courses. He divided the basin into 1000-foot classes and derived areas for each class. One or more snow courses were placed in each class. Church then divided the Lake Tahoe basin into four divisions: above 7000 feet east side, below 7000 feet east side, and similarly for the west side. Snow surveys in these four subdivisions were weighted according to the fraction of the total area in square miles found in each subdivision.

Bean and Thomas (5) subdivided the Androscoggin River basin into elevation classes and computed snow storage on the watershed by applying to snow courses located within certain altitudinal ranges a percentage-of-area factor.

Salo (43), working in the Merrimac River Basin, computed area-elevation distribution curves. From these he derived the altitude of mean elevation for each elevation zone. He assumed that the snow at that altitude would be the mean for that zone. Show surveys were taken at the mean elevation points. The method was well suited to the drainage basin and to the operational problems, since all courses were accessible from highways or cable cars. This excellent access made it possible to perform surveys at weekly intervals or oftener if desired.

The method of elevation-weighting snow survey data presented in this thesis introduces into the forecast computation one of the most individualistic and important watershed characteristics affecting seasonal water yield. The significance of this approach will become more evident after consideration is given to a discussion of the factors affecting seasonal water yield. This concept of elevation-weighting of snow survey data was used in connection with the analysis of one of the great floods of the Clinch River, on which the Norris Dam is located in Tennessee (21).

Chapter III

FACTORS AFFECTING SEASONAL WATER YIELD

Introduction

The controlling consideration in planning a forecasting organization is the value of the water. There is no point in setting up a superbly accurate forecasting procedure merely as an intellectual attainment. Present demands or the possibility of future developments must justify the expense of securing the basic data and maintaining a forecasting organization. At the present time, snow survey networks and forecasting organizations have attained the ultimate justifiable development in very few drainage basins. This may appear somewhat surprising in view of the current interest in water resources development. The somewhat primitive state of development of the art and science of water yield forecasting is due, in part, to the inherent intricacies of the interactions of hydrologic and meteorologic phenomena.

Meteorologic factors

Snow falls as a result of the functioning of certain well-established physical meteorologic processes.

The melting of snow and the release of runoff waters are, likewise, physical processes. However, when the melting of snow takes place upon a natural drainage basin, very intricate interactions of meteorologic and hydrologic processes occur, which will be considered more or less together in the remainder of this chapter. A separate consideration might not bring out the interaction of the melting processes with further complications introduced by the watershed characteristics.

The western states are subjected to a climate having in general, a more or less definite seasonal distribution of precipitation. By far the greater part of the precipitation, with some exceptions, falls in the winter months as snow, although significant volumes of runoff may result directly or indirectly from fall and spring rains. The forecaster's problem consists essentially of interpreting the significance of observed precipitation in terms of the future runoff as measured at some specific point along the stream channel.

An initial step in the computation of the forecast is that of evaluating the precipitation in terms of the drainage basin. The United States Weather Bureau, for some time, has published records of precipitation, both rain and snow, as measured by a standard 8-inch diameter gage and, more recently, it has published records from storage and intensity recording gages. As most of such gages are tended by cooperators in the immediate vicinity of their domiciles, the pattern of placement of almost all gages approximates the occupied land and road network pattern of the country.

Because of the well-known operation of basic meteorological principles which produces an increase of precipitation with increase in altitude, raingages in the valley rarely express precipitation in the mountains. Increase of precipitation with altitude has been commonly observed in mountainous regions. Unless there is a great difference in elevation, the increase may be slight and not readily noticeable. When the precipitation falls as snow, the increase of precipitation with rise of elevation is strikingly evident. The actual difference oftan may not be as great as it appears. This is due to increased opportunities for melting and disappearance at lower altitudes as compared with persistent low temperatures and preservation of snow at high altitudes.

Watershed characteristics

The form in which precipitation falls, either as snow or as rain, differs greatly for various watersheds and differs from year to year for the same watersheds. Watersheds exhibit great individuality in their vegetal, soil mantle, geologic, groundwater and drainage pattern characteristics.

For instance, the melting of low-altitude snows may release waters which immediately depart from the drainage basin as surface runoff in one watershed, whereas similar melting in another watershed will be detained in the drainage basin as replenishment of soil moisture deficiency, ground water recharge, or bank storage. Waters released by the snow melt in the one watershed, will not participate in the spring season runoff, while those released in the other will participate directly or indirectly.

The practicability of forecasting seasonal water yield on the basis of precipitation records alone has been successfully demonstrated for some watersheds having certain characteristics. This has taken place because of the recent application of advanced statistical analysis techniques which are now possible because of adequate lengths of records. There is little doubt that, for some watersheds, a superior seasonal forecast can be calculated using precipitation records alone.

Where differences of elevation between valley precipitation stations and headwaters areas in the mountains are great, the records of the valley stations do not represent precipitation catchment in the headwaters. Furthermore, the standard 8-inch gage is incapable of evaluating with any degree of consistency the water equivalent of snowfall. Old Weather Bureau records of snow-water equivalent are usually misleading because of the unfortunate general application of a uniform 10 percent density for snow at the time of fall. Instructions for Cooperative Observers, Circulars B and C of the Weather Bureau state:

> When the water equivalent cannot be determined accurately by melting, as given in paragraphs 41-43, inclusive, as a last resort take one-tenth the average measured depth of the snowfall on a level, open place as the water equivalent of the snowfall; for example, 10 inches of snow equals 1 inch of melted snow or water. (3:23)

Modern techniques of seasonal forecast computations for such areas, based on precipitation alone, have not been in use long enough to acquire a performance record. Accumulation of records by shielded seasonal-storage precipitation gages, from installations in the headwaters areas, especially where most of the winter precipitation falls as snow, may be necessary before ultimate accuracy can be expected of precipitation-based forecasts.

<u>Hydrologic factors</u>

All of the winter season's precipitation cannot be expected to appear as runoff in the spring.

There will be, no doubt, a soil moisture deficiency resulting from evapo-transpiration losses of the preceding dry season. This must be satisfied before the soil will release much water either to the ground water systems or as surface runoff.

Groundwater and bank storage deficiencies also must be satisfied before an appreciable volume of surface runoff can be released. It is evident, therefore, that only an estimate can be made of what fraction of a winter season's precipitation, as measured by gages, is left in the spring to yield runoff.

Snow is precipitation which rests, literally, in cold storage. A snow blanket may be subjected to melting at any time during the winter, especially at lower altitudes and on south-facing slopes. Never-ending recessions and advances of the snow line commonly are observed in mountainous regions. Since soils under a snow blanket rarely freeze, waters released from mid-winter snow melt are active in replenishing moisture deficiencies.

Another factor affecting water yield is that of evaporation loss sustained by precipitation during the winter. A snow survey discloses the water equivalent in inches depth of the snow at the time the survey is performed. A survey made just prior to the beginning of the snow melt season shows how much snow remains available for producing spring season runoff after the snow has been subjected to all the processes tending to deplete snow storage. Therein lies the value of snow surveying in relation to forecasting. Although rate-of-runoff or peak-flow forecasting is not the subject of this paper, it will be observed, in passing, that a knowledge of water equivalent in storage on a drainage basin is absolutely fundamental to any technique of forecasting peak rates of flood flow which may result from snow melt.

Chapter IV

CONSIDERATIONS AFFECTING THE DERIVATION OF A METHOD OF SEASONAL WATER YIELD FORECASTING

Elevation in relation to snow-water-equivalent storage

The initial step in the calculation of a seasonal water-yield forecast is that of evaluating the water equivalent of the snow cover on the watershed. The idea of elevation-weighting of snow courses is based upon the common observation that the amount of snow accumulation increases with altitude. This is mainly a result of two climatological processes. First, precipitation tends to fall as snow at the higher altitudes because of the cooling effect on air masses of uplifts induced by mountain ranges. This cooling process is known as the orographic effect. Second, lower air temperatures prevailing at higher altitudes tend to preserve the snow blanket until spring. It is recognized that the depth of snowfall and of snow accumulation is influenced by factors other than elevation. Among these are differences in precipitation caused by geographic size of the drainage basin, by local orographic and barrier effects and by prevailing storm paths. Also, the accumulation of snow on the ground at given points may be influenced considerably by prevalence and type of forest growth.

Intensiveness of snow sampling

The modern technique of snow course surveying consists of taking about 20 cores with a 1.485-inch diameter sampler along a designated course. This amounts to a total area of sampled snow of 0.464 square feet per snow course.

The drainage basin above Jackson Lake, Wyoming, is among the more intensively snow-sampled watersheds of the West. It has one course for each 90 square miles. On the assumption of 20 cores per course, there is a ratio of sampled area to total area of one to five and three quarters billions. There are watersheds of national importance within which snow sampling is less than one-tenth as intensive as it is in the Jackson Lake Basin.

Taking into account the sampling ratio of one to five and three quarters billions for the Jackson Lake drainage basin, it becomes evident that snow survey systems at present are merely general indices rather than valid statistical samples of snow water equivalent on the watersheds. In view of the minute fraction of a watershed area which is actually sampled, and taking into account watershed reactions and climatological hazards, it may be surprising that snow surveys have proven at all indicative.

The accuracy of seasonal water-yield forecasts might be improved by refining methods of interpretations of snow course data.

Effect of elevation upon forecasting

The study of a method of derivation of the forecast consists essentially of a search for a strong correlation between snow-surveyed water equivalent of the accumulated winter season's precipitation, or of observed precipitation in raingages, and the seasonal water yield. Simple graphic correlations seldom suffice, since a snow course measurement is ordinarily an index of water equivalent in storage, rather than a statistically valid sample of the snow field in the mountains.

The elevation-weighting procedure presented in this thesis introduces into the forecast computation one of the most fundamental characteristics of a drainage basin. Until an exhaustive study has been performed of the interaction of all of the various factors affecting the accuracy of a seasonal water yield forecast, it will not be known which of these factors or what combination of them produce the best results. Such an exhaustive study cannot be made for most drainage basins either because of non-existence of data, or because of the shortness of records. On the other hand, the topography of drainage basins can be ascertained from maps of the Civil Aeronautics Administration, even for areas not mapped by any other agency, either governmental or private.

Chapter V

MATERIALS AND METHODS

Sources of the basic data

Materials used in this investigation consisted of snow survey data (18), runoff records (44), and maps of the drainage basins. Geological Survey topographic sheets, state maps and Forest Service maps were consulted, but, for the most part the maps used were those prepared as Aeronautical Charts by the Civil Aeronautics Administration, as these maps show thousand-foot contours for portions of the drainage basins not otherwise topographically mapped.

The following snow courses were used:

Above Jackson Lake:

Number	Name of Course	Year record began
1.	Arizona Station, Wyoming	1919
2.	Aster Creek, Wyoming	1919
5.	Coulter Creek, Wyo.	1919
6.	Glade Creek, Wyo.	1919
7.	Huckleberry Divide, Wyo.	1919
9.	Lewis Lake Divide, Wyo.	1919
10.	Moran, Wyoming	1919
11.	Moran Bay, Wyoming	1919
13.	Snake River Station, Wyo.	1919

Jackson Lake, Wyoming to Heise, Idaho:

Number	Name of Course	Year record began
1.	Afton Ranger Station, Wyo.	1936
2.	Blackrock, Wyo.	1936
3.	Bryan Flat, Wyo.	1936
4.	C.C.C.Camp FF12, Wyo.	1936
5.	Cottonwood Lake, Wyo.	1936
6.	Deadman Ranch, Wyo.	1936
7.	East Rim Divide, Wyo.	1936
8.	Four Mile Meadows, Wyo.	1936
9.	Greys Boundary, Wyo.	1936
10.	Grover Park Divide, Wyo.	1936
11a	Teton Pass No. 1, Wyo.	1936
11.	Teton Pass No. 2, Wyo.	1946
12.	Togwotee Pass, Wyo.	1936
13.	Turpin Meadows, Wyo.	1936
14.	Yellowjacket, Wyo.	1936

The location of all snow courses used is shown in Figure 1.

Runoff records were from three stations reported in the Geological Survey's series of Water Supply Papers entitled: "Surface Water Supply of the Snake River Basin" reference (44):

Jackson Lake at Moran, Wyoming. Records are available beginning with July, 1908. Records through 1910 are fragmentary.

Snake River at Moran, Wyoming. Records are available beginning with September 1903. Drainage area is 816 square miles.

Snake River near Heise, Idaho. Records are available beginning with September, 1910, except for the winters of 1914 to 1924, inclusive. Drainage area is 5,740 square miles.

This study is based upon published and publicly available records. For this reason there is no tabulation of raw data in the Appendix.

Preparation of data for analysis

The initial step consisted of the tabulation of the records of all snow courses for each year of record. Averages were calculated for each snow course for each of the two drainage basins used in this investigation. Arithmetic averages of snow-water equivalents for all snow courses for each year for each drainage basin were also calculated. Similarly runoff records were secured from Water Supply Papers, together with information about the changes in content of Jackson Lake for each snow-melt season. Runoff records of the Snake River at Moran, Wyoming, were corrected for changes in storage at Jackson Lake to produce computed volumes of water-yield from the drainage basin above Jackson Lake.

The adjustment of runoff records for changes in storage in Jackson Lake is illustrated on the following page. An example of the correction as applied to the data for the 1940 snow melt season follows:

1940	Runoff, Snake River at Moran, Wyo.	Changes in content of Jackson Lake during month	Corrected inflow to Jackson Lake
	(Volumes in Acre-feet)		
April	2,990	+ 45,750	48,740
May	7,210	+ 257,330	264,540
June	160,900	+ 44,470	205,370
July	369,600	− 296,260	73,340

April to July, inclusive, inflow to Jackson Lake: 591,990

The elevation-weighting procedure

This method of elevation-weighting of snow course data differs from others in that it introduces into the forecasting computation the use of snow courses only to establish the curve of snow storage on a watershed in relation to elevation. Water equivalent values are derived from the curves plotted for each forecast date for each year of record and used in connection with area-elevation distribution fractions to compute the elevation-weighted snow-water equivalent for the drainage basin. This use of snow survey data takes into account portions of the drainage basin not sampled by snow surveys. It provides for the extrapolation of snow storage curves into higher elevations of a drainage basin which have not been sampled by snow surveys, or which are so remote or inaccessable as to render surveying of courses impractical.

Figure 2 shows the average water equivalent

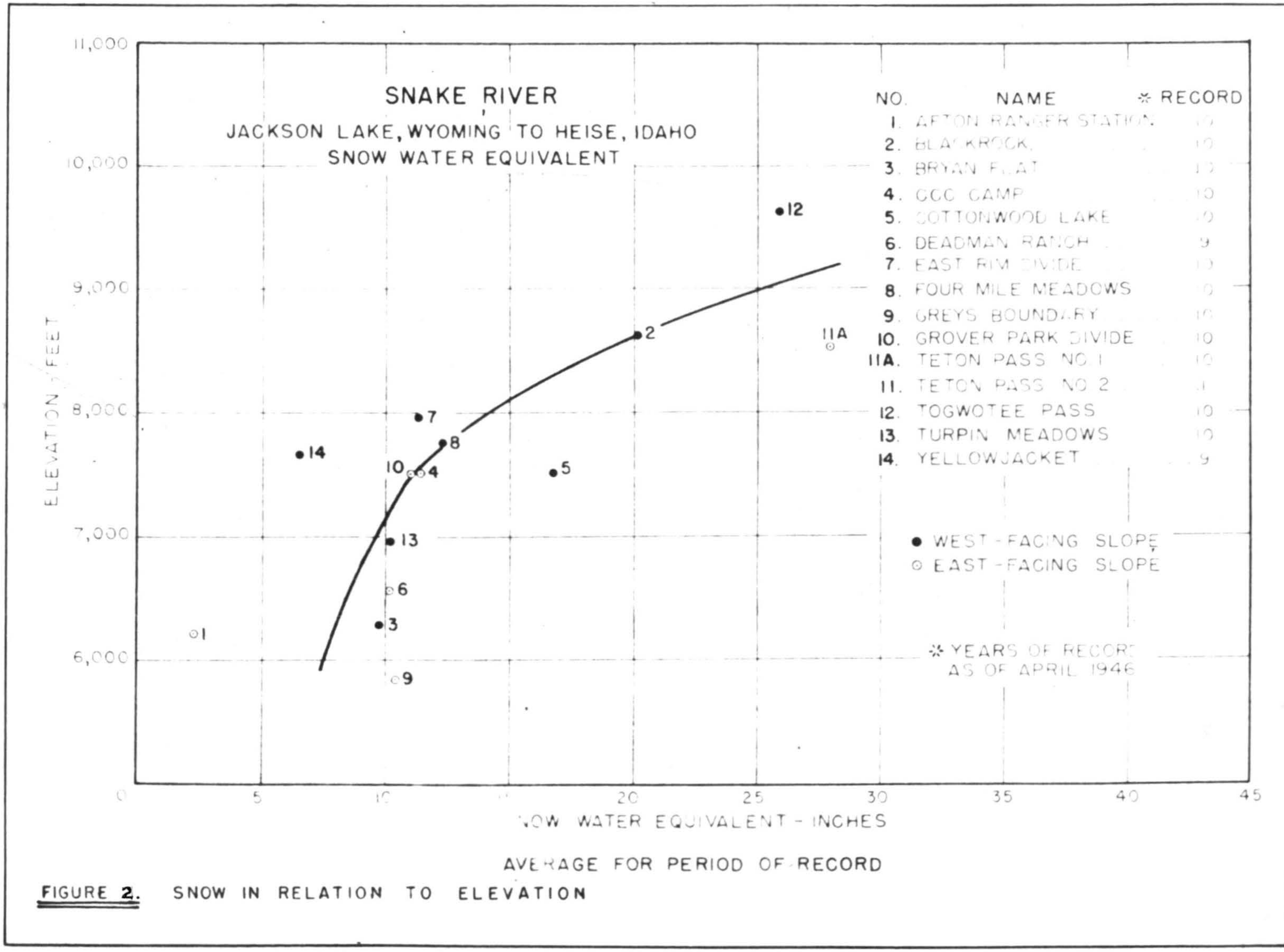


FIG. 2.-Snow in relation to elevation - Snake River, Jackson Lake, Wyoming to Heise, Idaho.

of snow courses as of April 1 in the Snake River drainage basin between Jackson Lake and Heise, for the period of record. The location of all snow courses used is shown on Figure 1. Figure 3 shows the distribution of the average water equivalent of the snow courses in the drainage basin above Jackson Lake in relation to elevation. Definite trends of increase of snow-water equivalent with elevation are evident.

Since Jackson Lake drainage basin is within the Snake River basin above Heise, all snow courses within the watershed above Heise were used in calculating the snow water equivalent for the watershed below Jackson Lake and above Heise. Only the snow courses above Jackson Lake were used for the computations for the Jackson Lake drainage basin.

In order to reduce the work of forecast derivation, charts similar to Figures 2 and 3 were not plotted using individual snow courses for each drainage basin for each forecast date for each year of record. Instead, snow courses were grouped according to elevation zones and average snow-water equivalents and elevations computed for each group of snow courses, for each year and forecast date. Separate curves were then drawn as positioned by the locations of the average-snow average-elevation points. Figure 4 shows the line for the watershed above Jackson Lake as

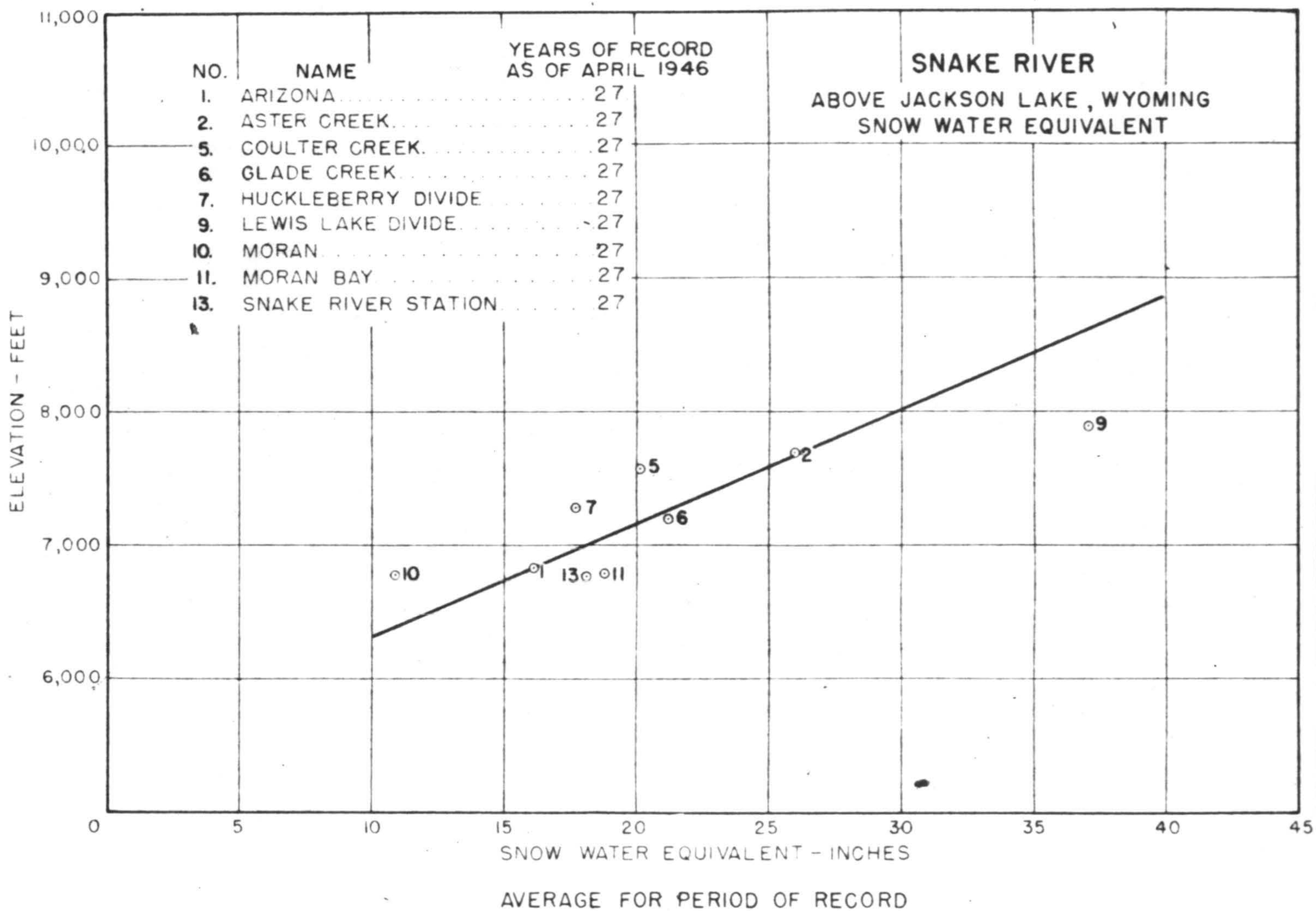


FIGURE 3. SNOW IN RELATION TO ELEVATION.

FIG. 3.-Snow in relation to elevation - Snake River above Jackson Lake, Wyoming

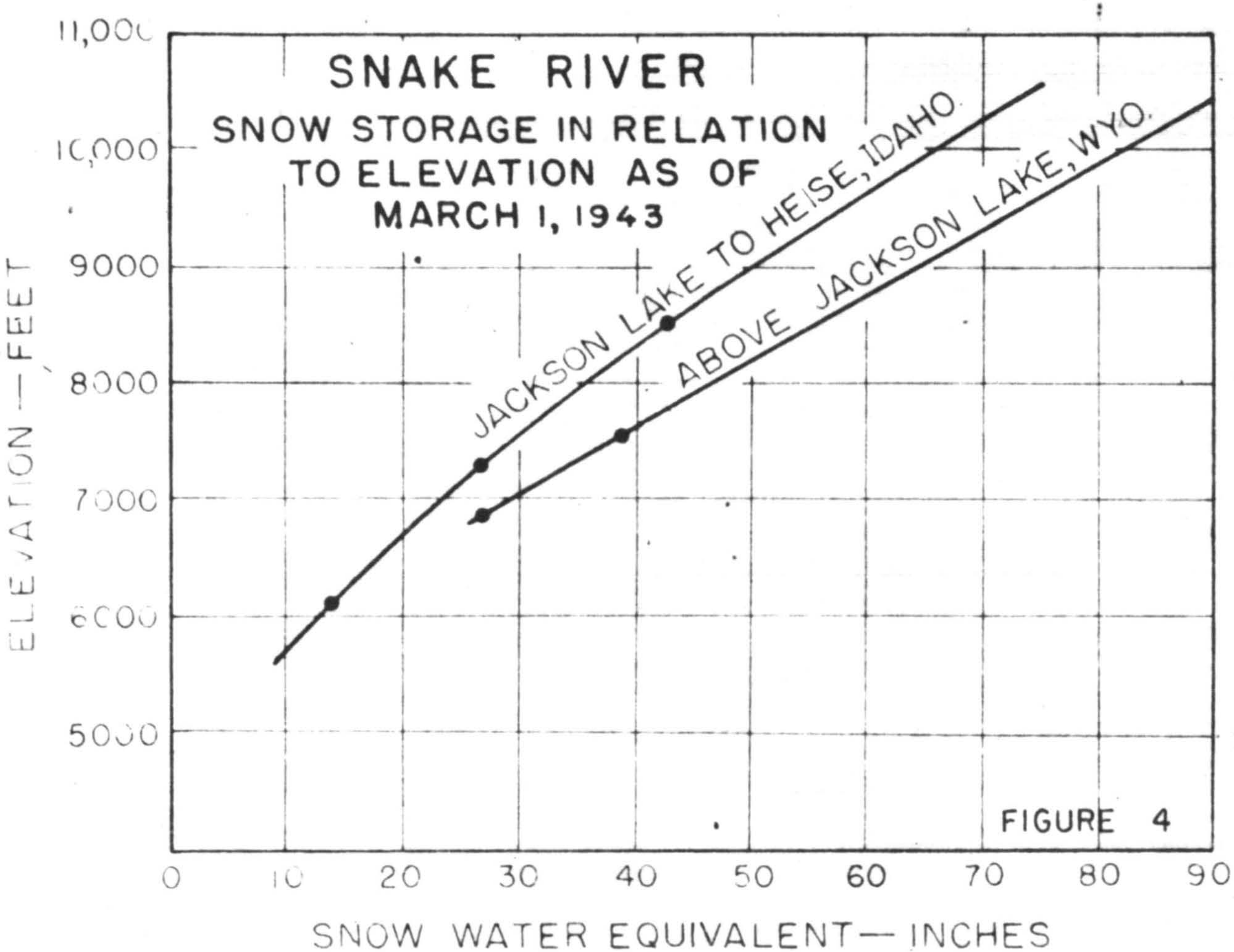


FIGURE 4. SNOW STORAGE - MARCH 1, 1943.

FIG. 4.-Snow storage in relation to elevation as of March 1, 1943 - Snake River

located by two points, and the curve for the watershed between Jackson Lake and Heise as located by three points.

The Jackson Lake snow courses were averaged in two classes: under 7000 feet, and over 7000 feet. An example of this computation is given in Table 1. Snow courses between Jackson Lake and Heise were averaged in three classes: under 6500 feet; 6500 to 8250 feet; and over 8250 feet. It was noticed that all of the courses above Jackson Lake fell into the 6500-to-8250 elevation class. To simplify calculations, totals of elevations and of snow-water equivalents which were summed up for the Jackson Lake calculation, were transferred without deriving the average from their work sheet, Table 1, to Table 2. The latter table is an example of the average point calculation for the Snake River between Jackson Lake and Heise.

Average points calculated in Tables 1 and 2 were plotted as shown in Figure 4. Curved lines were drawn through the three points plotted for the Snake River between Jackson Lake and Heise. It was observed that for some years the curves were concave, for others, convex. In the absence of any high-altitude courses above Jackson Lake, there was no guide point to help locate the upper part of the curve to show whether it should be concave or convex. Under the circumstances, a straight line was drawn through the two average points

Table 1.--MARCH 1 SNOW SURVEY

SNAKE RIVER ABOVE JACKSON LAKE

Under 7000 Feet

No.	Snow Course	Elevation Feet	Water Equivalent, Inches 1945	1944	1943
1	Arizona	6850	12.5	6.5	25.5
10	Moran	6800	9.2	4.0	17.3
11	Moran Bay	6800	12.3	8.6	33.1
13	Snake River Station	6780	15.2	7.9	28.8
	Sub-total	27,230	49.2	27.0	104.7
	Mean	6,808	12.3	6.8	26.2

Over 7000 Feet

No.	Snow Course	Elevation Feet	Water Equivalent, Inches 1945	1944	1943
2	Aster Creek	7700	16.4	11.6	46.4
5	Coulter Creek	7600	16.4	9.6	33.7
6	Glade Creek	7200	16.6	8.4	31.8
7	Huckleberry Divide	7300	13.7	8.1	27.3
9	Lewis Lake Divide	7900	26.0	16.2	55.4
	Sub-total	37,700	89.1	53.9	194.6
	Mean	7,540	17.8	10.8	38.9
Totals for all nine courses listed above.		64,930	138.3	80.9	299.3

Table 2.--MARCH 1 SNOW SURVEY

SNAKE RIVER BETWEEN JACKSON LAKE AND HEISE

No.	Snow Course	Elevation Feet	Water Equivalent, Inches 1945	1944	1943
	Under 6500 Feet				
1	Afton Ranger Station	6200	4.7	3.2	5.5
3	Bryan Flat	6250	7.7	3.2	17.4
9	Greys Boundary	5800	9.1	4.9	15.5
	Sub-total	18,250	21.5	11.3	38.4
	Mean	6,083	7.2	3.8	12.8
	6500 to 8250 Feet				
	Jackson Lake*	64,930	138.3	80.9	299.3
4	CCC Camp	7,500	9.4	5.9	14.2
5	Cottonwood Lake	7,500			
6	Deadman Ranch	6,534	8.9	2.9	19.8
7	East Rim Divide	7,950	6.8	5.8	15.9
8	Four Mile Meadow	7,770			
10	Grover's Park Divide	7,500	8.2	6.1	13.9
13	Turpin Meadow	6,930			
14	Yellow Jacket	7,675		1.0	10.1
	Sub-total - Elevations		94,414	102,089	102,089
	Average Elevations		7,263	7,292	7,292
	Sub-total Snowwater Equivalent		171.6	102.6	373.2
	Average Snowwater Equivalent		13.2	7.3	26.7

*Transposed sub-totals for 9 snow courses above Jackson Lake.

Table 2.--MARCH 1 SNOW SURVEY (CONTINUED)

SNAKE RIVER BETWEEN JACKSON LAKE AND HEISE

Over 8250

No.	Snow Course	Elevation Feet	Water Equivalent, Inches 1945	1944	1943
2	Blackrock	8,600			
11-a	Teton Pass #1	8,500	18.6	12.0	42.4
11	Teton Pass #2	8,500	24.1		
12	Togwotee Pass	9,600			
	Sub-total		42.7		
	Mean	(8,500)	21.4	12.0	42.4
Number of Courses			18	18	18

for the drainage basin above Jackson Lake.

Figure 5 shows the lines of snow-water equivalent in relation to elevation for Jackson Lake drainage basin for the years 1919 to 1948, inclusive. On Figure 5, points at elevations 6808 and 7540 are shown only on the lines for the years 1944 and 1927. The slopes of the lines for all years on Figure 5 were fixed by similarly plotted points. These points were not indicated on the finished drawing, as it was desired to retain clarity on the chart in the areas where the lines for numerous years intersect.

Figure 6 shows the curves of snow storage in relation to elevation for the Snake River between Jackson Lake and Heise. Curves on Figure 6 were positioned by average points at elevations of about 6100, 7300 and 8800 as computed in Table 2.

Figure 7 shows the shapes of curves of snow storage in relation to elevation for three forecast dates; February, March and April, for the Snake River between Jackson Lake and Heise. Curves are shown for a low-volume water-yielding year, 1940, and a large-volume water-yielding year, 1943.

Areas of the two drainage basins by thousand-foot elevation zones were determined by planimeter. Area-elevation distribution relationships were computed. Table 3 shows the percentage of watershed area by

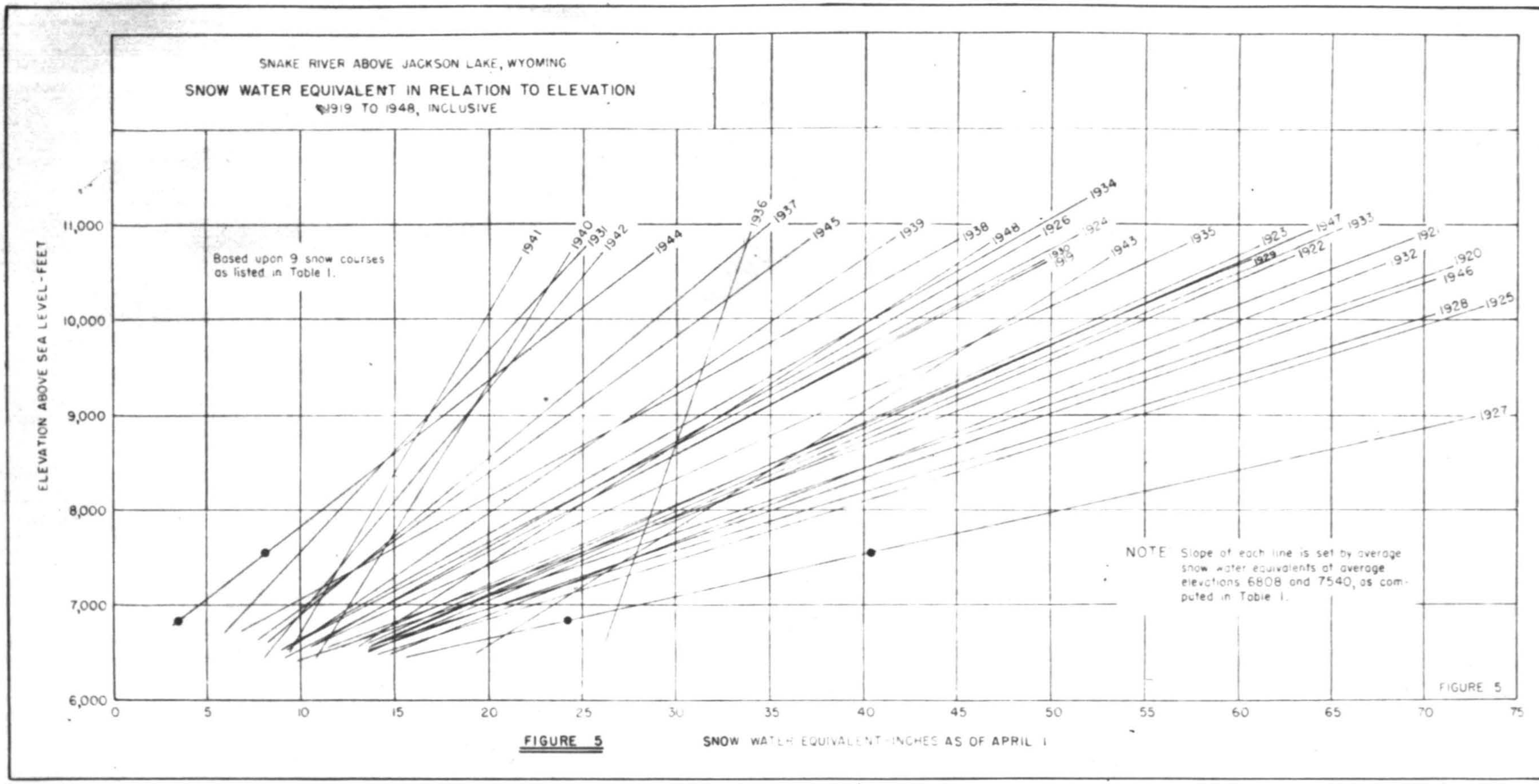


FIG. 5.-Snow-water equivalent in relation to elevation as of April 1, for the period 1919 to 1948, inclusive - Snake River above Jackson Lake, Wyoming

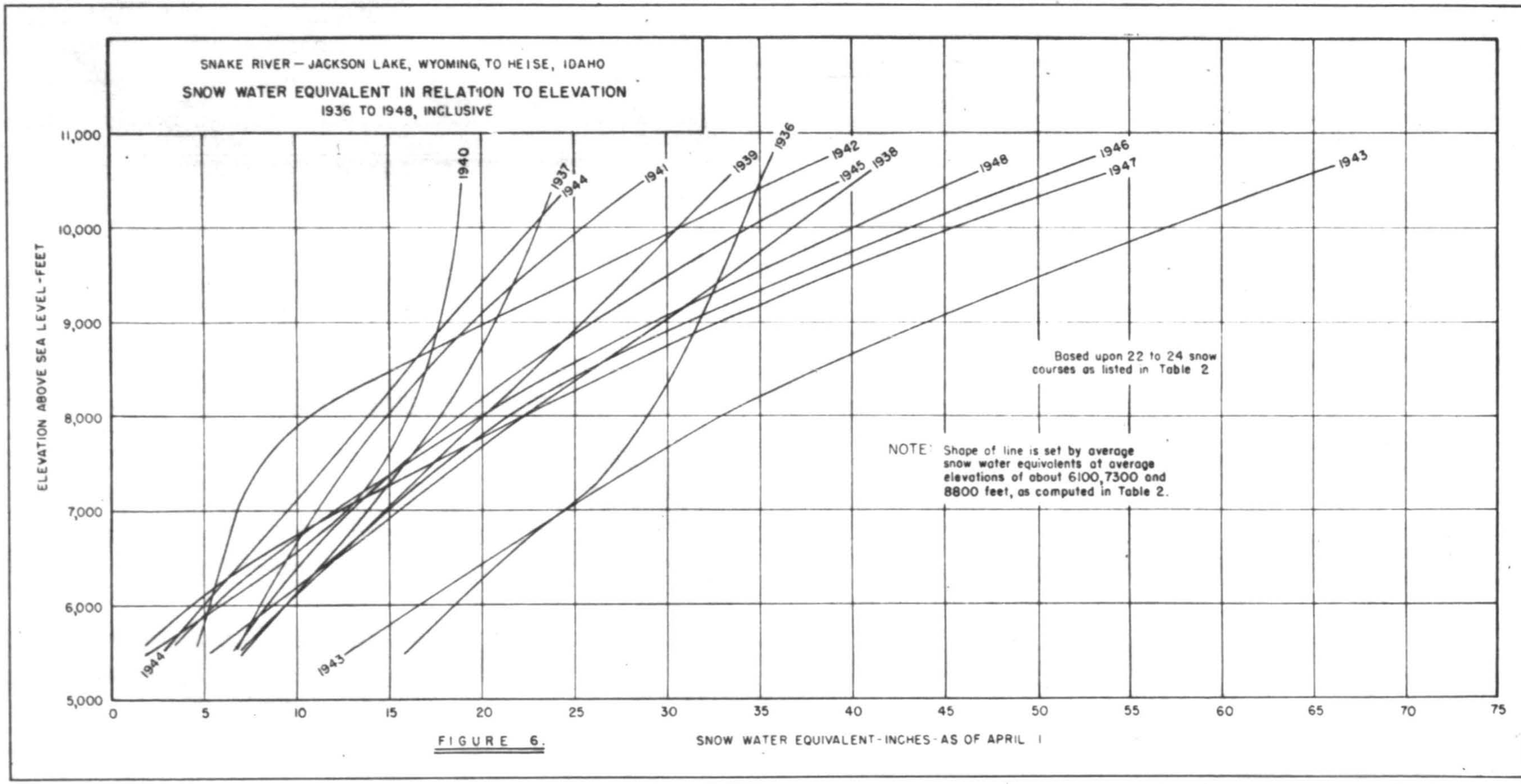


FIG. 6.-Snow-water equivalent in relation to elevation as of April 1, for the period 1936 to 1948, inclusive, - Snake River, Jackson Lake to Heise

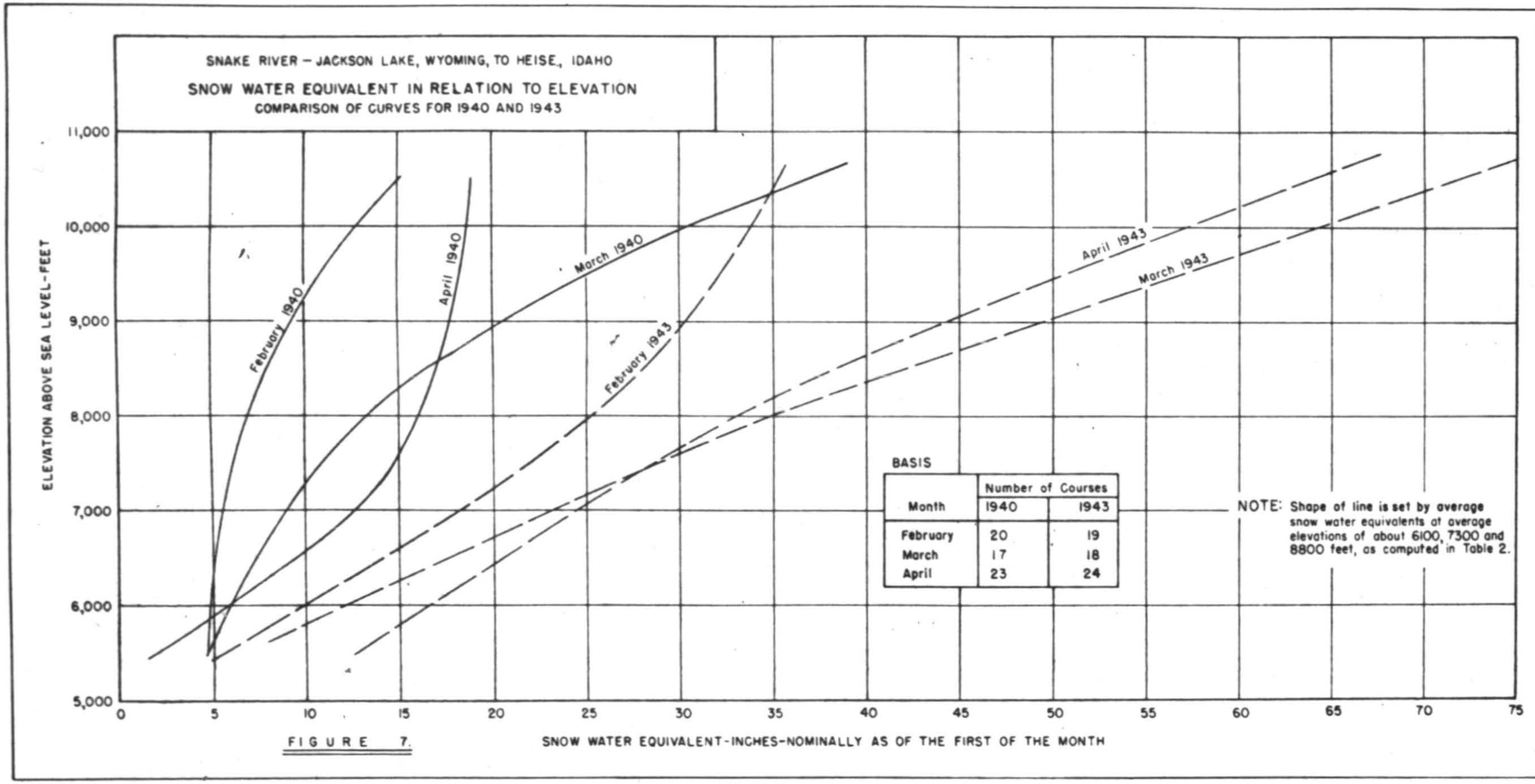


FIG. 7.-Comparison of curves for 1940 and 1943, as of February, March and April 1st - Snake River, Jackson Lake to Heise - snow-water equivalent in relation to elevation

Table 3.--PERCENTAGE OF AREA BY ELEVATION CLASSES--
SNAKE RIVER

	Above Heise, Idaho	Above Palisades Damsite	Above Jackson Lake, Wyoming
	5740 sq. mi.	5260 sq. mi.	816 sq. mi.
	Percentage of Total Area by Elevation Classes		
Elevation Class (ft.)			
5000-6000	5.8	3.0	0
6000-7000	24.0	22.7	11.3
7000-8000	37.8	40.1	37.4
8000-9000	13.5	13.8	39.0
9000-10000	13.5	14.4	10.5
10000-11000	5.2	5.8	01.6
Over 11000	0.2	0.2	0.2
Total	100%	100%	100%

elevation classes. The same information is given graphically in Figure 8.

Elevation-weighted snow-water equivalents for the two drainage basins were calculated as shown in Tables 4 and 5. "Fractions of area" in columns so designated in Tables 4 and 5 were taken from Table 3. "Snow-water equivalent inches" values appearing in columns so designated in Tables 4 and 5 were taken from the curves of snow-storage in relation to elevation at the elevations listed in the first columns of Tables 4 and 5.

Table 6 presents the end products of the examples of elevation-weighting computation performed in Tables 4 and 5.

Statistical test of the effectiveness of the method

Statistical approaches provide an impersonal and mathematically valid criterion for ascertaining the strength of a correlation. The basic mathematical derivations of the statistical processes used are not the subject of this thesis. They are presented in detail in numerous text-books and dissertations on statistics. The correlation coefficient r which is derived through the method of Least Squares from the data under scrutiny, expresses the strength of the correlation. A value of plus 1 or minus 1 indicates

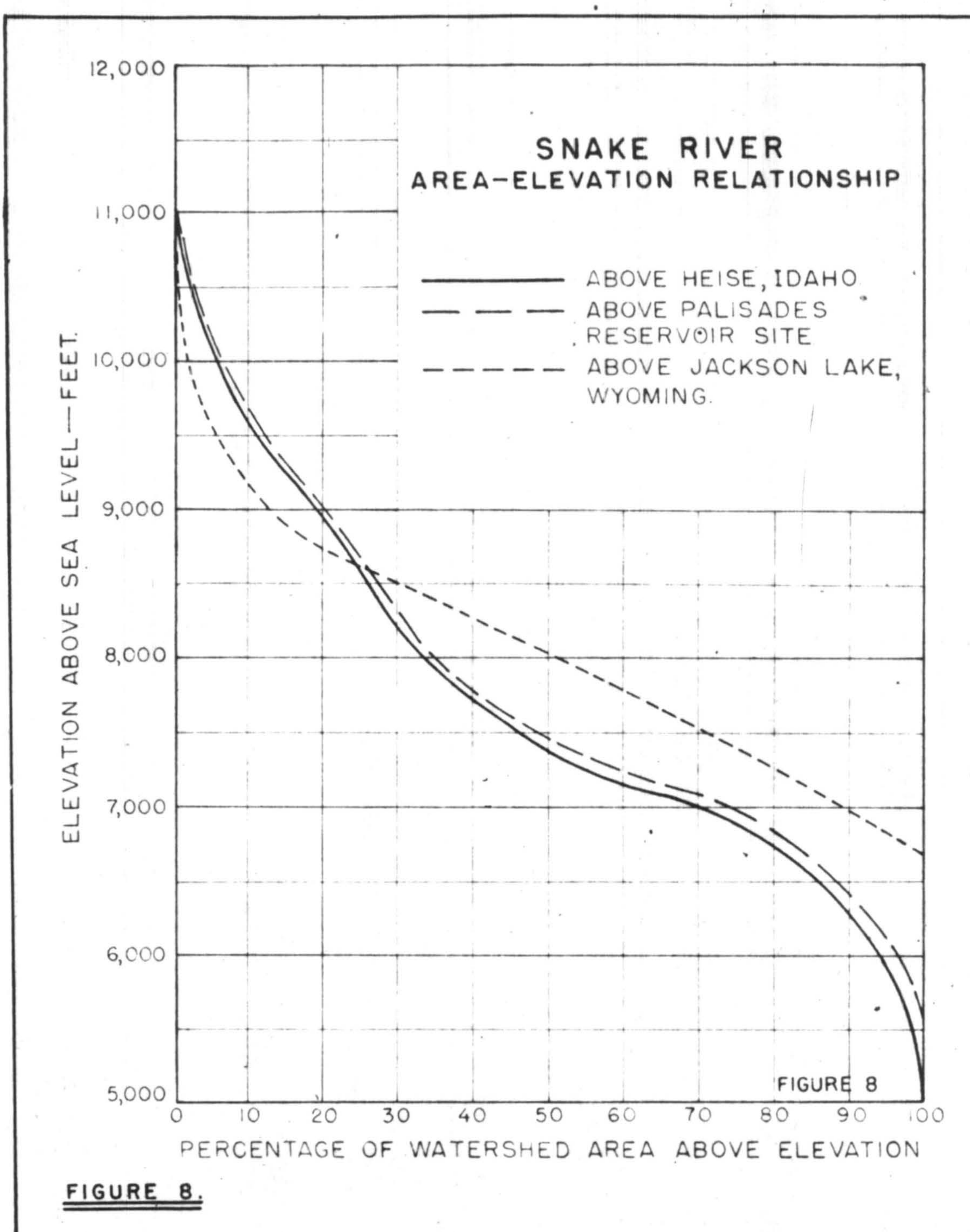


FIG. 8.-Area-elevation relationship - Snake River

Table 4.--ELEVATION - WEIGHTED SNOW STORAGE COMPUTATION MARCH 1

SNAKE RIVER ABOVE JACKSON LAKE

		1945		1944		1943	
Elevation Feet	Fraction of Area	Snow Water Equivalent Inches	Product	Snow Water Equivalent Inches	Product	Snow Water Equivalent Inches	Product
6800	0.113	12.3	1.39	6.8	0.77	26.2	2.96
7500	0.374	17.6	6.58	10.6	3.96	38.1	14.25
8500	0.390	25.1	9.80	16.2	6.32	55.9	21.80
9500	0.105	32.9	3.46	21.8	2.29	73.5	7.72
10500	0.018	40.5	0.73	27.3	0.49	91.0	1.64
Totals	1.000		21.96		13.83		48.37
Water Equivalents		22.0"		13.8"		48.4"	

Table 5.--ELEVATION - WEIGHTED SNOW STORAGE COMPUTATION MARCH 1

SNAKE RIVER BETWEEN JACKSON LAKE AND HEISE

Elevation Feet	Fraction of Area	1945 Snow Water Equivalent Inches	1945 Product	1944 Snow Water Equivalent Inches	1944 Product	1943 Snow Water Equivalent Inches	1943 Product
5800	0.067	6.0	0.40	2.3	0.15	10.0	0.67
6500	0.261	9.3	2.43	4.9	1.28	17.2	4.49
7500	0.379	14.9	5.65	8.2	3.11	29.1	11.03
8500	0.094	21.4	2.01	12.0	1.13	42.4	3.99
9500	0.140	30.1	4.21	17.0	2.38	57.5	8.05
10500	0.059	40.4	2.38	22.0	1.30	73.3	4.32
Totals	1.000		17.08		9.35		32.55
Water Equivalents		17.1"		9.3"		32.5"	

Table 6.--PRODUCT OF COMPUTATION

	Elevation Weighted Snow Water Equivalent, Inches		
	Nominally March 1		
	Year 1945	Year 1944	Year 1943
Snake River above Jackson Lake	22.0	13.8	48.4
Between Jackson Lake and Heise	17.1	9.3	32.5

full correlation, positive and negative, respectively. A positive value indicates correlation only if the inherent characteristics and physical properties of the items under study are such that an increase in positive value of the independent variable is correlated with some increase in the positive value of the dependent variable. The relationship between snow-water equivalent and runoff is of this type; the greater the snow, the more water-yield.

In analyzing the results of the use of the elevation-weighting procedure described in this thesis, the strength of the correlation is shown by the magnitude of the numerical value of the correlation coefficient r.

Another criterion of the strength of the correlation is the standard deviation : $\sigma_{r_{xy}}$, of the correlation coefficient. This is computed by the equation:

$$\sigma_{r_{xy}} = \frac{1 - r^2}{\sqrt{n-2}}$$

The higher the numerical value of the $\sigma_{r_{xy}}$, the weaker is the correlation.

A linear correlation can be expressed, through the application of simple analytical geometry, as an equation for the slope and position of a line in a Cartesian coordinate system. Such an equation presents in condensed form the correlation also shown in the form of graphs. Further treatment of statistical considerations is presented in the Appendix, in which is included a multiple-correlation performed to learn if the snows of the preceding winter, in addition to those of the current season, influenced the current season's water yield.

Chapter VI

DISCUSSION OF RESULTS

Snow courses and the area-elevation relationship of the watershed

A very definite trend of increase of snow-water equivalent with altitude is evident on Figures 2 and 3, of averages of snow courses for the periods of record. Figures 5, 6, and 7 likewise show this very definite relationship with reference to individual years.

A good geographic distribution of snow courses within the drainage basins, as is shown on Figure 1, and the existence of the trend of increase of snow-water equivalent with elevation, indicate that the network of snow courses reflects the snowfall and storage for the watershed. The vertical position of the individual snow course plottings on Figures 2 and 3 shows the relationship of snow storage with respect to elevation. Horizontal displacement, or the position of snow courses located in different parts of the drainage basin at or about the same altitude, may reflect the effects of geographic location, storm paths, and factors other than elevation, such as old forest fires. A curve through the points averages the snow courses both vertically and horizontally, and thus expresses the average snow-water equivalent for the watershed.

As is evident in Figures 5 and 6, no two years produced the same shape of curves having the same slope for the same date of the survey. As is shown in Figure 7, for the Snake River between Jackson Lake and Heise, curves differed greatly for February, March and April 1st, 1940, (a small runoff-volume yielding year) as compared with similar curves for 1943 (a large runoff-volume yielding year). Not enough courses have been surveyed as of May 1st to permit the addition of similar curves for May 1st. In a few instances, such as February 1, 1940 and February 1, 1941, the curves plotted almost vertically, indicating much greater water equivalent storage at lower altitudes than at higher-lying portions of the drainage basin.

Elevation-weighted snow-water equivalent in relation to water yield

Tables 7 and 8 contain data on the seasonal water yield, and both arithmetic and elevation-weighted averages of snow-water equivalent. Figure 9 is a regression-line type of forecast chart based upon

Table 7.--RUNOFF AND SNOW

SNAKE RIVER ABOVE JACKSON LAKE, WYOMING

Nominally April 1

Year	Flow acre-feet April to July, inclusive	Arithmetic average 9 snow courses	Elevation weighted (2-point) average of 9 snow courses
1919	455,870	16.8	23.1
1920	725,370	21.5	32.8
1921	792,440	20.6	31.8
1922	739,810	22.0	32.0
1923	710,290	20.7	30.4
1924	455,730	15.8	24.0
1925	1,003,620	25.9	39.5
1926	538,680	16.6	24.2
1927	1,082,810	33.0	52.5
1928	990,820	23.8	37.9
1929	614,650	20.2	30.5
1930	560,650	16.8	25.1
1931	382,160	8.3	12.4
1932	757,290	24.0	35.1
1933	646,410	21.6	31.5
1934	455,370	15.3	21.1
1935	701,750	17.9	27.6
1936	823,310	29.9	30.7
1937	590,890	19.7	23.2
1938	869,230	22.5	28.6
1939	642,600	24.0	28.2
1940	591,990	18.5	19.2
1941	528,860	15.8	17.0
1942	631,340	16.6	19.1
1943	1,095,010	37.5	40.1
1944	566,060	13.5	17.7
1945	657,110	18.7	24.5
1946	770,300	23.6	35.8

Table 8.--RUNOFF AND SNOW

SNAKE RIVER BETWEEN MORAN, WYOMING, AND HEISE, IDAHO

Nominally April 1

Year	Total Runoff April to July, Inclusive Acre Feet	Arithmetic Average Inches	Elevation Weighted Mean of 22 to 24 Snow Courses Including those Above Jackson Lake Inches
1936	3,028,070	24.4	26.6
1937	1,819,320	14.7	16.0
1938	2,696,830	17.6	20.5
1939	2,021,600	16.2	18.3
1940	1,465,600	13.0	13.7
1941	1,680,140	11.9	14.3
1942	2,147,890	12.0	14.1
1943	3,597,750	27.0	31.5
1944	1,758,250	10.9	12.5
1945	2,331,200	15.7	17.8
1946		17.2	21.1

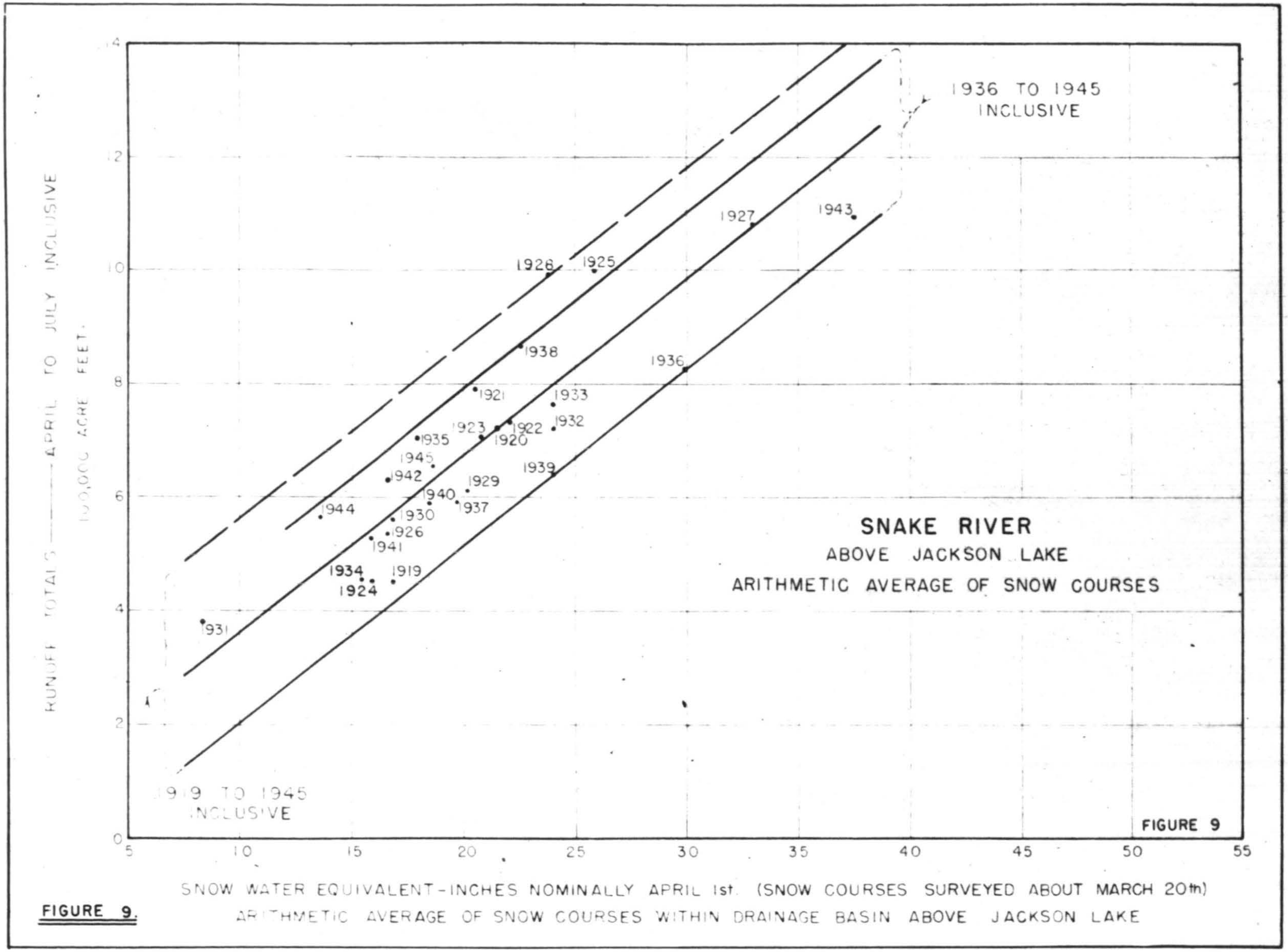


FIG. 9.-Forecast chart - Snake River above Jackson Lake based upon elevation-weighted averages of snow courses

arithmetic averages of snow courses and Figure 10 is a forecast chart based upon elevation-weighted equivalents. Both charts are for the drainage basin above Jackson Lake. Similarly Figures 11 and 12 are forecast charts for the Snake River between Jackson Lake and Heise.

Percentages of snow as of April 1st appearing as runoff in the Snake River above Jackson Lake are presented in Table 9. This relationship is shown graphically on Figure 13. It was observed that years of small snow storage, such as: 1931, 1941, and 1944 exhibited high percentages of snow appearing as runoff; 71.0, 71.8 and 73.4, respectively. Years of heavy snow storage, such as: 1925, 1927, and 1943 exhibited low percentages of snow appearing as runoff: 58.5, 47.4, and 62.8, respectively. This unlooked-for relationship may be explained in part by reference to Figure 5. The small runoff-volume years: 1931, 1940, 1942 and 1944 were years of small snow storage at both low and high altitudes. During the years 1925, 1927, and 1928 (large runoff-volume years) there was heavy snow accumulation at both low and high elevations. It is possible that the low-altitude snow packs were subjected to earlier melting and especially to greater evaporation losses than the high-altitude accumulations. Thus, since more of the snow reposed at higher altitudes,

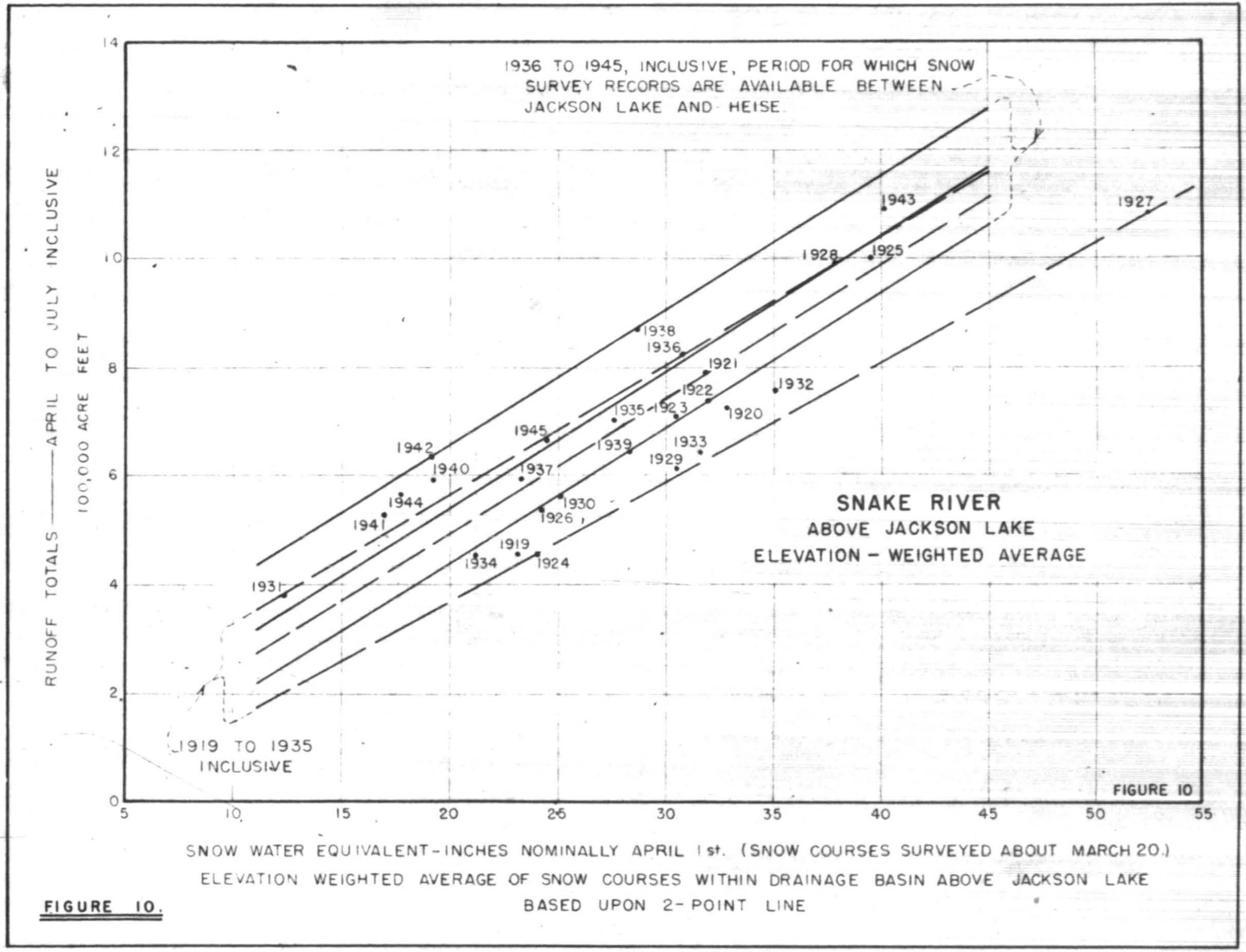


FIG. 10.-Forecast chart - Snake River above Jackson Lake based upon elevation-weighted averages of snow courses

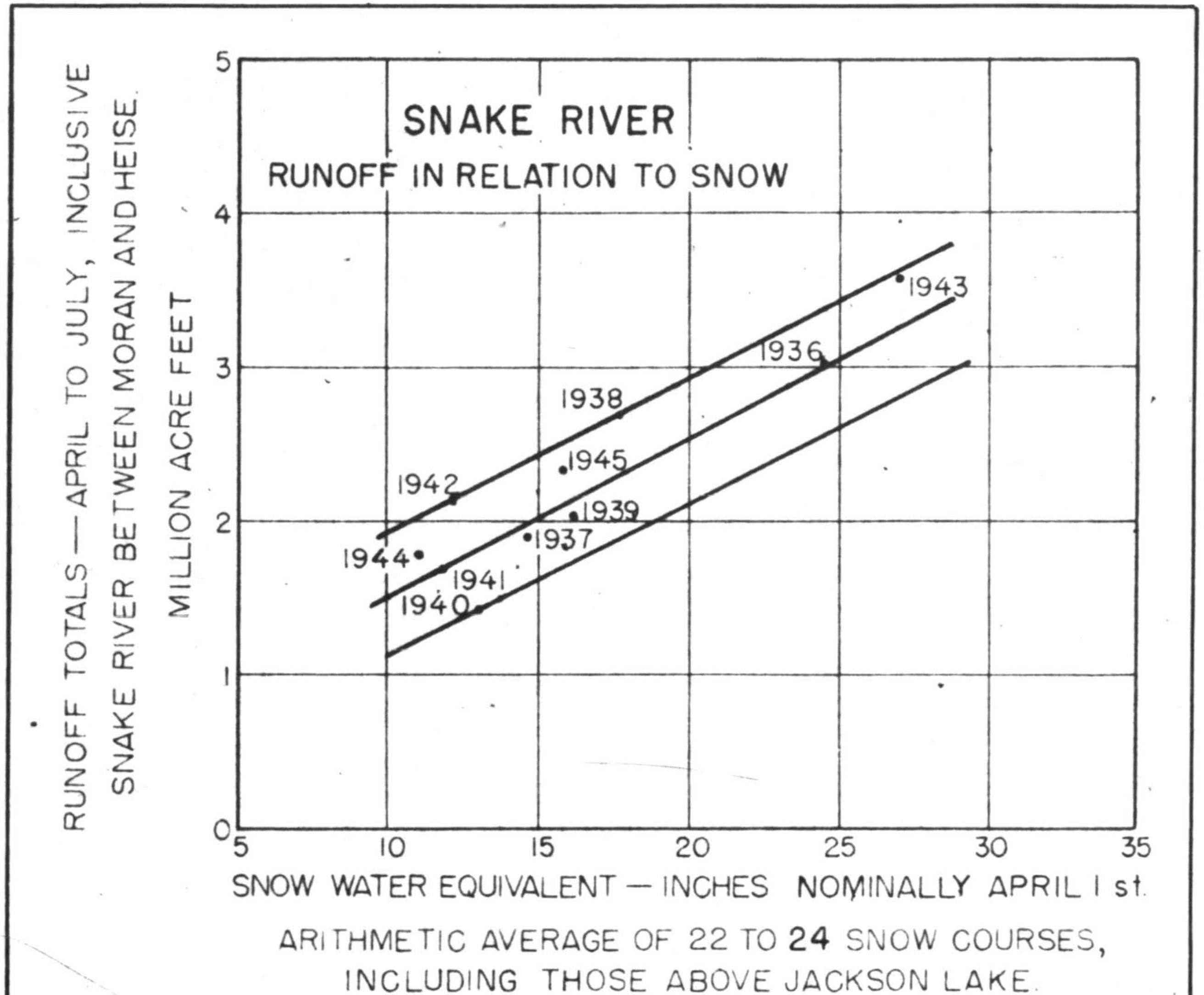


FIGURE 11.

FIG. 11.-Forecast chart - Snake River between Jackson Lake and Heise - based upon arithmetic averages

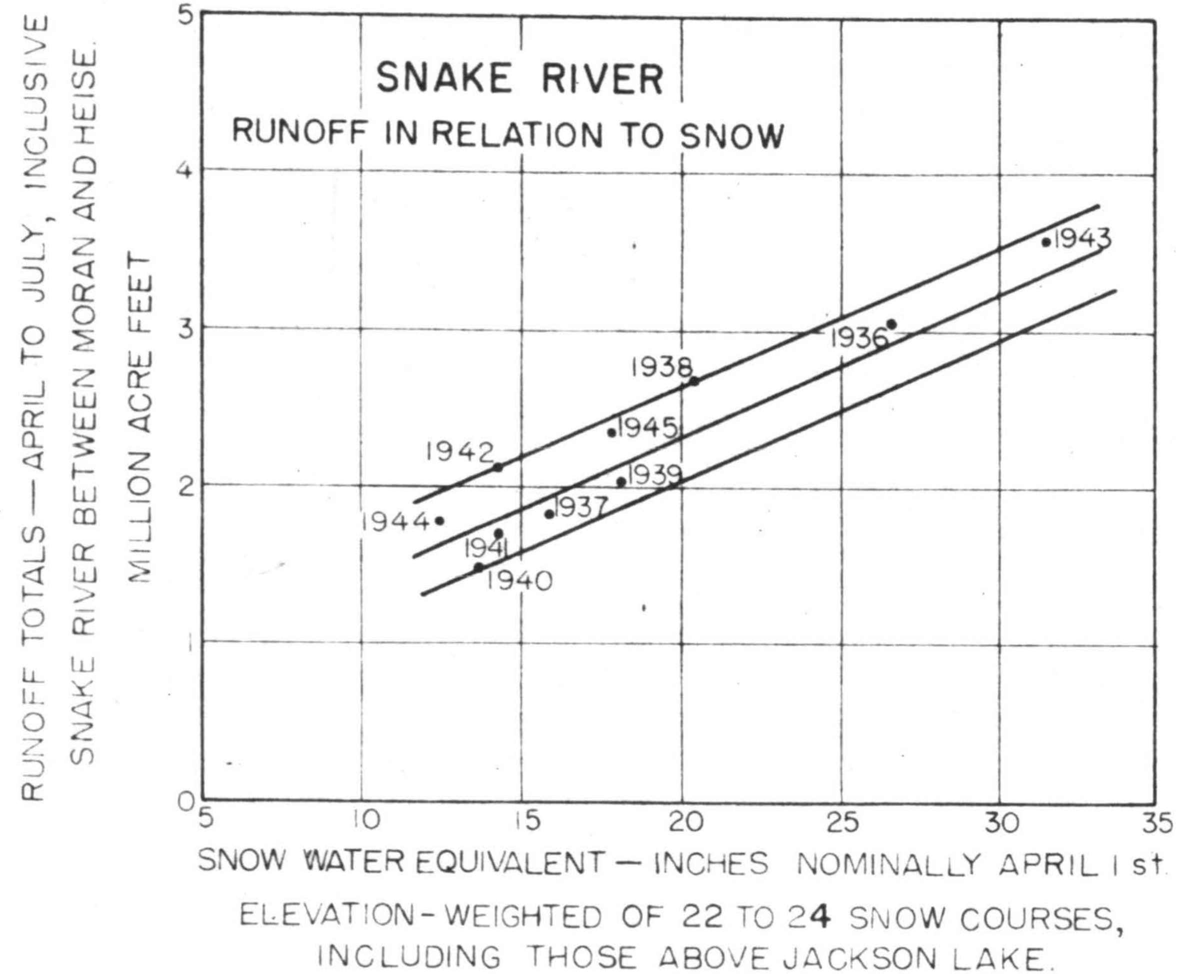


FIGURE 12.

FIG. 12.-Forecast chart - Snake River between Jackson Lake and Heise - based on elevation-weighted averages

Table 9.--PERCENTAGE OF SNOW WATER APPEARING AS RUNOFF

SNAKE RIVER ABOVE JACKSON LAKE, WYOMING

As of April 1

Year	April to July Runoff (A.F.)	Inches Depth Equivalent of Runoff	Elevation Weighted Snow Water Equivalent Inches	Percentage of Snow Appearing as Runoff
1919	455,870	10.5	23.1	45.5
1920	725,370	16.7	32.8	50.9
1921	792,440	18.2	31.8	57.2
1922	739,810	17.0	32.0	53.1
1923	710,290	16.3	30.4	53.6
1924	455,730	10.5	24.0	43.8
1925	1,003,620	23.1	39.5	58.5
1926	538,680	12.4	24.2	51.2
1927	1,082,810	24.9	52.5	47.4
1928	990,820	22.8	37.9	60.2
1929	614,650	14.1	30.5	46.2
1930	560,650	12.9	25.1	51.4
1931	382,160	8.8	12.4	71.0
1932	757,290	17.4	35.1	49.6
1933	646,410	14.9	31.5	47.3
1934	455,370	10.5	21.1	49.8
1935	701,750	16.1	27.6	58.3
1936	823,310	18.9	30.7	61.6
1937	590,890	13.6	23.2	58.6
1938	869,230	20.0	28.6	69.9
1939	642,600	14.8	28.2	52.5
1940	591,990	13.6	19.2	70.8

Table 9.--PERCENTAGE OF SNOW WATER APPEARING AS RUNOFF (CONTINUED)

SNAKE RIVER ABOVE JACKSON LAKE, WYOMING

As of April 1

Year	April to July Runoff (A.F.)	Inches Depth Equivalent of Runoff	Elevation Weighted Snow Water Equivalent Inches	Percentage of Snow Appearing as Runoff
1941	528,860	12.2	17.0	71.8
1942	631,340	14.5	19.1	75.9
1943	1,095,010	25.2	40.1	62.8
1944	566,060	13.0	17.7	73.4
1945	657,110	15.1	24.5	61.6
Average	689,264	15.9	28.1	57.6

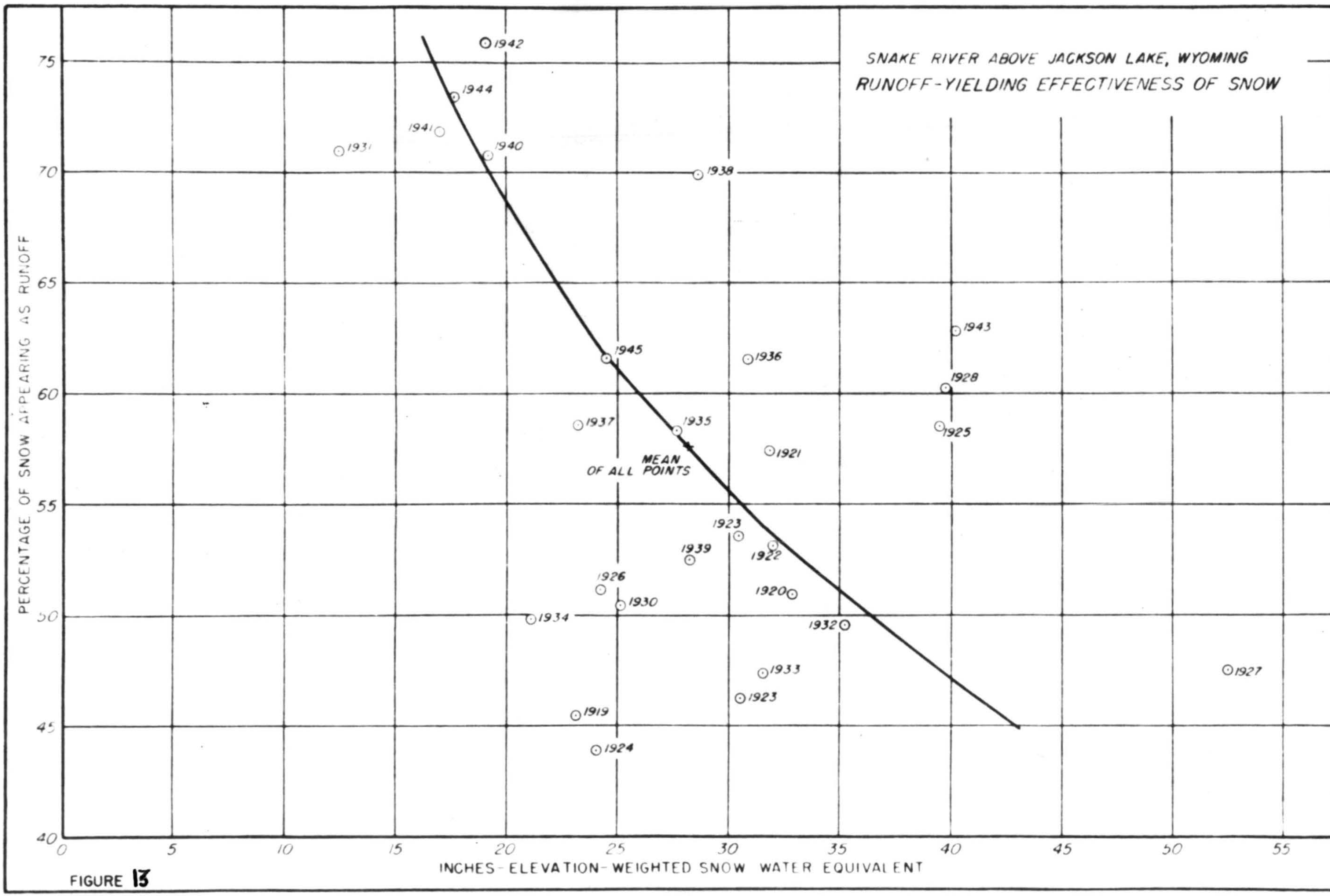


FIG. 13.-Runoff-yielding effectiveness of snow - Snake River above Jackson Lake, Wyoming

in terms of total drainage basin storage, during small runoff-volume yielding years, it was subjected to less loss and, therefore, the runoff-yielding effectiveness of the snow was greater than during large runoff-volume yielding years.

Differences among storage-elevation curves as shown in Figures 5 and 6, may serve to explain why many efforts at more precise statistical correlation analyses of data from individual snow courses have not yielded as promising results as is ordinarily expected from such analytical techniques. This may be due, in part, to the observation that lower elevation-centered snow-packs are known to result either in early snow melts, or, if persistent, in rapid rates of melt producing high rates of runoff.

<u>Conversion of snow-course layouts to the west-wide system</u>

The snow survey records above Jackson Lake, Wyoming, are unusual not only in the length of their record, but also in their completeness. They were first established and later maintained and surveyed by the Bureau of Reclamation. Surveys are still performed by the Bureau of Reclamation. In 1936, the snow course system was incorporated into the West-wide system of snow surveys coordinated by the Division of Irrigation of the Soil Conservation Service, at which time the snow courses were staked out in the standard manner.

Figures 9 and 10 present two sets of mean and upper and lower enveloping lines. The solid lines are for the period beginning with 1936, when the snow courses were incorporated into the West-wide system. The broken lines are for the period of record, beginning with 1919. Only the accumulation of records in the future can disclose which of these two sets of lines most nearly reflects the relationship of snow-water equivalent in storage to runoff in the drainage basin of the Snake River above Jackson Lake, Wyoming.

Statistical analysis of the results of this investigation

A discussion of pertinent statistical concepts was presented in Chapter V. Additional discussion is found in the Appendix, together with Tables 10 and 11, correlation analysis work sheets. Correlation coefficients were not calculated for the forecasts for the Snake River between Jackson Lake and Heise, because of the small number of years of record of snow surveys in that portion of the drainage basin.

The correlation coefficient for the arithmetic average-based forecast for the Snake River above Jackson Lake was computed in Table 10 with the result:

$$r = 0.760 \pm 0.086$$

The elevation-weighted snow-water equivalent-based forecast showed a correlation coefficient of:

$$r = 0.824 \pm 0.066$$

The improvement in the correlation between snow and runoff effected by the elevation-weighting procedure is shown by the increase in the value of the correlation coefficient and reduction of the standard deviation. The results indicate a practically significant degree of correlation of the elevation-weighted snow-water equivalent-based forecast for multiple-purpose reservoir operation. The forecast can be expressed in the following equation derived from table 11:

$$Y = 154.3 + 19.2\,X$$

in which: Y is the April to July, inclusive, inflow to Jackson Lake, in units of 1000 acre-feet; X is the elevation-weighted snow-water equivalent based upon 9 snow courses in the watershed above Jackson Lake, Wyoming, expressed in inches, as of the first of April.

Chapter VII

SUMMARY AND RECOMMENDATIONS

Summary

A method is presented for seasonal water-yield forecast derivation based upon snow survey data. The method takes into account snow-water equivalent by area-elevation zones, and interpolates derived snow-water equivalents for higher altitudes and for other portions of a watershed not actually sampled by snow courses. The seasonal water yield forecast derived by this method for the Upper Snake River in Wyoming, above Jackson Lake reservoir, has a correlation coefficient r of 0.824 ± 0.066, which indicates a practically significant degree of correlation for multiple-purpose reservoir operation.

General recommendations

Recent trends in seasonal water yield forecasting indicate the potential value of multiple-correlation analyses for forecast computation. Because it is known that the spring season's flows are influenced by numerous factors, discussed previously in this thesis, it appears logical to introduce values which could serve as representatives of otherwise unrecognized but possibly important factors in affecting seasonal yield. Thus, total autumn precipitation or departures of autumn precipitation from the normal may indicate the soil moisture and ground water deficiencies or surpluses and therefore foreshadow the runoff-yielding effectiveness of the subsequent winter's snowfall. Flow of rivers in the autumn may likewise serve to indicate potential trends and thus be of value in improving the accuracy of a forecast. Temperatures during the autumn, winter, and spring seasons, up to the dates of computation of a forecast, have been observed to bear an influence, but the meager data available on temperatures as they occurred often precludes critical analyses, chiefly because the temperature records commonly available are of daily maxima and minima. Hourly temperatures are needed to evaluate more precisely the heat factor, especially during the snow-melt period. The introduction of wind, when records become available, should improve the accuracy of a seasonal water yield forecast. Data on the position and rates of fluctuation of ground-water levels should, likewise, contribute to the accuracy of seasonal water-yield forecasts. The unfortunate dearth of the necessary meteorologic and hydrologic data prevents the more general application of potentially valuable relationships at the present time. Multiple-correlation statistical analysis should be very fruitful, since it makes possible the calculation of the net effect of the interaction of several factors operative in influencing seasonal water yield.

By far the greatest fraction of the cost of performing a snow survey is that expended on travel time to and from a snow course. Where present courses are located at high altitudes, additional courses could be surveyed at low and intermediate altitudes at very slight increased costs. It should be possible, when establishing or expanding a snow course network, to so locate the courses as to have them distributed according to elevation classes and snow accumulation zones, so that a simple arithmetic average would yield a properly weighted watershed storage average.

Recommendations with reference to the Upper Snake River

A multiple-correlation analysis of the relative weight of the various elevation zones may be of interest. However, the calculation of a forecast using the elevation-weighted snow-water equivalents, with autumn and spring rainfall, and with autumn, winter, and spring temperatures, up to the date of the forecast, should yield some interesting improvements. Autumn run-off of the Upper Snake River may prove to be of importance in influencing the spring season's water yield. The pursuit of the ultimate in a forecast is a never-ending quest, especially because interrelations may change with continuing accumulation of records.

A P P E N D I X

APPENDIX

Pertinent statistical considerations

General statistical considerations underlying any sampling procedure are found in numerous text-books on statistics, among which are references (40) and (42). The concept of sampling is that by evaluating a sample out of a universe, it is possible to acquire, within limits, some knowledge of the character of the universe. The ultimate degree of knowledge of the universe would be to evaluate every individual in the universe. This may not be justifiable for the purpose, or practical because of physical or financial limitations. Therefore, samples are taken and the characteristics of the universe are estimated from the samples. The advanced application of theories of sampling to snow surveys is remote, since the size of the sample taken at a snow course is too small to justify the name. For example, as has been discussed previously, only one five and three quarters billionth of the Upper Snake River above Jackson Lake drainage basin is actually sampled by the combined snow survey network.

Snow courses are indices of conditions on the watershed, rather than samples of stored water equivalent. It is not necessary that some item be a truly representative sample of a universe, if it bears some undiscernable but definite relationship to the behavior of the universe. With reference to snow courses, experience has shown that they are of value for forecasting seasonal water yield within certain limits of precision for practical purposes. The objective of a forecast is to ascertain a correlation of factor or factors with a desired dependent variable and to evaluate the strength of this correlation with reference to forecasting the dependent variable.

Work sheets for multiple correlation analyses

The following tables (10) and (11) are work sheets for a multiple-correlation analysis of the snow-water equivalent of the current and the preceding year's snow surveys in relation to the current year's seasonal water yield and a work sheet for the computation of the coefficient of correlation for the arithmetic-average based snow-water equivalent in relation to seasonal water yield.

The multiple correlation analysis in Table (11) was performed using the Doolittle system as modified by Ford (19). An analysis was made to ascertain whether or not there was an effect of the preceding year's snowfall upon the current year's runoff. This analysis

Table 10. Snake River above Jackson Lake, Wyoming.

Arithmetic Average Correlation (WUG - 10-29-48) ✓

Year	Snow Water Equivalent Arithmetic Average Inches x_2	Runoff April-July, Incl. 1000 A.F. x_1	$(x_2)^2$	$(x_1)^2$	$x_1 x_2$	Σx
1920	21.5	725.4	462.25		15,596.10	746.9
1921	20.6	792.4	424.36		16,323.44	813.0
1922	22.0	739.8	484.00		16,275.60	761.8
1923	20.7	710.3	428.49		14,703.21	731.0
1924	15.8	455.7	249.64		7,200.06	471.5
1925	25.9	1003.6	670.81		25,993.24	1029.5
1926	16.6	538.7	275.56		8942.42	555.3
1927	33.0	1082.8	1089.00		35,732.40	1115.8
1928	23.8	990.8	566.44		23,581.04	1014.6
1929	20.2	614.6	408.04		12,414.92	634.8
1930	16.8	560.6	282.24		9,418.08	577.4
1931	8.3	382.2	68.89		3,172.26	390.5
1932	24.0	757.3	576.00		18,175.20	781.3
1933	21.6	646.4	466.56		13,962.24	668.0
1934	15.3	455.4	234.09		6,967.62	470.7
1935	17.9	701.7	320.41		12,560.43	719.6
1936	29.9	823.3	894.01		24,616.67	853.2
1937	19.7	590.9	388.09		11,640.73	610.6
1938	22.5	869.2	506.25		19,557.00	891.7
1939	24.0	642.6	576.00		15,422.40	666.6
1940	18.5	592.0	342.25		10,952.00	610.5
1941	15.8	528.9	249.64		8,356.62	544.7
1942	16.6	631.3	275.56		10,479.58	647.9
1943	37.5	1095.0	1406.25		41,062.50	1132.5
1944	13.5	566.1	182.25		7,642.35	579.6
1945	18.7	657.1	349.69		12,287.77	675.8
Total Mean	540.7 20.8	18,154.1 698.23	12,176.77	13,569,779.95	403,035.88	18694.8 18694.8

$$r = \frac{\Sigma(x_2 x_1) - n M_2 M_1}{\sqrt{[\Sigma(x_2^2) - nM_2^2][\Sigma(x_1^2) - nM_1^2]}}$$

$$r = \frac{403,035.88 - 26 \times 698.23 \times 20.8}{\sqrt{[12,176.77 - 26 \times (20.8)^2][13,569,779.95 - 26 \times (698.23)^2]}}$$

$$r = \frac{403,035.88 - 377,602.78}{\sqrt{(12,176.77 - 11,248.64)(13,569,779.55 - 12,675,126.57}}$$

$$r = \frac{25,433.10}{\sqrt{928.13 \times 1,014,126.57}} = \frac{25433.10}{\sqrt{941,241,293}}$$

$$r = \frac{25,433}{33,333} = 0.760$$

$$\sigma_{r_{xy}} = \frac{1-r^2}{\sqrt{n-2}} = \frac{1-0.578}{\sqrt{24}} = \frac{.422}{4.9} = 0.086$$

Coefficient of Correlation, $r = 0.760 \pm 0.086$

Table 11.

*Snake River above Jackson Lake, Wyoming.

Table 1.

Year	Elevation-Weighted Snow Water Equivalent Inches: Current x_2	Preceding x_3	Runoff April-July inc. 1000 A.F. x_1	Σx	x_2^2	x_2x_3	x_2x_1	$x_2\Sigma x$ ✓	x_3^2	x_3x_1	$x_3\Sigma x$ ✓	x_1^2	$x_1\Sigma x$ ✓
1919	23.1												
1920	32.8	23.1	725.4	781.3	1075.84	757.68	23,793.12	25,626.64	533.61	16,756.74	18,048.13	526,205.16	566,755.02
1921	31.8	32.8	792.4	857.0	1011.24	1043.04	25,198.32	27,252.60	1075.84	25,990.72	28,109.60	627,897.76	679,086.80
1922	32.0	31.8	739.8	803.6	1024.00	1017.60	23,673.60	25,715.20	1011.24	23,525.64	25,554.48	547,304.04	594,503.28
1923	30.4	32.0	710.3	772.7	924.16	972.80	21,593.12	23,490.08	1024.00	22,729.60	24,726.40	504,526.09	548,848.31
1924	24.0	30.4	455.7	510.1	576.00	729.60	10,936.80	12,242.40	924.16	13,853.28	15,507.04	207,662.49	232,452.57
1925	39.5	24.0	1003.6	1067.1	1560.25	948.00	39,642.20	42,150.45	576.00	24,086.40	25,610.40	1,007,212.96	1,070,941.56
1926	24.2	39.5	538.7	602.4	585.64	955.90	13,036.54	14,578.08	1560.25	21,278.65	23,794.80	290,197.69	324,512.88
1927	52.5	24.2	1082.8	1159.5	2756.25	1270.50	56,847.00	60,873.75	585.64	26,203.76	28,059.90	1,172,455.84	1,255,506.60
1928	37.9	52.5	990.8	1081.2	1436.41	1989.75	37,551.32	40,977.48	2756.25	52,017.00	56,763.00	981,684.64	1,071,252.96
1929	30.5	37.9	614.6	683.0	930.25	1155.95	18,745.30	20,831.50	1436.41	23,293.34	25,885.70	377,733.16	419,771.80
1930	25.1	30.5	560.6	616.2	630.01	765.55	14,071.06	15,466.62	930.25	17,098.30	18,794.10	314,272.36	345,441.72
1931	12.4	25.1	382.2	419.7	153.76	311.24	4,739.28	5,204.28	630.01	9,593.22	10,534.47	146,076.84	160,409.34
1932	35.1	12.4	757.3	804.8	1232.01	435.24	26,581.23	28,248.48	153.76	9,390.52	9,979.52	573,503.29	609,475.04
1933	31.5	35.1	646.4	713.0	992.25	1105.65	20,361.60	22,459.50	1232.01	22,688.64	25,026.30	417,832.96	460,883.20
1934	21.1	31.5	455.4	508.0	445.21	664.65	9,608.94	10,718.80	992.25	14,345.10	16,002.00	207,389.16	231,343.20
1935	27.6	21.1	701.7	750.4	761.76	582.36	19,366.92	20,711.04	445.21	14,805.87	15,833.44	492,382.89	526,555.68
1936	30.7	27.6	823.3	881.6	942.49	847.32	25,275.31	27,065.12	761.76	22,723.08	24,332.16	677,822.89	725,821.28
1937	23.2	30.7	590.9	644.8	538.24	712.24	13,708.88	14,959.36	942.49	18,140.63	19,795.36	349,162.81	381,012.32
1938	28.6	23.2	869.2	921.0	817.96	663.52	24,859.12	26,340.60	538.24	20,165.44	21,367.20	755,508.64	800,533.20
1939	28.2	28.6	642.6	699.4	795.24	806.52	18,121.32	19,723.08	817.96	18,378.36	20,002.84	412,934.76	449,434.44
1940	19.2	28.2	592.0	639.4	368.64	541.44	11,366.40	12,276.48	795.24	16,694.40	18,031.08	350,464.00	378,524.80
1941	17.0	19.2	528.9	565.1	289.00	326.40	8,991.30	9,606.70	368.64	10,154.88	10,849.92	279,735.21	298,881.59
1942	19.1	17.0	631.3	667.4	364.81	324.70	12,057.83	12,747.34	289.00	10,732.10	11,345.80	398,539.69	421,329.62
1943	40.1	19.1	1095.0	1154.2	1608.01	765.91	43,909.50	46,283.42	364.81	20,914.50	22,045.22	1,199,025.00	1,263,849.00
1944	17.7	40.1	566.1	623.9	313.29	709.77	10,019.97	11,043.03	1608.01	22,700.61	25,018.39	320,469.21	353,189.79
1945	24.5	17.7	657.1	699.3	600.25	433.65	16,098.95	17,132.85	313.29	11,630.67	12,377.61	431,780.41	459,510.03
Total	736.7	735.3	18,154.1	19,626.14 / 19626.1	22,732.97	20736.88	550,154.53	553,724.88 (553,724.88)	22,666.28	509,891.45	553,394.86 (553,394.76)	13,563,773.95	14,629,826.93 (14,629,825.93)
Mean	28.33	28.28	698.23	754.85 / 754.84									

Table 2.

Product Sums corrected to departures from Means with check.

	x_2	x_3	x_1	Σx
Sum	736.7	735.3	18,154.1	19626.1
Mean	28.33	28.28	698.23	754.84
	(736.58)	(735.28)	(18,152.98)	
Extension with x_2	22732.97	20,836.98	550,154.53	553,724.88
Correction	20,867.31	20,830.48	514,302.25	556,000.05
Extension with x_2	1,865.66	6.50	35,852.28	37,724.83
Extension with x_3		22,666.33	509,891.45	553,394.76
Correction		20,793.72	513,394.55	555,018.75
Extension with x_3		+1,872.61	-3,503.10	-1623.99
Extension with x_1			13,563,773.95	14,629,826.93
Correction			12,675,653.45	13,703,350.26
Extension with x_1			894,126.50	926,476.67

$$r=\frac{\Sigma(x_1x_2)-nM_2M_1}{\sqrt{[\Sigma(x_2)^2-nM_2^2][\Sigma(x_1)^2-nM_1^2]}}$$

$$r=\frac{35,852.17}{43,500.00}=0.824$$

$$\sigma_{r_{xy}}=\frac{1-r^2}{\sqrt{n-2}}=\frac{1-.679}{4.9}$$

$$\sigma=\frac{0.321}{4.9}=0.066$$

Table 3.

Regression equations and Solution with Check

	x_2	x_3	x_1	Σx
Eq. 1	1,865.66	6.50	35,852.28	37,724.83
Eq. 2	6.50	1872.61	-3,503.10	-1,623.99
I	1865.66	6.50	35,852.28	37,724.83
I'	-1.0000	-.0035	-19.2169	-20.2206
II	6.50	1872.61	-3503.10	-1,623.99
(-.0035) × I	-6.50	-.0227	-125.4830	-132.0370
Σ_2	0	+1,872.59	-3,628.58	-1,756.03
III'		-1.000	+1.9377	-0.9377

Table 4

	x_2	x_3	Σx	x_1	Regression Coefficient	
	b_2	b_3				
		-1.9377				
III'		-1.000		+1.9377	-1.9377	x_3
					Out	
I'	-1.0000	-.0035		-19.2169		
		+.0068	+.0068	+.0068		
				-19.2101	+19.2101	x_2

Simple Correlation Recomputation.

Table 3'

	x_2	x_1
Eq. 1	1865.66	35852.28

$b_2 = 19.2$

$28.33 \times 19.20 + a = 698.23$

$a = 698.23 - 543.94 = 154.29$

$y = 154.29 + 19.20x$

$$\left(\begin{array}{c}\text{April-July inclusive}\\ \text{Runoff* in}\\ \text{1000 A.F.}\end{array}\right) = 154.29 + 19.20\left(\text{Elevation-Weighted Snow Water Equivalent in Inches.}\right)$$

based upon snow courses within the drainage basin.

$r = 0.824 \pm 0.066$

*Snake River, corrected for changes in Storage at Jackson Lake

P.M.F.-W.U.G.
10-26-48

disclosed a negative correlation between the current year's runoff and past year's snow, with regression coefficients of -1.94 for the preceding year's snow and + 19.21 for the current year's snow.

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