PREDICTION OF WATER YIELD IN HIGH MOUNTAIN WATERSHEDS BASED ON PHYSIOGRAPHY

By

Robert W. Julian, Vujica Yevjevich
and
Hubert J. Morel-Seytoux

August 1967

HYDROLOGY PAPERS
COLORADO STATE UNIVERSITY
Fort Collins, Colorado

22

PREDICTION OF WATER YIELD IN HIGH MOUNTAIN WATERSHEDS BASED ON PHYSIOGRAPHY

by

Robert W. Julian, Vujica Yevjevich
and
Hubert J. Morel-Seytoux

HYDROLOGY PAPERS
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

August 1967 No. 22

ACKNOWLEDGMENTS

The present paper is based primarily upon Mr. Robert W. Julian's M. S. thesis in the Department of Civil Engineering, Colorado State University: "Water Yield - Physiographic Relationship in Colorado Headwaters." The work was supported by the U. S. Bureau of Reclamation, whose help is gratefully acknowledged.

RELATION OF HYDROLOGY PAPER NO. 22 TO RESEARCH PROGRAM: "HYDROLOGY OF WEATHER MODIFICATION"

The present study is part of a more comprehensive project which has as one of its objectives the determination of criteria, methods and procedures to be used in selecting drainage basins suitable for atmospheric water resources programs.

The forthcoming era of weather modification will change the traditional relation between atmospheric hydrology and surface water hydrology which was taken to mean, in many instances, a statistically determined relation between rainfall and runoff. Until data samples from the new populations of precipitation and runoff under weather modification conditions are obtained in sufficient quantities, water resources analysts seeking the reclamation of atmospheric water on an optimal regional basis will have to take a new and broader look at the relation between atmospheric hydrology and surface water hydrology.

The present study is still very traditional. The study of the hydrology of weather modification has just begun.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

A statistical method is presented that permits the estimation of yield of high mountain watersheds in terms of physiographic characteristics evaluated from maps.

The method is advantageous because it does not require the knowledge of the climatic or hydrologic characteristics of the basin or of the region. The method is, however, limited to regions of reasonable climatic and hydrologic homogeneity.

The applicability of the method is illustrated for several regions in the Upper Colorado River Basin. A coefficient of determination as high as 77 percent is obtained in the best case. In the worst result the coefficient falls below 50 percent.

The estimate of specific yield is valuable for many applications. It provides, in particular, a means of deciding upon the suitability of basins to weather modification programs.

PREDICTION OF WATER YIELD IN HIGH MOUNTAIN WATERSHEDS BASED ON PHYSIOGRAPHY

by Robert W. Julian, Vujica Yevjevich, and Hubert J. Morel-Seytoux

CHAPTER I

INTRODUCTION

1. Water Resources Planning. The increasing demand, and in some parts of the world, the desperate need for water has almost inevitably led men in positions of responsibility to be concerned with the problem of water shortage in particular and of water resources in general [1]. Planning of water resources had, until the recent past, been confined, primarily to the task of redistribution in space and time of the naturally available water or to the task of better utilization and reutilization. It is only recently that the idea [2] of increasing the water supply beyond the natural yield of the hydrologic cycle has started to be realized. At present, at least two engineered means of increasing the water supply seem to hold promise for the near future: ocean water desalination [3] and induced cloud water precipitation [4].

Once the feasibility of a new process has been demonstrated in the laboratory, there remains a multitude of technological barriers that must be overcome before the process can mature into large scale operation. The initial breakthrough opens a scientific era, which in turn opens a technological era, which in turn leads to an economic era. Emphasis changes, but each new discipline brought into play must assimilate the applicable findings of other disciplines and accept the constraints that result. Present-day problems become more and more multidisciplinary and complex [5]. Such problems cannot be solved at once in their entirety, but rather in a piecemeal fashion.

The present study is only a fragmentary answer to one among a myriad of technological problems that arise in the experimental and operational phases of the conservation and use of atmospheric water. The value of the study is probably best comprehended when viewed in proper perspective against the background of the broader problem of weather modification planning.

2. Study in Perspective. Following the discovery by Schaefer [6] in 1946 of the potentiality of inducing the Bergeron ice-crystal process in naturally subcooled clouds [7], great hopes of weather control have developed.

However, for various technological reasons [7], particular attention has been given to seeding of clouds in air masses subjected to an orographic lift. The Rocky Mountains form an admirable natural barrier in the path of the air masses, which makes the region an excellent ground for experimentation [8], notwithstanding the fact that within the area lie the headwaters of rivers that supply the water-short West. Whether in the experimental or the large-scale operational stage of the program, a site for the operation must be selected. Simply put, the question to be answered at the time of decision is: What makes a basin more suitable for a weather modification operation than another?

Clearly, one needs a yardstick or criterion by which to measure the suitability of one basin relative to others. Ideally, the criterion should be objective and simple. It should also be meaningfully amenable to some simple arithmetic operations. For example, let us suppose the choice is restricted to three basins A, B and C. If, according to the criterion, A is more suitable than either B or C, then A gets rank 1. If B is more suitable than C, it gets rank 2, and C, the least suitable, gets rank 3. One can test the relative merit of two basins by comparing their ranking index. However, one cannot test whether A is more suitable than the combination of B and C. If the numerical value derived from the criterion and attached to a basin does not permit comparison of this basin with a combination of others, the ranking variable is called ordinal [9]. If it does, it is called cardinal. To the extent that the original question: "What makes one basin more suitable than another?" may be modified into the following: "What makes one group of basins more suitable than another group?", it is important that the ranking variable should be cardinal.

In summary, the criterion should be objective and simple. The ranking variable derived from the criterion and associated with the basin should be cardinal. In addition, that variable should be readily available or of easy calculation. It is not sufficient to state that the criterion for suitability of a basin to weather modification is a high specific yield, that is a high water yield per unit area of basin. One must also be able to determine this yield even when the basin is not gaged. The central objective of the present study is to provide a means of estimating the specific yield when streamflow records are not available.

3. Present Study. The determination of the specific yield for ungaged mountainous basins is the objective of this study. The technique by which the objective is attained is statistical. A correlation between specific yield and physiography is established, based on existing records. For basins which are ungaged, the correlation equation becomes an estimator [10] of the unknown yield. Though the prediction equations were developed in the context of weather modification planning, their value extends beyond atmospheric hydrology.

CHAPTER II

CHOICE OF TYPE OF APPROACH

The suitability of any basin to an atmospheric water resources program depends upon many variables. It will depend, in particular, upon the naturally prevailing meteorological conditions, the type and state of weather modification technology, the ability of the basin to retain precipitation and transform it into runoff, and upon the marginal worth of the increased water availability. In the present study only the technical factors are considered.

Approaches in the domain of hydrology can often be summarily reduced to two broad categories: deterministic or statistical. The reason for the choice between the two may best be understood by reviewing first, in a symbolic manner, the relation between the various parameters.

1. Relation Between Yield, Physiography and Meteorological Factors Over a Basin. Experience and scientific knowledge both point to the fact that the meteorological factors over a basin and the physiographic characteristics of a basin are not independent (e.g. orographic lift). Symbolically, one may write:

$$M = f_1 (P, M_o) \qquad (1)$$

where M represents the set of all relevant meteorological variables and P represents the corresponding set for physiography. M_o is the set of initial meteorological variables or, in other words, the variables that characterize the air masses as they reach the basin and before they are affected by the basin, for example, the relative humidity [11]. The relationship between M and P may be affected by man's intervention so that one can write more generally:

$$M = f_2 (P, M_o, I) \qquad (2)$$

where I is a set of variables characteristic of man's intervention. If man's intervention is only local it can be assumed that M_o is independent of I. However, the converse is not strictly true because for some weather modification operations intervention is attempted only under favorable conditions [12] and consequently:

$$M = f_2 \left\{P, M_o, I(Mo)\right\} \qquad (3)$$

However, it will serve adequately the purpose to retain eq. (2).

Without a priori justification one can simply state that the specific yield of a basin is a function of atmospheric conditions, physiography and man's intervention, symbolically:

$$q = Q(M, P, M_o, I) \qquad (4)$$

Equation (4) is a condensed way of expressing the following few facts (among others). The air masses reach the basin at a certain speed with a given relative humidity (M_o). As the air rises over the slope of the mountain (P), it tends to cool. Water may reach the lifting condensation level (M), a level which depends upon the equivalent potential temperature of the incoming air (M_o) [11]. Later on, the air may have risen enough to reach a nucleation level [13] which may trigger precipitation. If the air contains relatively few nuclei (M_o), man may decide to intervene and seed the cloud with additional nuclei (I). As a result of precipitation (M) less, say, evaporation (M) and infiltration (P), runoff is established (q). Of course, one would like to know the exact functional dependence of q on the sets of parameters M_o, M, P and I in eq. (4). The ranking variable of suitability of a basin may not be the specific yield but it will certainly involve it in a more or less direct and weighted form. Thus, if the form of eq. (4) was exactly known, the definition of a criterion and its calculation would be quite simple.

Even though the functional forms of eqs. (4) and (2) are not known, the theoretical possibility exists of eliminating the set of parameters M between the two. Thus:

$$q = Q\left\{f(P, M_o, I), P, M_o, I\right\} = R(P, M_o, I). \qquad (5)$$

Ideally, one would like to know the resultant function R exactly. At any rate, eq. (5) shows that q can be evaluated in terms of the P alone and not the M, provided the region is meteorologically homogeneous and man does not interfere.

The choice of approach can now be seen in the light of which functional forms among eqs. (2), (4), and (5) will be investigated. To clarify the form of eqs. (2) and (4), a primarily deterministic approach will be necessary and for eq. (5), a statistical one.

2. A Model for the Interaction Between Physiography, Meteorological Factors and Man's Intervention. Figure 1 shows an extremely simplified model of the precipitation process not necessarily valid at every point but grossly acceptable over a uniformly rising basin of angle θ. T_n is the temperature of nucleation and H_n the corresponding height. Based on a limited sample of data, [14], this temperature, T_n, seems to fluctuate between -13°C and -25°C whereas the height of nucleation may vary between 14,000 and 18,000 ft. MSL. The height of nucleation over the basin is a function of the temperature of the incoming air at gage elevation and of the relative humidity. The cloud top height, H_t, is probably to some degree also a function of these parameters among others. It is, however, assumed for the time being that H_t and H_n are independent parameters. We shall assume that $H_t < H_n$, or, in other words, that nucleation occurs over the basin and

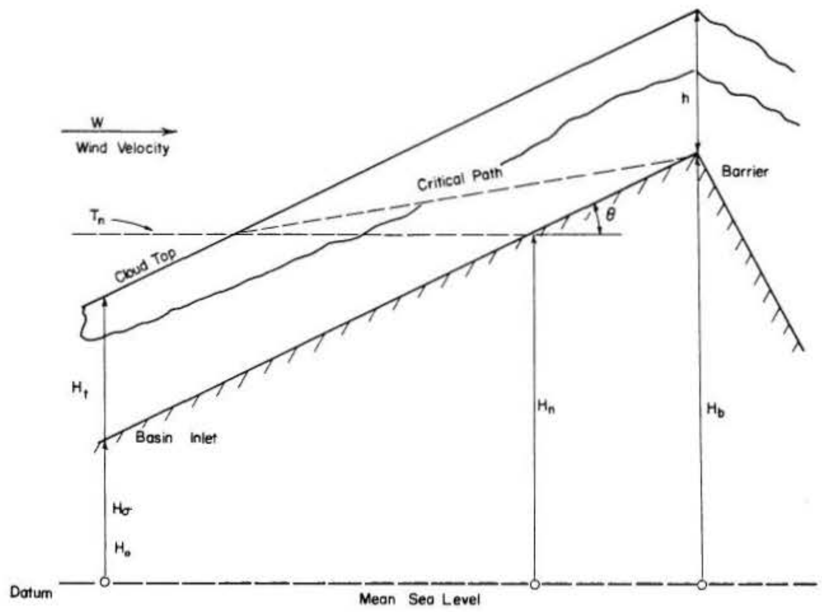

Fig. 1 Orographic Lift Precipitation Model

not before reaching it. With these assumptions, it becomes a simple matter to calculate the critical value of H_n beyond which little precipitation can be expected:

$$H_n^c = H_b - \left(\frac{W \tan\theta}{V_f} - 1\right)(H_t - H_o) \tag{6}$$

where H_b is the basin barrier height, W is the horizontal component of the wind velocity, and V_f is a mean fall velocity of ice crystals (roughly 500 meters/1000 seconds [15]). Let M^* be the variable obtained from the equation:

$$M^* = 1/2 \left\{ (H_n^c - H_n) + \left| H_n^c - H_n \right| \right\} \tag{7}$$

M^* represents a measure of the amount of precipitation per unit basin area to be expected by orographic lift and eqs. (6) and (7) combined give an explicit, though crude, form of eq. (2). From eq. (7) one can easily, at least in theory, determine the basins which will provide the greatest increase in specific precipitation under cloud seeding operations. An additional assumption is still necessary: that the effectiveness of cloud seeding is entirely in the lowering of the nucleation temperature to about -10°C. (Recent results [16] show that seeding has other effects.) The ranking variable of suitability for a basin could be defined by the expression:

$$\left(\frac{d M^*}{d H_n}\right) \cdot \left(\frac{d H_n}{d T_n}\right) \cdot \Delta T_n \tag{8}$$

Unfortunately, even such a simple model cannot be utilized at present. First the model would have to be checked, which requires the availability of local meteorological data for at least a few basins under truly orographic precipitation conditions. Second, even if the model was adequately checked, the use of eq. (8) to determine the rank of suitability of basins would require the knowledge of many additional local meteorological variables which are not measured and are difficult to reconstruct from other data. However, as more data are rapidly collected, the present difficulties may disappear in the near future. In the meanwhile, to obtain a criterion of suitability that is accessible, the elimination of the troublesome meteorological factors seems appropriate. For this reason, one may take a trial at the functional form of eq. (5).

3. A Statistical Approach to the Prediction Equation for Specific Yield. Under natural conditions one can attempt to approximate the functional form of eq. (5) by a multiple regression technique as data are available. Under natural conditions, eq. (5) simplifies to:

$$q = R_n(P, M_o) \tag{9}$$

because $I = I_o$ = constant and the variable I drops out. The meteorological factors vary considerably with time. However, over many years (say 25 years), one can define an average set of climatic factors $\overline{M}_o$. The time average transform of eq. (9) is then:

$$\overline{q} = R_n(P, \overline{M}_o) \tag{10}$$

where $\overline{q}$ is a N years -mean annual specific yield. If the region of concern is meteorologically homogeneous, eq. (10) further simplifies to

$$\overline{q} = R_{n,h}(P) \tag{11}$$

the value of M_o being a constant. Even in this simplest case only an approximation to $R_{n,h}$ is obtained. Even P must be approximated. Symbolically,

$$\overline{q} = \widehat{R}_{n,h}(\widehat{P}) \tag{12}$$

e.g., for a linear regression $\widehat{R}_{n,h}(\widehat{P}) = a + b\widehat{P}$. The constants a and b are obtained by a least squares technique using the data $\overline{q}_i$. The set $\widehat{P}$ consists of parameters such as mean elevation of basin, upper quartile elevation, rise, slope, etc. The coefficients of determination were encouraging but not wholly satisfactory. A possible explanation might lie in the nonhomogeneity of meteorological factors of the region. Therefore, an equation of the form

$$q = \widehat{R}_n(\widehat{P}, \widehat{M}_o) \tag{13}$$

was used where $\widehat{M}_o$ consisted of latitude and longitude. The resulting equations showed an improvement in the coefficient of determination. For some subregions the coefficient of determination is as high as 77 percent. It can be concluded that the statistical approach did provide a means of estimating the specific yield with reasonable accuracy.

But can one identify the specific yield with the ranking variable of suitability? This cannot be proven at present, but there are indications that the specific yield may be a reasonable approximation. It seems that among atmospheric scientists working in the field of weather modification there exists a consensus that the present technology is not sufficiently developed to induce precipitation above a small percentage (10 - 20%) of the natural occurrence [4, 7]. The consensus seems also to be that the perturbation introduced by man does not propagate beyond the narrowly localized region of operations. In other words, it can be assumed that operations in a basin will hardly affect the natural process in the neighborhood. Based on these opinions, one can formulate as a first approximation the following postulates:

a. The specific water yield of a basin is not affected by operations of weather modification over an adjoining basin (assuming, of course, that the operations of seeding can be accurately controlled in space), and

b. The increase in precipitation by cloud seeding is directly proportional to the basin's natural yield.

Inasmuch as statements a. and b. are reasonably true, specific yield is a reasonable approximation for the ranking variable and it has the previously described cardinal property. The considerable interest in weather modification makes the prediction of specific yield for mountainous basins based on physiography particularly timely and worthy. In the following chapters the detailed methodology, procedures and data assembly are described.

CHAPTER III

METHODOLOGY OF STATISTICAL APPROACH

1. Introduction. The main subject of this study is a development of prediction equations for small, high mountain river basins based on the physiographic characteristics of these river basins. The specific water yield is defined as the average flow rate of these basins for a long period, expressed in cubic feet per second per square mile. Small, high mountain river basins in the Rocky Mountain Region of Colorado, Wyoming, and Utah are used as an example of the type of prediction equations to be obtained, thus showing how accurate a prediction can be developed by this approach.

Although many middle or large size rivers are fairly well gaged in many regions, it is not practical to gage the upper reaches of mountain rivers in a comprehensive manner. Often there is little need for such information on a regional basis, but only at a specific location in order to evaluate a potential dam site, transmountain diversion, irrigation or water supply, or similar examples.

In recent years, the increasing demand for water, especially in arid and semi-arid regions, has spurred engineers to consider the utility of large scale atmospheric programs aimed at increasing river basin yields through weather modification techniques. This is particularly attractive in areas of high orographic effects on precipitation. Assuming that it is uneconomical to attempt weather modification in all basins, it becomes necessary to objectively appraise the relative merits of individual basins for that purpose. One criterion is the present specific water yield of basins; hence, the prediction of basin yields on a regional basin may be necessary in planning weather modification programs.

Due to the paucity of stream gages in the headwaters of rivers, it is desirable to be able to estimate specific yields of ungaged basins from the information of gaged basins. For the purposes of this paper, the mean annual specific yield, in units of cubic feet per second per square mile (c. f. s./mi^2), will be used as the only dependent variable.

Previous investigators [17, 18, 19] have shown that, in mountainous watersheds, orographically affected precipitation can be related to such physiographic factors as elevation, rise, and orientation. It follows that streamflow, having precipitation as its source of supply, must likewise be dependent upon physiographic factors. It is proposed in this paper that basin yield in reasonably homogenous and mountainous regions can be related to physiographic parameters, without passing through intermediate meteorologic and hydrologic processes.

2. Assumptions. The following three assumptions are made in this study:

(a) There exists, during the period of major precipitation and snow accumulation, a prevailing direction of moisture inflow over the mountain river basins of a region. It is also assumed that the prevailing wind patterns are modified to some extent by the local topography.

(b) The principal source of variation in moisture deposited over watersheds in climatologically homogeneous regions is due to orographic effects.

(c) The parameters affecting the runoff-rainfall relationship may be considered as approximately constant for reasonably homogeneous regions.

In mountainous watersheds, groundwater is normally of little significance since the extent of this medium is limited by the closeness of the bedrock to the surface. Evapotranspiration, however, is a significant quantity in the hydrologic balance of a watershed. Evapotranspiration is a function of temperature, wind, humidity, solar radiation, kind and extent of vegetation, and extent of evaporative surfaces. The last three factors do vary somewhat between watersheds, and an endeavor is made to minimize this error through appropriate physiographic parameters.

3. Selection of Physiographic Parameters. It is well established that precipitation increases with altitude up to a given height. Hence, those basins with relatively higher elevations would be expected to have higher specific water yields. In addition, because of the decrease in temperature with altitude, evaporation decreases with elevation, thus contributing to higher yields.

The rise in a basin reflects the orographic lift available. Larger values of this parameter should be indicative of higher values of yield. For those basins in which the air is more rapidly lifted, greater quantities of vapor are condensed in a given time or over a specified area. Consequently, basin slope (slope of air masses rise) would seem to be an important parameter. However, the best index of slope is not readily apparent, as the stream flow lines of an air mass passing over a barrier may not completely conform to the topography of the basin.

The elevation and configuration of the ridge line over which an air mass passes might be expected to have bearing on the amount of water deposited over the basin. The higher the mean elevation of the topographic barrier, the greater is the orographic lift available in the basin. A barrier with gaps permitting the passage of air masses around the higher portions of the ridge would be expected to have less orographic lift than that indicated by the mean barrier elevation. The variance of barrier elevation about the mean elevation may reflect this situation.

The orientation of a basin with respect to incoming solar radiation and prevailing wind direction during storms would be expected to have a bearing on the basin yield. As noted earlier, solar radiation is a factor affecting the evapotranspiration in a watershed. Basins oriented to the south receive the greatest amount of radiation and hence tend to have a greater potential for evapotranspiration. These basins would be expected to have relatively lower yields. Orientations deviating from the south are symmetrical with respect to the north-south axis, with a decrease in potential evapotranspiration as the orientation shifts towards the north. An additional factor in evapotranspiration is the extent of vegetal cover. Obviously, the more vegetation a watershed contains, the greater the potential for evapotranspiration and therefore reduction in yield.

Naturally, a basin oriented so as to face directly into the prevailing wind direction during storms will be expected to be more efficient in producing orographic precipitation. The phenomenon of a "rain shadow" on the leeward side of mountain ranges is well established. Although this implies relatively lower yields for leeward basins, such may not always be the case. For leeward basins with a high proportion of their area near the topographic barrier elevation, yields may compare closely with those of similar basins situated on the windward side of the barrier. This phenomenon can be explained by the carryover of precipitation formed by orographic lifting on the windward side of the barrier but with a trajectory such that it reaches the ground on the leeward side.

Another factor concerning storm paths and barriers is the location of a basin along the path of moisture inflow. In other words, is the basin located downwind from the moisture source, so that much of the moisture may have been depleted by passage over upwind barriers? One convenient way of expressing this factor is through the coordinates of the stream gage or basin mouth.

4. Independent Variables. For the purposes of this paper, the independent variables are divided into three groups - objectively selected variables, semi-objectively selected variables, and common variables.

a. Objectively selected variables. Hypsometric analysis, or the relation of a basin's horizontal cross-sectional area above a given elevation to this elevation, can give important information regarding the morphology of a basin. Once the hypsometric curve is constructed, the elevation above which lies a given percent of the total basin area may readily be determined. Hypsometric curves can form the basis for a number of variables, such as the median elevation of the basin, as well, as other significant elevations. The rise in a basin may be represented by the difference between two elevations such as those corresponding to the 5 and 95 percent areas or similar. The rise divided by the length represents the average slope of a basin. The elevation versus the area above it within a basin is approximately log-normally distributed. Therefore, the hypsometric curves can be linearized by plotting on log-probability paper, and two additional parameters may be obtained - geometric mean elevation and standard deviation about the mean elevation.

b. Semi-objectively selected variables. A quantitative representation of the elevation and configuration of the barrier over which an air mass passes can be made in terms of two variables, mean elevation, and standard deviation of elevation about the mean. The question naturally arises as to what constitutes the topographic barrier and what are the horizontal limits for this barrier in a given basin. For basins abutting on a major divide, such as the Continental Divide in the United States, one may reasonably assume that the barrier is this divide with horizontal limits determined by the intersection of the basin perimeter and the divide. Although, in general, this may seem to be a rational definition, examination of topographic maps will reveal some basins located on the windward side of a major divide with an important ridge line parallel to the principal drainage direction, at a small angle to the major divide, such that the air flow could easily be forced to pass this barrier rather than travel up the valley and subsequently be lifted over the divide.

The selection of the principal barrier for basins not located on a major divide should be based on the expected major barrier for the particular region as a whole, as well as the horizontal and vertical configuration of the basin perimeter. It is difficult to define a topographic barrier in a precise quantitative manner; hence, some judgment must be exercised by the investigator. For this particular reason, the method of definition and selection of these variables is called semi-objective.

One problem in barrier selection is the lack of adequate information regarding the air flow patterns in mountainous basins. Investigation indicates that, in general, information of this nature would only be made available by actual observations in each basin, or by making wind tunnel studies, which may be an attractive approach in the future.

c. Common variables. These variables are used in conjunction with both the objective and semi-objective groups of variables. They include orientation, latitude, longitude, basin area, and percent vegetal cover. The foregoing variables are self explanatory with the exception of orientation.

In this paper, we are actually concerned with two orientations, one with respect to the wind and the other with respect to the solar radiation. In the case of the latter orientation, the entire basin is of interest, while in the former case the topographic barrier is of importance. Therefore, it is necessary to measure two orientations.

An index of orientation with respect to wind should be measured about an axis of symmetry parallel to the prevailing wind direction during storms. The best measure of this orientation is not easily determined, and in addition, is not amenable to precise definition. In this paper, the orientation is measured by the normal to the basin's topographic barrier described in the previous sub-topic. In the event of considerable curvature in the ridge line, the average orientation is used. This should generally coincide with the orientation of the center segment of the barrier, which is also normally the most exposed portion of the ridge; hence, the most significant orientation is obtained.

In the case of solar radiation, orientation should be measured about an axis of symmetry in the north-south direction. For this paper, the basin periphery is approximated by a polygon, the normals to the sides being used to determine orientation. An average orientation, weighted with respect to length of the side and its mean elevation, is used. More research is needed on the subject of basin orientation. Ideally, orientation with respect to solar radiation should be measured throughout the basin area and topographic shading should be considered. However, because of the infinite complexity of mountain watersheds, it is impractical to precisely measure exposure to solar radiation. The slope of the topography is another factor to be considered.

Future investigators may wish to apply the method of Lee [20, p. 36] in which a statistical plane is fitted to the basin in such a manner that the plane's inclination and direction of slope can be used to determine an index of radiation.

5. Mathematical Techniques. Multiple regression is one of the few numerical methods which can be used to evaluate the effect of several causative factors acting simultaneously on a dependent variable. This is a well established technique for predictive purposes in hydrologic investigations. As in this study, most experiments in hydrology are of the uncontrolled type, wherein the causative factors cannot be held constant as in a laboratory experiment. In multiple relationships, linear equations are much easier to treat than non-linear ones. Hence, non-linear relations are often linearized by appropriate transformations prior to multiple regression analysis.

The following three mathematical models are employed in this paper: linear, multiplicative (log transformation), and Taylor series (first and second order terms only). Although the logarithmic transformation is convenient for solving curvilinear relations with linear computer programs, it has the undesirable tendency to weight the low value of the variables. Approximating a curvilinear realtionship by a Taylor series is easily manageable in existing linear computer programs if no terms higher than the second order are used.

When intercorrelations exist among a number of the independent variables, as is frequently the case in hydrology, the multiple regression technique does not evaluate the absolute contribution of each independent variable; hence, the relative importance of the selected variables cannot be determined. The prediction equation may not necessarily be consistent with hydrologic reasoning, and the true physical relationship may thus be masked. The influence of high correlation between so-called independent variables is one of the major drawbacks of the multiple regression approach to hydrologic analysis. To circumvent these difficulties, some investigators are beginning to consider the utility of multivariate analysis in hydrologic studies. By this technique, many of the foregoing problems are eliminated, and it is possible to identify the highly significant variables and their independent contribution to the dependent variable. However, this technique is normally advocated when the structure of the solution is more important than predicting the dependent variable with minimum error. It is generally agreed that multiple regression is preferable if prediction of the dependent variable with minimum error is the desired result. For this reason multiple regression is used to derive the prediction equations in this study.

A stepwise multiple linear regression program is utilized for the data analysis. In the stepwise procedure, a number of intermediate regression equations are obtained, as well as the complete multiple regression equation. The variable added is that one which will, in combination with those variables previously included, effect the greatest reduction in the unexplained variance of the dependent variable in a single step. Equivalently, it is the variable which has the highest partial correlation with the dependent variable partialed on the variables which have already been added; or similarly, it is the variable which, if it were added, would have the highest F-value [10].

The stepwise multiple regression method does not necessarily give the optimum equation, however. In other words, there may be other combinations of the initial set of variables which will explain more of the variance in the dependent variable than the particular combination selected in the stepwise procedure. For example, the first variable entered in the stepwise procedure exerts some control on the second variable entered. Thus, if we consider just two variables, the pair with the highest correlation with the dependent variable may not necessarily be the pair in which the first variable entered has the highest partial correlation with the dependent variable. In this case the optimum combination is the pair giving the highest multiple correlation coefficient. Therefore, it may be concluded that other promising combinations of variables should be investigated rather than to assume that the first set selected by the stepwise procedure is the optimum one. However, in general, one should not expect to obtain a large increase in explaining variance but should rather explore additional combinations of variables with the objective of refining the original equation. In most cases, particularly when using a Taylor series approximation, one would expect to find a number of combinations of variables giving about the same multiple correlation coefficient as the one obtained from the initial stepwise regression result.

CHAPTER IV

DATA ASSEMBLY

1. Region of Analysis. The region encompassed by this study extends from 43° on the north to 37° on the south and from 105° on the east to 112° on the west. It includes portions of the states of Colorado, Wyoming and Utah. The location of each drainage basin studied is shown in fig. 2. As indicated in this figure, most of the basins are located on the headwaters of several important rivers, namely the Colorado River, the Rio Grande, the Arkansas River, and the Platte River. Also displayed in this figure are the U. S. Geological Survey drainage basin numbers and the numbers of the gages used in the respective basins. Data were used from Parts 6-A, 6-B, 7, 8, 9, and 10. The basins studied are located in four principal mountain complexes: the Rocky Mountains of Colorado, the Wind River Range in Wyoming, the Uinta Mountains in Utah and Wyoming, and the Wasatch Mountains in Utah.

2. Data Assembly for Dependent Variables. Considerable effort was involved in obtaining the necessary data for the dependent variable, mean annual specific yield. In many cases, basins highly suitable for analysis in other respects were not used due to inadequacy or paucity of data required for computation of the dependent variable. It was for this reason that only 79 basins in such a large region were found suitable for analysis.

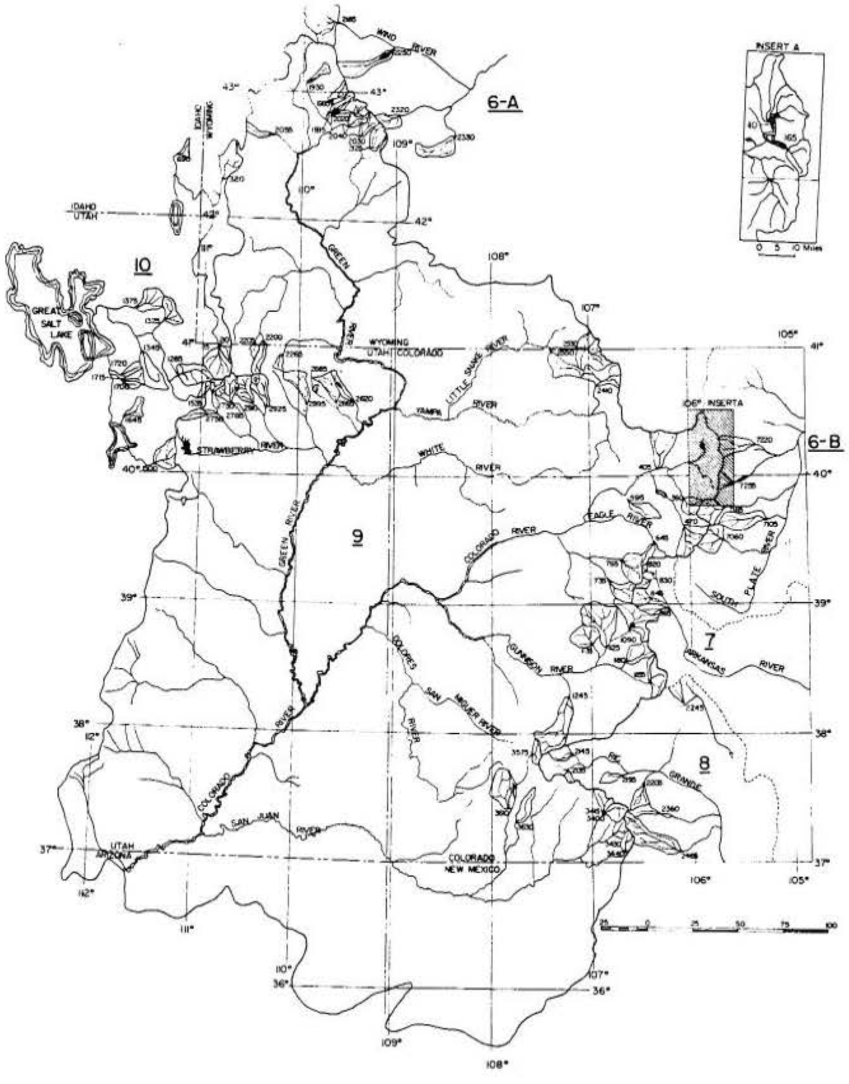

Fig. 2 Location of Basins Used in Analysis

a. Criteria for selection of stations. The stations used for analyses were selected on the basis of information contained in the U.S. Geological Survey "Water Supply Papers." After selecting the 25-year period from 1940 through 1964 for analyses, any gage with 12 or more years of record missing was automatically excluded from consideration. Thus, the maximum length of record estimated is 44 percent. Stations with incomplete records were retained only if the flow could be reliably estimated from nearby stations. Of the 79 stations used in the analysis, 40 had incomplete records requiring estimation of annual discharge [21].

Another criterion for the selection of stations was the percentage correction needed to establish the virgin discharge of the basin. It is imperative that the nonhomogeneity induced by man's activity be removed if a reliable relation is expected to be established between specific yield and physiographic parameters. The three principal sources of such nonhomogeneity are irrigation diversion, transmountain diversion, and streamflow regulation. The last two can frequently be obtained with considerable reliability. However, irrigation diversions are normally not available and must be estimated from the acreages provided in the station's description found in the U.S. Geological Survey "Water Supply Papers." These acreages are estimates themselves and do not reflect the changes from year to year, being revised only when a large expansion or contraction of land development occurs. Therefore, stations for which the estimated irrigation exceeded eight percent of the mean annual discharge were excluded from the study. In addition, because of the uncertainty involved in estimating the amount of water diverted past the gage for irrigation of land below the gage, no station was used in which such irrigation diversions exceeded four percent of the mean annual flow.

The stations meeting the above criteria are listed in Table 1 along with the location and accuracy of each gage. The U.S. Geological Survey classifies the accuracy of its records as excellent, good, fair, and poor, depending on whether the errors are believed to be less than 5, 10, and 15 percent, or greater than 15 percent, respectively. It would be expected that, in general, the figures used for mean 25-year discharge would be more accurate than indicated by these percentages, which presumably refer to daily flow records.

TABLE 1 LOCATION AND ACCURACY OF GAGES

Station number	Long.	Lat.	River	Approximate location	Accuracy
9-110	105°51'	40°13'	Colorado River	Grand Lake, Colorado	Good
9-165	105°45'	40°07'	Arapaho Creek	Monarch Lake Outlet, Colorado	Good
9-360	106°03'	39°50'	Williams Fork R.	Leal, Colorado	Good
9-405	106°17'	40°09'	E. Troublesome Cr.	Troublesome, Colorado	Good
9-470	106°03'	39°37'	Blue River	Dillon, Colorado	Fair
9-595	106°35'	39°48'	Piney River	State Bridge, Colorado	Good
9-645	106°22'	39°28'	Homestake Creek	Red Cliff, Colorado	Good
9-735	106°49'	39°11'	Roaring Fork River	Aspen, Colorado	Good
9-785	106°40'	39°21'	N. Fork Fryingpan Cr.	Norrie, Colorado	Good
9-1090	106°37'	38°49'	Taylor River	Below Taylor Park Res., Colo.	Good
9-1125	106°51'	38°40'	East River	Almont, Colorado	Good
9-1135	107°00'	38°42'	Ohio Creek	Baldwin, Colorado	Good
9-1155	106°25'	38°24'	Tomichi Creek	Sargents, Colorado	Good
9-1180	106°38'	38°34'	Quartz Creek	Ohio, Colorado	Good
9-1245	107°14'	38°18'	Lake Fork	Gateview, Colorado	Good
9-3400	106°54'	37°22'	E. Fork San Juan R.	Pagosa Springs, Colorado	Good
9-3415	106°54'	37°23'	W. Fork San Juan R.	Pagosa Springs, Colorado	Good
9-3430	106°48'	37°13'	Rio Blanco	Pagosa Springs, Colorado	Good
9-3440	106°41'	37°05'	Navajo River	Chromo, Colorado	Fair
9-3575	107°36'	38°50'	Animas River	Howardsville, Colorado	Good
9-3610	107°50'	37°26'	Hermosa Creek	Hermosa, Colorado	Good
9-3630	107°45'	37°20'	Florida River	Durango, Colorado	Good
9-2410	106°55'	40°43'	Elk River	Clark, Colorado	Good
9-2530	107°09'	41°00'	Little Snake R.	Slater, Colorado	Good
9-2550	107°23'	40°59'	Slater Fork	Slater, Colorado	Good
8-2135	107°15'	37°44'	Rio Grande R.	Creede, Colorado	Good
8-2145	107°12'	37°53'	Clear Creek	Below Continental Res., Colo.	Good
8-2195	106°39'	37°40'	S. Fork Rio Grande R.	South Fork, Colorado	Good
8-2205	106°27'	37°36'	Pinos Creek	Del Norte, Colorado	Good
8-2245	106°08'	38°15'	Kerber Creek	Villa Grove, Colorado	Good
8-2360	106°21'	37°23'	Alamosa Creek	Above Terrace Reservoir, Colo.	Good
8-2465	106°11'	37°03'	Conejos River	Mogote, Colorado	Good
9-2200	110°24'	41°03'	E. Fork Smith Fork	Robertson, Wyoming	Good
9-2205	110°29'	41°01'	W. Fork Smith Fork	Robertson, Wyoming	Good
9-2265	110°11'	40°57'	Mid. Fork Beaver Cr.	Lonetree, Wyoming	Good
9-1930	110°01'	43°05'	New Fork River	Cora, Wyoming	Good

TABLE 1 - Continued

Station number	Long.	Lat.	River	Approximate location	Accuracy
9-1985	109°43'	42°53'	Pole Creek	Pinedale, Wyoming	Good
9-1995	109°43'	42°51'	Fall Creek	Pinedale, Wyoming	Good
9-2020	109°43'	42°50'	Boulder Creek	Boulder, Wyoming	Good
9-2030	109°25'	42°40'	East Fork	Big Sandy, Wyoming	Good
9-2040	109°31'	42°45'	Silver Creek	Big Sandy, Wyoming	Fair
9-2055	110°21'	42°39'	North Piney Cr.	Mason, Wyoming	Good
9-2121	109°17'	42°35'	Big Sandy Creek	Big Sandy, Wyoming	Good
9-2620	109°26'	40°35'	Brush Creek	Vernal, Utah	Good
9-2665	109°37'	40°35'	Ashley Creek	Vernal, Utah	Good
9-2685	109°49'	40°38'	N. Fork Dry Fork	Dry Fork, Utah	Good
9-2730	110°53'	40°38'	Duchesne River	Hanna, Utah	Fair
9-2750	110°59'	40°27'	W. Fork Duchesne R.	Hanna, Utah	Good
9-2785	110°40'	40°33'	Rock Creek	Hanna, Utah	Good
9-2910	110°29'	40°34'	Lake Fork	Mountain Home, Utah	Good
9-2925	110°21'	40°31'	Yellowstone Cr.	Altonah, Utah	Good
9-2995	109°56'	40°34'	Whiterocks R.	Whiterocks, Utah	Good
10-115	110°51'	40°58'	Bear River	Utah-Wyoming State Line	Good
10-210	111°16'	41°29'	Woodruff Cr.	Woodruff, Utah	Good
10-320	110°52'	42°17'	Smiths Fork	Border, Wyoming	Good
10-690	111°19'	42°30'	Georgetown Cr.	Georgetown, Idaho	Good
10-1285	111°15'	40°44'	Weber River	Oakley, Utah	Good
10-1325	111°24'	41°11'	Lost Creek	Croydon, Utah	Good
10-1345	111°36'	40°55'	East Canyon Cr.	Morgan, Utah	Good
10-1375	111°40'	41°16'	S. Fork Ogden R.	Huntsville, Utah	Good
10-1500	111°27'	40°04'	Diamond Fork	Thistle, Utah	Good
10-1535	111°01'	40°35'	Provo River	Kamas, Utah	Good
10-1645	111°41'	40°27'	American Fork	American Fork, Utah	Good
10-1700	111°47'	40°41'	Mill Creek	Salt Lake City, Utah	----
10-1715	111°47'	40°43'	Parleys Creek	Salt Lake City, Utah	----
10-1720	111°49'	40°45'	Emigration Creek	Salt Lake City, Utah	----
6B-7060	105°39'	39°27'	N. Fork South Platte R.	Grant, Colorado	Good
6B-7105	105°12'	39°39'	Bear Creek	Morrison, Colorado	Poor
6B-7165	105°39'	39°46'	Clear Creek	Lawson, Colorado	Good
6B-7220	105°21'	40°14'	N. St. Vrain Cr.	Lyons, Colorado	Good
6B-7255	105°30'	39°58'	Middle Boulder Cr.	Nederland, Colorado	Good
7-820	106°24'	39°16'	Lake Fork	Above Sugarloaf Res.,Colorado	Poor
7-830	106°23'	39°11'	Halfmoon Creek	Malta, Colorado	Good
7-845	106°24'	39°04'	Lake Creek	Above Twin Lakes Reservoir, Colorado	Fair
7-865	106°17'	39°01'	Clear Creek	Above Clear Creek Res., Colo.	Good
6A-2185	109°46'	43°35'	Wind River	Dubois, Wyoming	Good
6A-2250	109°01'	43°15'	Bull Lake Creek	Lenore, Wyoming	Good
6A-2320	108°54'	42°52'	North Popo Agie R.	Milford, Wyoming	Good
6A-2330	108°39'	42°43'	Little Popo Agie R.	Lander, Wyoming	Good

b. Streamflow corrections. After reviewing the limited amount of literature available on irrigation losses [22, 23, 24, 25, 26, 27] and consulting with Agricultural Extension Service personnel at Colorado State University, the following assumptions were made with regard to irrigation diversions. Water diverted above the stream gage for irrigation of land below the gage and not measured at the gaging station depleted four acre-feet per acre irrigated per year from the basin, while diversions for irrigation of land lying above the gage accounted for a depletion of one acre-foot per acre irrigated per year. The aforementioned diversions are denoted as downstream and upstream diversions, respectively. The latter figure is considered to be a fairly good estimate, being based on a normal irrigation consumption of 8 to 13 inches in the mountain valleys, where most of the acreage is in alfalfa, hay and pasture. It is also assumed that the losses associated with return flow are minor. The figure for downstream diversion is less reliable since more water is diverted than actually consumed by irrigated crops, and the remainder does not pass the gage as return flow as in the previous case.

Corrections for transmountain or transbasin diversions were applied on an annual basis using the diversions as recorded in the "Water Supply Papers." Upstream flow regulation caused by the construction of dams and reservoirs was corrected in a similar manner. In the event that storage changes were unaccountable, the station was excluded from further study unless it was safe to assume that the error introduced by inclusion of the station would be less than one percent. In relatively small mountain reservoirs, it is reasonable to assume that storage changes will have a negligible effect on the 25-year mean annual discharge unless the initial filling of the reservoir occurred during the period of record being used.

The net water loss introduced by a reservoir was approximated from figures contained in Chow's "Handbook of Applied Hydrology," [28]. Figure 11-3 (b) gives the average annual evaporation, and Table 6-7 contains figures from which the evapotranspiration can be estimated. The changes in storage and evaporation corrections were found to be minor, being approximately one or two percent of the outflow measured by the gage.

3. Data Assembly for Independent Variables. A summary of the independent variables and their corresponding definitions are given in Table 2. A tabulation of the values of variables is presented in Table 3.

The basic data for all but three of the variables were obtained from topographic maps published by the U. S. Geological Survey at a scale of 1:250,000. For the majority of parameters these maps were enlarged by a factor of 2.5 with a Map-O-Graph Model 55 enlarger. The basins selected for analysis were carefully delineated on these maps.

Due to the labor involved in obtaining the data for hypsometric curves, only a limited number of points was used. In rugged mountainous terrain, where the contours follow a devious pattern, planimetering the area above a given elevation can be a rather time-consuming task. Representative hypsometric curves are shown in figs. 3 through 5, [21]. The parameters obtained from the hypsometric curves, some of which are alternative definitions of the same item, are as follows:

$H_{.05}$, $H_{.10}$, $H_{.50}$, $H_{.75}$, $H_{.90}$, $H_{.95}$ = elevation above which lies the fraction of basin area indicated by the subscript.

$\Delta H_1 = H_{.05} - H_{.95}$

$\Delta H_2 = H_{.10} - H_{.90}$

$A_{9.0}$, $A_{9.5}$, $A_{10.0}$ = percent area above 9,000, 9,500 and 10,000 feet respectively.

The basin slope was represented by $\Delta H_1/L$ and $\Delta H_2/L$, where L is the longest horizontal distance from the major drainage divide to the stream gage at the basin mouth.

The hypsometric data were also plotted on log-probability paper with elevation on the log scale and percent area on the probability scale [21]. Representative graphs are shown in fig. 6. The geometric mean elevation μ, was read at the 50 percent point. By reading the elevation corresponding to a probability of 84.13 percent and subtracting this figure from μ, a measure of the deviation about the mean elevation, designated σ, was obtained.

TABLE 2 SUMMARY LIST OF VARIABLES

Symbol	Definition
q	mean 25 year annual specific yield (cfs/mi^2)
A	area of drainage basin (sq mi)
$H_{.05}$	elevation above which lies 5% of the basin area (ft)
$H_{.10}$	elevation above which lies 10% of the basin area (ft)
$H_{.50}$	elevation above which lies 50% of the basin area (ft)
$H_{.75}$	elevation above which lies 75% of the basin area (ft)
$H_{.90}$	elevation above which lies 90% of the basin area (ft)
$H_{.95}$	elevation above which lies 95% of the basin area (ft)
ΔH_1	$H_{.05} - H_{.95}$ (ft)
ΔH_2	$H_{.10} - H_{.90}$ (ft)
$A_{9.0}$	per cent basin area above 9000 feet
$A_{9.5}$	per cent basin area above 9500 feet
$A_{10.0}$	per cent basin area above 10,000 feet
$\Delta H_1/L$	$(H_{.05} - H_{.95})$/length of basin (ft/mi)
$\Delta H_2/L$	$(H_{.10} - H_{.90})$/ length of basin (ft/mi)
μ	mean basin elevation (ft)
σ	deviation about mean basin elevation (ft)
$(\mu - H_o)/L$	mean basin elevation - gage elevation/length of basin (ft/mi)
$\bar{H}_p$	mean boundary elevation (ft)
σ_p	deviation about mean boundary elevation (ft)
$(\bar{H}_p - H_o)/L$	mean boundary elevation - gage elevation/ length of basin (ft/mi)
% Cover	per cent vegetal cover
Long.	longitude minus 104°
Lat.	latitude minus 36°
L	length of basin
α	orientation with respect to solar radiation
β	orientation with respect to wind

TABLE 3 DATA FOR VARIABLES

COMMON VARIABLES										OBJECTIVE VARIABLES					
Station No.	Case No.	q (cfs/mi^2)	A (mi^2)	Cover (%)	L (mi)	Lat.	Long.	α (deg.)	β (deg.)	$H_{0.05}$ (ft)	$H_{0.10}$ (ft)	$H_{0.50}$ (ft)	$H_{0.75}$ (ft)	$H_{0.90}$ (ft)	$H_{0.95}$ (ft)
9-110	1	1.07	103.0	86.9	18.5	4.22	1.85	83	90	12,480	12,050	10,250	9,300	8,800	8,650
9-165	2	1.72	47.1	63.4	6.7	4.12	1.75	91	1	12,500	12,100	10,740	9,950	9,170	8,750
9-360	3	1.14	89.5	72.6	11.5	3.83	2.05	107	15	12,340	12,000	10,950	10,250	9,600	9,250
9-405	4	0.31	178.0	65.8	20.7	3.07	2.32	62	81	10,620	10,300	9,090	8,210	7,700	7,510
9-470	5	0.83	129.0	66.3	17.5	3.62	2.05	103	60	12,810	12,400	10,860	10,060	9,460	9,210
9-595	6	0.85	82.6	83.4	13.5	3.80	2.58	94	40	11,570	11,100	9,770	9,110	8,500	8,150
9-645	7	1.33	58.9	62.8	13.5	3.47	2.37	96	150	12,480	12,150	10,900	10,200	9,540	9,200
9-735	8	1.32	109.0	56.8	17.5	3.18	2.82	107	16	12,840	12,600	11,400	10,640	9,750	9,050
9-785	9	1.16	41.2	77.8	9.0	3.35	2.67	83	20	12,050	11,860	10,480	9,870	9,350	9,060
9-1090	10	0.78	245.0	73.3	15.3	3.82	2.62	78	25	12,500	12,170	10,850	10,300	9,920	9,610
9-1125	11	1.08	295.0	57.5	26.5	2.67	2.85	74	84	12,140	11,740	10,220	9,360	8,750	8,430
9-1135	12	0.76	124.0	72.0	11.4	2.70	3.00	77	127	11,760	11,300	9,750	9,150	8,650	8,420
9-1155	13	0.40	155.0	93.1	11.2	2.40	2.42	89	20	11,730	11,400	10,170	9,500	9,010	8,920
9-1180	14	0.53	106.0	82.4	15.1	2.57	2.63	75	55	12,180	11,910	10,650	9,940	9,250	8,800
9-1245	15	0.72	338.0	N.A.	35.0	2.30	3.23	95	120	12,940	12,700	11,000	9,800	8,870	8,470
9-3400	16	1.33	86.9	N.A.	13.6	1.37	2.90	87	20	11,890	11,590	10,000	9,180	8,500	8,230
9-3415	17	1.70	87.9	N.A.	12.9	1.38	2.90	77	48	11,920	11,620	10,590	9,380	8,380	7,970
9-3430	18	1.41	58.0	N.A.	10.2	1.22	2.80	78	17	11,930	11,630	10,100	9,180	8,500	8,240
9-3440	19	1.45	69.8	N.A.	12.0	1.08	2.68	74	29	11,980	11,860	10,400	9,200	8,450	8,410
9-3575	20	1.85	55.9	N.A.	9.0	1.83	3.60	91	1	13,040	12,910	12,060	11,350	10,450	10,010
9-3610	21	0.71	172.0	N.A.	20.0	1.42	3.83	85	100	11,120	10,800	9,500	9,010	8,400	7,950
9-3630	22	0.95	96.0	N.A.	14.9	1.33	3.75	76	67	12,250	11,940	9,950	8,850	8,300	7,940
9-2410	23	1.51	206.0	77.6	17.1	4.72	2.92	87	38	10,930	10,560	8,850	8,300	8,030	7,750
9-2530	24	0.76	285.0	83.0	19.4	5.00	3.15	81	39	9,900	9,550	8,510	8,000	7,500	7,250
9-2550	25	0.44	161.0	65.3	21.0	4.98	3.38	110	85	9,800	9,460	8,350	7,660	7,100	6,850
8-2135	26	1.22	163.0	N.A.	16.8	1.72	3.25	89	180	12,730	12,450	11,890	11,090	10,250	9,950
8-2145	27	0.61	51.7	N.A.	9.3	1.88	3.20	84	140	12,610	12,270	11,220	10,840	10,450	10,250
8-2195	28	0.86	216.0	N.A.	17.4	1.67	2.65	97	126	11,850	11,620	10,500	9,750	9,000	8,650
8-2205	29	0.45	53.0	N.A.	12.1	1.59	2.45	113	135	11,900	11,700	10,500	9,880	9,320	9,000
8-2245	30	0.32	38.0	N.A.	7.5	2.25	2.13	163	133	11,900	11,590	10,570	10,000	9,600	9,450
8-2360	31	0.97	107.0	N.A.	20.3	1.38	2.35	83	175	12,000	11,820	10,850	10,150	9,550	9,250
8-2465	32	1.07	282.0	N.A.	34.0	1.05	2.18	98	150	11,950	11,780	10,440	9,620	9,030	8,750
9-2200	33	0.83	53.0	67.7	19.6	5.05	6.40	103	82	12,140	11,720	10,260	9,680	9,240	9,050
9-2205	34	0.53	37.2	88.0	11.3	5.02	6.48	101	92	10,780	10,510	9,750	9,460	9,150	9,000
9-2265	35	0.77	28.0	69.7	8.5	4.77	6.18	104	98	12,000	11,660	10,470	9,880	9,250	9,070
9-1930	36	1.37	36.2	39.4	13.0	7.08	6.01	99	35	11,050	10,940	9,200	8,380	8,100	7,950
9-1985	37	1.22	87.5	52.3	16.9	6.88	5.72	79	20	11,760	11,240	9,720	8,800	8,000	7,700
9-1995	38	1.04	37.2	54.2	14.8	6.85	5.72	80	46	11,160	10,820	9,320	8,520	7,600	7,420
9-2020	39	1.46	130.0	55.8	20.0	6.83	5.72	85	45	11,400	11,060	9,950	9,250	7,690	7,400
9-2030	40	1.24	79.2	72.6	14.7	6.67	5.42	76	45	11,430	11,050	9,800	9,300	8,700	8,320
9-2040	41	0.95	45.4	82.7	10.5	6.75	5.52	75	80	10,830	10,600	9,580	9,280	8,500	8,070
9-2055	42	1.04	58.0	54.7	15.2	6.65	6.35	88	22	10,400	10,070	8,860	8,320	8,000	7,800
9-2125	43	0.87	94.0	66.4	14.2	6.58	5.28	75	29	11,400	10,950	9,410	8,820	8,300	8,060
9-2620	44	0.46	82.0	67.8	9.0	4.58	5.43	81	115	9,710	9,450	8,640	7,410	6,170	5,900
9-2665	45	0.94	101.0	86.5	18.5	4.58	5.62	85	106	10,900	10,520	9,510	8,890	8,310	7,950
9-2685	46	0.50	12.0	82.0	4.9	4.63	5.81	71	100	11,480	11.380	10,020	9,740	9,250	8,950
9-2730	47	1.51	39.0	77.7	9.4	4.62	6.88	76	82	11,340	11,030	10,270	9,740	9,150	8,820
9-2750	48	0.81	47.0	58.3	11.6	4.45	6.98	91	175	9,810	9,660	9,100	8,880	8,450	8,170
9-2785	49	1.27	120.0	70.8	13.0	4.55	6.67	81	92	11,600	11,290	10,290	9,920	9,240	8,730
9-2910	50	1.12	110.0	61.4	16.5	4.56	6.48	76	98	11,900	11,530	10,700	10,130	9,260	8,750
9-2925	51	1.04	131.0	57.0	17.5	4.52	6.34	78	98	12,160	11,780	10,670	9,750	8,730	8,200
9-2995	52	0.97	115.0	65.5	19.3	4.57	5.93	85	95	11,800	11,500	10,400	9,880	8,920	8,200
10-115	53	1.09	176.0	52.1	18.5	4.97	6.85	110	90	11,450	10,910	9,700	9,020	8,730	8,570
10-210	54	0.42	65.0	19.7	13.0	5.48	7.27	90	146	8,780	8,580	7,940	7,500	7,170	7,000
10-320	55	1.12	165.0	64.8	15.5	6.28	6.87	70	20	9,620	9,310	8,240	7,620	7,210	7,030
10-690	56	1.38	22.2	62.3	7.5	6.50	7.32	89	73	9,270	8,950	7,720	7,710	6,830	6,610
10-1285	57	1.20	163.0	84.5	18.0	4.73	7.25	96	65	10,580	10,310	9,300	8,260	7,650	7,420
10-1325	58	0.21	133.0	42.6	11.0	5.18	7.40	85	135	8,170	8,000	7,340	7,050	6,750	6,510
10-1345	59	0.32	155.0	64.8	21.5	4.92	7.60	94	155	7,790	7,610	6,850	6,430	6,180	5,980
10-1375	60	0.72	148.0	75.5	14.5	5.27	7.67	84	1	8,370	8,260	7,350	6,740	6,130	5,780
10-1500	61	0.20	146.0	90.0	14.0	4.07	7.44	90	10	8,540	8,240	7,200	6,620	6,000	5,670
10-1535	62	1.64	29.6	89.0	9.0	4.58	7.01	84	80	11,090	10,700	9,840	9,380	8,770	8,460
10-1645	63	1.04	51.1	81.2	10.0	4.47	7.68	83	60	10,580	10,040	8,330	7,490	7,060	6,720
10-1700	64	0.64	21.7	97.3	9.5	4.69	7.78	100	5	9,700	9,170	7,770	6,980	6,290	5,940
10-1715	65	0.46	50.1	92.3	9.5	4.72	7.78	96	20	8,560	8,180	6,850	6,150	5,740	5,600
10-1720	66	0.39	18.0	96.6	8.0	4.75	7.81	77	20	7,930	7,510	6,450	5,910	5,680	5,470
6B-7060	67	0.53	127.0	62.7	12.0	3.46	1.66	81	150	12,730	12,310	10,950	10,190	9,620	9,270
6B-7105	68	0.30	164.0	11.2	24.5	3.65	1.19	93	180	11,830	11,130	8,550	8,650	7,740	7,040
6B-7165	69	0.93	145.0	54.0	15.5	3.76	1.65	99	170	12,810	12,500	11,370	10,460	9,560	9,080
6B-7220	70	0.87	106.0	79.2	17.0	4.23	1.35	88	180	12,070	11,620	9,160	8,330	7,560	7,030
6B-7255	71	1.48	36.2	64.5	9.5	3.96	1.50	75	180	12,190	11,820	10,350	9,300	8,800	8,570
7-820	72	1.90	18.0	55.3	6.0	3.27	2.39	84	175	12,160	11,940	11,160	10,660	10,170	9,970
7-830	73	1.21	23.0	37.7	8.0	3.19	2.38	95	170	13,960	13,200	11,980	11,190	10,360	10,020
7-845	74	1.34	75.0	39.9	10.0	3.06	2.41	92	170	13,400	13,110	9,960	11,340	10,550	10,140
7-865	75	1.13	59.0	48.2	13.5	3.02	2.28	93	135	13,430	13,080	11,830	10,940	10,040	9,480
6A-2185	76	0.74	232.0	66.0	20.5	7.58	5.76	77	180	10,580	9,990	8,790	8,140	7,670	8,430
6A-2250	77	1.31	201.0	29.0	30.5	7.24	5.02	91	160	12,080	11,820	10,240	9,050	6,340	5,870
6A-2320	78	1.23	98.4	60.9	18.0	6.86	4.91	107	140	11,790	11,400	9,960	9,400	8,510	7,690
6A-2330	79	0.60	125.0	51.4	19.5	6.72	4.64	96	135	10,670	10,170	8,190	7,000	5,940	5,660

TABLE 3 - Continued

OBJECTIVE VARIABLES												SEMI-OBJECTIVE VARIABLES		
Station No.	Case No.	ΔH_1 (ft)	ΔH_2 (ft)	$A_{9.0}$ (%)	$A_{9.5}$ (%)	$A_{10.0}$ (%)	$\frac{\Delta H_1}{L}$ (ft/mi)	$\frac{\Delta H_2}{L}$ (ft/mi)	μ (ft)	σ (ft)	$\frac{\mu - H_o}{L}$ (ft/mi)	$\bar{H}_p$ (ft)	σ_p (ft)	$\frac{\bar{H}_p - H_o}{L}$ (ft/mi)
9-110	1	3,810	3,250	83.3	69.8	56.9	207	176	10,100	1,100	93	11,890	551	194
9-165	2	3,750	2,930	92.5	85.0	73.6	560	437	10,500	1,100	327	12,586	399	638
9-360	3	3,090	2,400	97.3	91.5	81.5	269	209	10,850	800	179	12,407	384	315
9-405	4	3,110	2,600	52.8	33.0	16.2	150	126	8,780	780	70	11,103	465	182
9-470	5	3,600	2,940	98.2	89.2	76.6	206	168	10,930	960	121	12,519	525	211
9-595	6	3,420	2,600	78.5	61.4	39.1	253	193	9,760	960	184	11,459	1,099	310
9-645	7	3,280	2,610	97.0	90.6	80.3	243	193	10,800	920	149	12,249	369	257
9-735	8	3,790	2,850	95.3	92.2	97.2	217	163	11,200	950	189	13,049	508	295
9-785	9	2,990	2,510	96.0	86.4	70.0	332	279	10,450	850	228	12,295	289	433
9-1090	10	2,890	2,250	100.0	96.5	88.1	189	147	11,000	800	120	12,749	401	234
9-1125	11	3,710	2,990	84.9	71.0	56.4	140	113	10,200	1,030	83	11,725	1,295	140
9-1135	12	3,340	2,650	80.8	60.7	40.3	293	232	9,850	1,000	146	11,256	674	270
9-1155	13	2,810	2,390	90.2	75.0	58.0	251	213	10,200	800	159	11,659	623	289
9-1180	14	3,380	2,660	92.5	86.5	72.5	224	176	10,750	1,050	191	12,321	210	295
9-1245	15	4,470	3,830	88.2	80.5	71.6	128	109	11,000	1,400	91	12,702	443	139
9-3400	16	3,660	3,090	79.8	66.2	49.7	269	227	10,000	1,000	177	11,824	589	311
9-3415	17	3,950	3,240	81.8	72.8	63.4	306	251	10,250	820	204	12,181	211	354
9-3430	18	3,690	3,130	79.6	66.8	52.4	362	307	10,100	900	211	11,800	580	377
9-3440	19	3,570	3,410	78.6	69.4	59.1	298	284	10,200	850	188	11,872	285	328
9-3575	20	3,030	2,460	100.0	100.0	95.2	337	273	11,400	400	198	13,093	171	386
9-3610	21	3,170	2,400	75.3	50.0	30.4	158	120	9,400	800	135	11,242	535	227
9-3630	22	4,310	3,640	70.0	59.2	48.6	289	244	9,950	1,350	178	12,752	251	366
9-2410	23	3,180	2,530	44.7	30.2	19.4	186	148	9,300	750	119	11,145	572	227
9-2530	24	2,650	2,050	27.7	11.0	4.2	137	106	8,600	700	91	9,779	333	152
9-2550	25	2,950	2,360	21.6	9.4	3.0	140	112	8,250	800	79	9,489	883	138
8-2135	26	2,780	2,200	100.0	99.0	93.9	165	131	11,500	750	131	12,649	318	199
8-2145	27	2,360	1,820	100.0	100.0	99.8	254	196	11,200	650	108	12,585	466	256
8-2195	28	3,200	2,620	90.4	81.4	67.3	184	151	10,450	850	128	11,568	365	192
8-2205	29	2,900	2,380	94.5	86.4	68.5	240	197	10,450	750	174	11,987	266	301
8-2245	30	2,450	1,990	100.0	93.5	75.5	327	265	10,650	820	180	12,006	547	361
8-2360	31	2,750	2,270	97.4	90.7	80.0	135	112	10,700	800	103	12,173	453	176
8-2465	32	3,200	2,750	90.7	84.5	63.4	94	81	10,250	650	58	12,080	327	112
9-2200	33	3,090	2,480	96.2	81.8	61.6	158	126	10,450	750	100	12,465	304	203
9-2205	34	1,780	1,360	95.2	72.0	32.7	158	120	9,800	500	102	11,076	305	215
9-2265	35	2,930	2,410	97.6	83.3	71.6	345	284	10,550	780	229	12,433	188	451
9-1930	36	3,100	2,840	53.8	44.7	35.8	238	218	9,450	900	137	11,239	246	275
9-1985	37	4,060	3,240	70.7	56.9	40.8	240	192	9,600	1,100	133	12,339	199	295
9-1995	38	3,740	3,220	61.8	44.1	29.5	253	218	9,250	1,050	132	11,561	285	288
9-2020	39	4,000	3,370	79.5	68.8	47.7	200	168	9,700	740	125	11,828	328	231
9-2030	40	3,110	2,350	84.0	67.0	39.5	212	160	9,800	800	136	11,882	257	278
9-2040	41	2,760	2,100	83.0	62.0	24.6	263	200	9,500	700	190	10,594	510	295
9-2055	42	2,600	2,070	43.7	24.0	11.3	171	136	9,100	700	104	10,232	528	178
9-2125	43	3,340	2,650	68.2	45.7	27.2	235	187	9,400	900	113	11,832	570	284
9-2620	44	3,810	3,280	30.5	9.1	1.6	423	364	8,000	820	274	10,175	185	516
9-2665	45	2,950	2,210	70.3	50.0	25.8	159	119	9,300	700	165	10,620	574	236
9-2685	46	2,890	2,130	94.3	84.2	51.8	590	435	10,200	800	431	10,995	642	593
9-2730	47	2,520	1,880	92.5	82.6	61.7	268	200	10,150	800	214	11,348	535	342
9-2750	48	1,640	1,210	64.2	16.5	0.4	141	104	9,000	400	118	10,000	000	204
9-2785	49	2,870	2,050	92.7	86.1	70.6	221	158	10,150	750	195	11,973	314	335
9-2910	50	3,150	2,270	93.1	87.1	78.1	191	138	10,600	700	159	12,252	271	260
9-2925	51	3,960	3,050	86.9	79.6	70.2	226	174	10,300	700	164	12,728	389	303
9-2995	52	3,600	2,580	89.4	82.7	71.6	186	134	10,100	850	162	11,840	435	252
10-115	53	2,880	2,180	75.5	57.7	39.2	156	118	9,800	750	99	11,583	377	196
10-210	54	1,780	1,410	1.3	0.0	0.0	137	108	7,870	550	98	8,656	288	158
10-320	55	2,590	2,100	17.9	6.7	1.7	167	135	8,200	700	100	9,622	355	192
10-690	56	2,660	2,120	9.0	2.1	0.0	355	283	7,700	700	180	9,413	159	408
10-1285	57	3,160	2,660	57.5	44.3	21.7	176	148	8,820	990	123	10,493	388	216
10-1325	58	1,660	1,250	0.0	0.0	0.0	151	114	7,250	520	130	7,846	513	184
10-1345	59	1,810	1,430	0.5	0.0	0.0	84	67	6,800	570	62	8,428	754	138
10-1375	60	2,590	2,130	0.1	0.0	0.0	179	147	7,200	700	139	8,150	86	204
10-1500	61	2,870	2,240	1.3	0.7	0.2	205	160	7,100	780	140	8,772	443	259
10-1535	62	3,440	1,930	86.0	69.9	35.2	382	214	9,700	720	177	10,850	313	305
10-1645	63	3,860	2,980	31.5	19.4	10.7	386	298	8,380	1,080	288	10,068	674	412
10-1700	64	3,760	2,880	12.2	6.8	2.2	396	303	7,620	1,000	271	9,440	338	462
10-1715	65	2,960	2,440	1.4	0.1	0.0	312	257	6,820	770	203	8,189	517	347
10-1720	66	2,460	1,830	0.0	0.0	0.0	308	229	6,450	750	198	8,104	518	404
6B-7060	67	3,460	2,690	97.7	92.0	81.0	288	224	10,950	950	199	12,591	563	336
6B-7105	68	4,790	3,390	39.7	30.3	22.5	196	138	8,580	1,600	114	12,009	975	254
6B-7165	69	3,730	2,940	95.7	90.7	84.0	241	190	11,000	950	181	12,672	513	289
6B-7220	70	5,040	4,060	52.8	43.9	35.4	296	239	9,280	1,290	190	12,199	654	379
6B-7255	71	3,620	3,020	84.2	70.0	59.1	381	318	10,250	1,060	217	13,075	342	514
7-820	72	2,190	1,770	100.0	100.0	93.8	365	295	11,000	800	200	12,126	170	388
7-830	73	3,940	2,840	100.0	100.0	95.3	493	355	11,850	1,100	264	13,311	344	446
7-845	74	3,260	2,560	100.0	99.5	96.3	326	256	11,850	950	255	12,946	329	365
7-865	75	3,950	3,040	98.7	94.9	90.4	293	225	11,850	1,450	219	13,033	186	335
6A-2185	76	2,150	2,320	41.5	22.5	10.0	105	113	8,630	980	70	10,875	494	180
6A-2250	77	6,210	5,480	75.5	68.0	55.7	204	180	8,200	1,600	84	12,039	531	209
6A-2320	78	4,100	2,890	84.0	71.7	47.5	228	161	9,000	950	156	11,891	325	317
6A-2330	79	5,010	4,230	31.0	20.8	12.2	257	217	8,000	270	131	10,919	757	281

N.A. Not Available

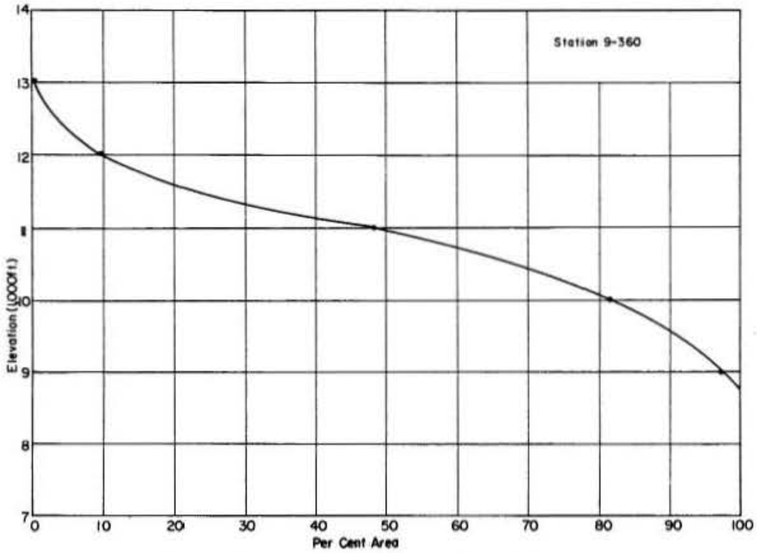

Fig. 3 Sample Hypsometric Curve

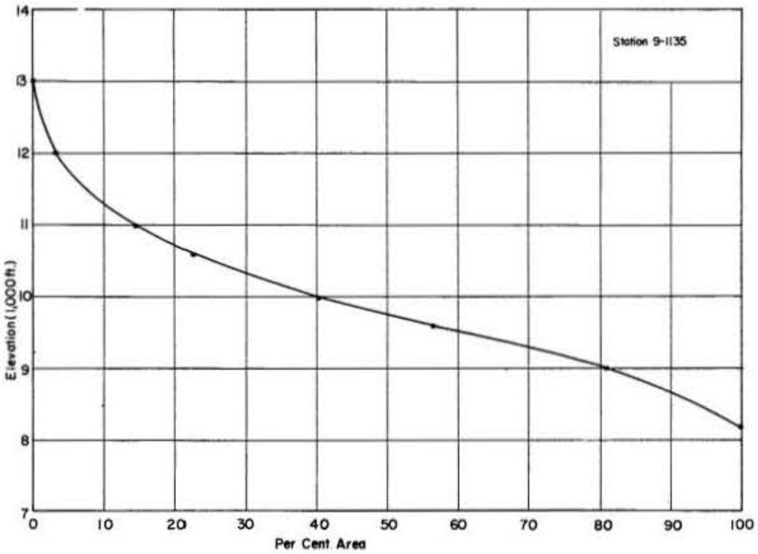

Fig. 4 Sample Hypsometric Curve

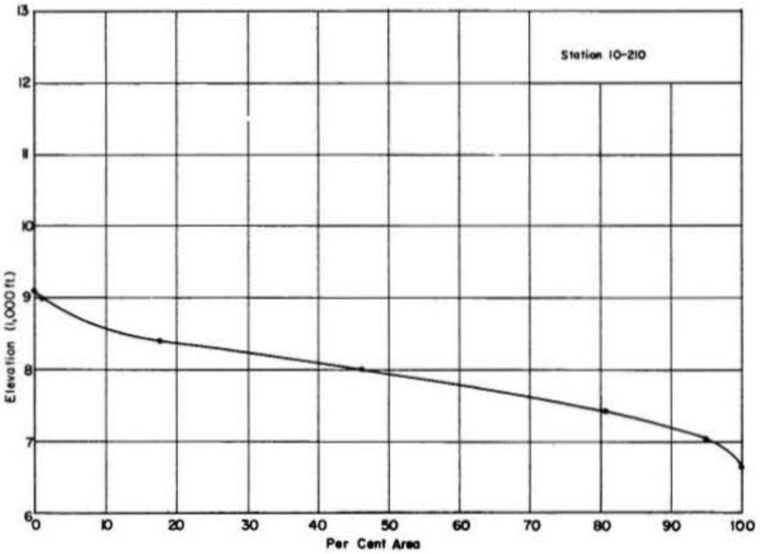

Fig. 5 Sample Hypsometric Curve

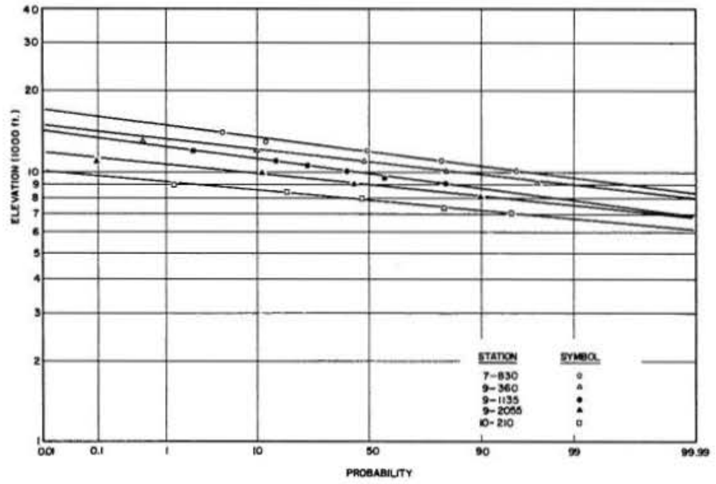

Fig. 6 Sample Hypsometric Curves on Log-Probability Paper

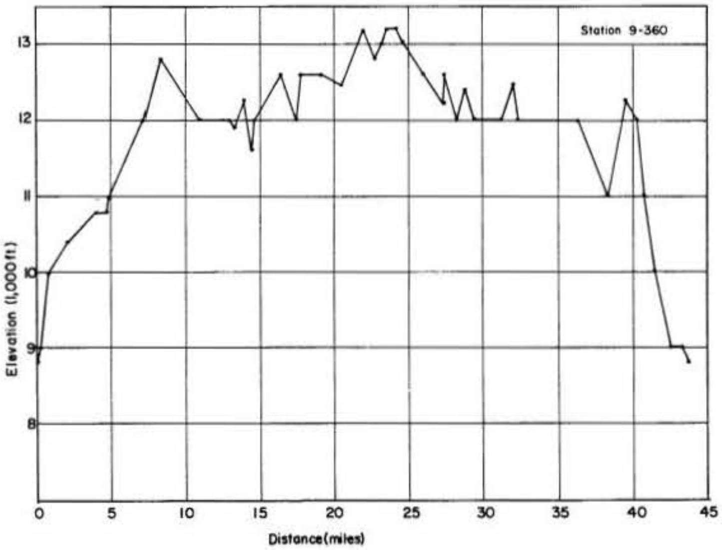

Fig. 7 Sample Basin Profile

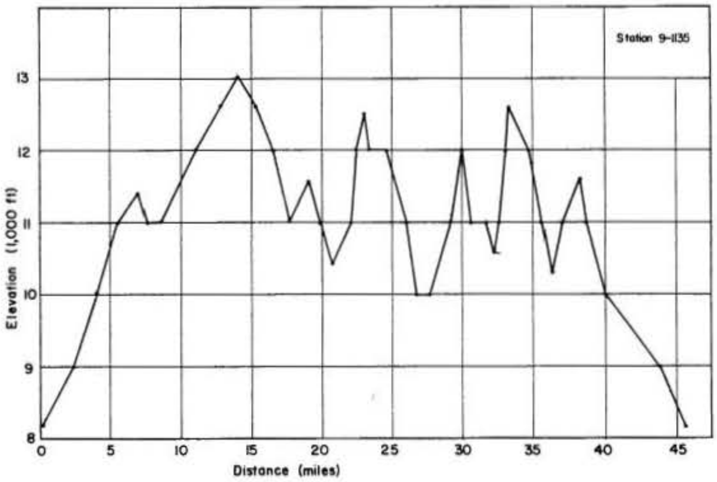

Fig. 8 Sample Basin Profile

As discussed previously, the topographic barrier for basins abutting on the Continental Divide or other major divide is taken as the divide and the limits as the intersection of the basin perimter with this divide. The selection of the principal barrier for the remaining basins was perhaps more subjective, being based on the expected major barrier for the particular region as a whole as well as the horizontal and vertical configuration of the basin perimeter. In general, the upper portion of the basin boundary or ridge line was used except that more weight was given to that portion nearest to the major barrier for the surrounding region. Thus, for some basins, the horizontal view of the selected barrier is more closely approximated by the shape of the letter "J" than the truncated "U" shape obtained when equal weight was given to both sides of the ridge line.

The perimeter profile for each basin was obtained in order to compute the two parameters $\overline{H}_p$ and σ_p, denoting mean barrier elevation and standard deviation of barrier elevation about the mean, respectively. Normally, the distance between elevation measurements was one or two miles. A maximum change in elevation of 1,000 feet was permitted if no significant slope changes were present. The profile data were plotted [21] as shown in the typical samples of figs. 7 and 8. $\overline{H}_p$ was computed by numerical integration. σ_p was computed by the sum of squares procedure, assuming a straight line between profile points and taking discrete points from this continuous series of line segments at equal increments.

In the region of this study, the average wind direction during storms is from the west. Hence, an east-west axis of symmetry was selected for the measurement of basin orientation with respect to wind. The orientation, designated β, was measured from west to east in degrees. Thus, due west had a value of zero degrees and due east a value of 180 degrees.

Orientation with respect to solar radiation, denoted as α, was measured by a weighted average of the normals to the sides of polygons circumscribed about the basin periphery in such a manner as to approximate the shape of the basin. The various orientations were weighted equally by the length of the periphery represented by each side of the polygon and the mean elevation represented by each side. The elevations were taken from the previously constructed profile curves. Orientation was measured symmetrically from south to north with due south equal to zero degrees and due north equal to 180 degrees.

With the present day mapping techniques, it is common practice for the U.S. Geological Survey to indicate the areal distribution of vegetation on maps by green shading. To obtain an index of the amount of vegetation in a basin, the green areas within the basin boundaries were planimetered and expressed as a percentage of total basin area. These data were unfortunately not available for one area in Colorado.

Three parameters not obtained from the maps are basin area, longitude, and latitude. Basin area, designated A, was taken from the "Water Supply Papers." Longitude and latitude of stations, abbreviated Long. and Lat., respectively, were obtained from the same source. To magnify the differences in the station location, 104 degrees were subtracted from each longitude figure and 36 degrees from the latitude. This gave a range of about one to eight for each coordinate.

CHAPTER V

RESULTS

The derived prediction equations are divided into three groups representing the three mathematical models employed in the data analysis. These equations are further subdivided into objective and semi-objective categories and each of the latter categories is divided into three parts representing the entire region and two subregions designated A and B. The variables in the equations are listed in descending order of significance. Only statistically significant variables, as determined by the F-test at the ten percent level, are included. The derived prediction equations, categorized as discussed above, are presented in Table 4.

It is, of course, desirable to develop a prediction equation for the entire region under investigation. Of the six equations using data from all 79 basins, number (7) has the highest explained variance with an R^2 of 0.46. In order to obtain a more reliable means of estimating specific yield, the region was subdivided on the basis of climatological homogeneity. However, this endeavor was restricted by the size of the total sample as well as the areal distribution of the samples. Because of these restrictions and in order to obtain adequate prediction equations, it was necessary to delete from analysis the 16 basins located on the eastern side of the Continental Divide in Parts 6-B, 7 and 8. Two subregions were used as delineated on fig. 9. Subregion A, composed of

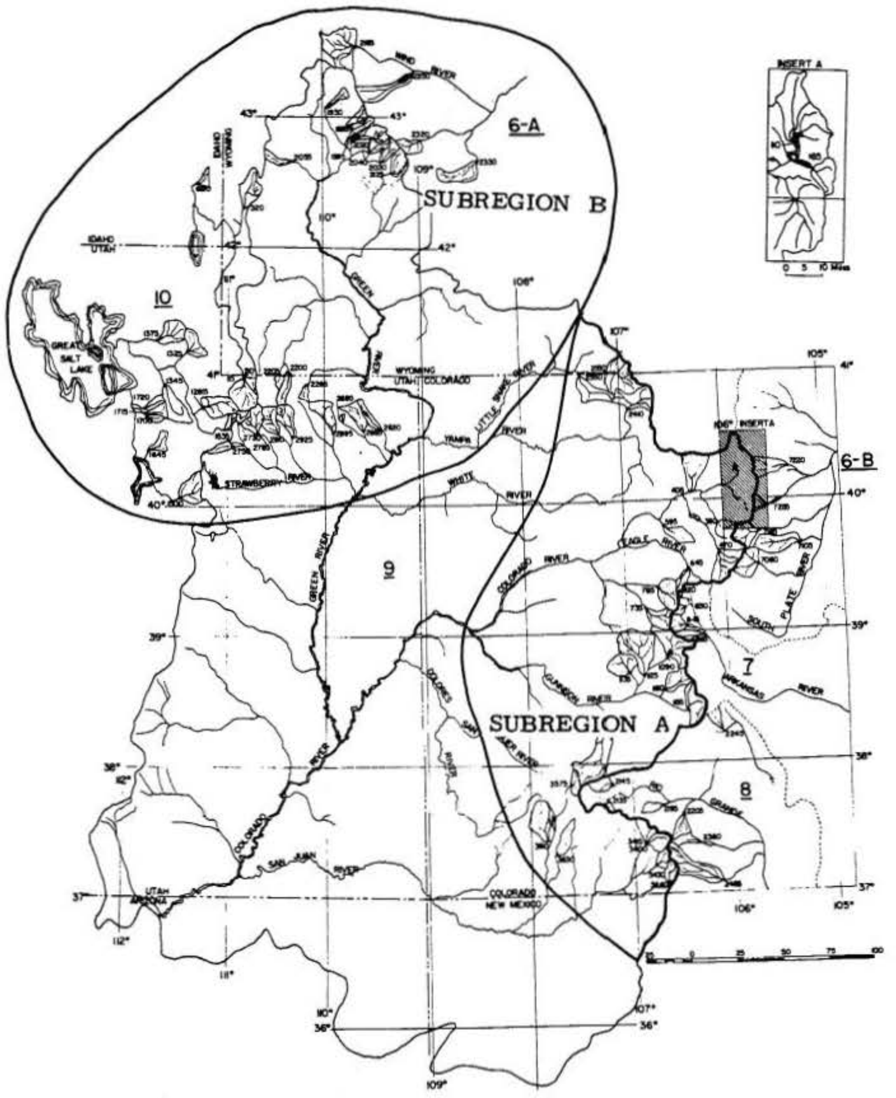

Fig. 9 Location of Subregions

25 stations, includes all basins on the western slope of the Continental Divide except those in the northern headwaters of the Green River. Subregion B, with 38 stations, includes all basins tributary to the Green River in Wyoming and Utah, as well as those basins on the Western slope of the Wasatch Mountains and those on the eastern slope of the Wind River Range. For subregions A and B, the equations with the highest explained variance are (14) and (9), respectively. Both equations have an R^2 of 0.77.

TABLE 4 PREDICTION EQUATIONS

Region	Eq. No.	Type	Equation	R^2
Entire	1	Objective, Linear	$q = -.8029 + .00020(H_{.50}) - .00148(\beta) + .05889(\text{Lat.}) - .00540(\alpha) + .00065(\frac{\Delta H_1}{L})$	.40
A	2	Objective, Linear	$q = -.6764 - .00193(\sigma) + .00086\ \Delta H_1 + .00223(\frac{\Delta H_1}{L})$	.72
B	3	Objective, Linear	$q = -5.1162 + .00030(H_{.10}) + .1964(\text{Lat.}) + .2961(\text{Long.})$	.62
Entire	4	Semi-Obj., Linear	$q = .05877 + .00015(\overline{H}_p) - .00044(\sigma_p) - .00140(\beta) - .00513(\alpha)$	.35
A	5	Semi-Obj., Linear	$q = .3905 + .00231[(\overline{H}_p - H_o)/L]$	.36
B	6	Semi-Obj., Linear	$q = -4.4322 + .00025(\overline{H}_p) + .1750(\text{Lat.}) + .2.682(\text{Long.})$	.55
Entire	7	Objective, Log	$\log q = -12.3015 + 3.2923\log(H_{.10}) + 0.3762\log(\text{Long.}) - .0968\log(\beta) - .05725\log(\alpha)$	.46
A	8	Objective, Log	$\log q = -6.6535 + 2.4420(\Delta H_1) + 0.5764(\frac{\Delta H_1}{L}) - 1.1369(\sigma)$	.56
B	9	Objective, Log	$\log q = -17.3753 + 3.2128\log(H_{.50}) + 2.4618\log(\text{Long.}) + 0.3969\log(\Delta H_1) + 1.6865\log(\text{Lat.})$	.77
Entire	10	Semi-Obj., Log	$\log q = -12.5996 + 3.0876(\overline{H}_p) + .3345(\text{Long.}) - .1009(\beta)$	.40
A	11	Semi-Obj., Log	$\log q = -7.1399 + .6655\log[(\overline{H}_p - H_o)/L]$	.29
B	12	Semi-Obj., Log	$\log q = -17.3997 + 3.6341\log(\overline{H}_p) + 1.3179\log(\text{Lat.}) + 2.1395\log(\text{Long.})$	.62
Entire	13	Objective, Taylor series	$q = -1.1318 + .0001994(H_{.50}) - .2020\times10^{-4}(\alpha\times\beta) + .00799(\text{Lat.})^2 + .1831\times10^{-6}(\Delta H_1 \times \frac{\Delta H_1}{L})$	.41
A	14	Objective, Taylor series	$q = -.2688 + 2.5279\times10^{-6}(\Delta H_1 \times \frac{\Delta H_1}{L}) - 6.664\times10^{-6}(\frac{\Delta H_1}{L}\times\sigma) + 2.81\times10^{-6}(\Delta H_1 \times \alpha) + .05464(\text{Lat.})^2 - .00278(\text{Lat.}\times\alpha)$	.77
B	15	Objective, Taylor series	$q = -2.1955 + 4.249\times10^{-5}(H_{.50}\times\text{Long.}) + 2.858(\Delta H_1\times\text{Lat.}) + .02345(\text{Lat.}\times\text{Long.}) - .00117(\text{Long.}\times\alpha)$	.74
All	16	Semi-Obj., Taylor series	$q = -0.7160 + 1.693\times10^{-4}(\overline{H}_p) - 3.86\times10^{-6}(\sigma_p\times\beta) + .00526(\text{Lat.})^2 - .00003(\alpha)^2$	.40
A	17	Semi-Obj., Taylor series	$q = 0.4297 + .1803\times10^{-6}[\overline{H}_p\times(\overline{H}_p - H_o)/L]$	.38
B	18	Semi-Obj., Taylor series	$q = -2.7335 + .0001756(\overline{H}_p) + .02943(\text{Lat.}\times\text{Long.}) + .00001100(\overline{H}_p\times\text{Long.})$	.55

CHAPTER VI

DISCUSSION AND CONCLUSIONS

1. Discussion of Results. It is apparent from Table 4 that the objective equations explain more variance than the semi-objective ones. The latter equations are consistent with hydrologic reasoning, however, and reveal that yield is dependent upon the barrier elevation, which appears in all equations, and other parameters which vary among the equations. Variability in parameters contained in the objective equations is also evident. One might expect to find a consistent set of parameters in all equations. However, it must be recalled that many of the physiographic parameters are correlated among themselves, and, in the stepwise regression procedure, one variable with an F-value just slightly higher than another will be entered at the exclusion of other correlated variables. When the sample is divided, as in this analysis, it is not at all unreasonable to expect variations in the relative significance of variables.

Although the logarithmic equation (7) explains more variance than any other using data from the entire region, eqs. (1) and (13) do not have a substantially lower value of R^2. Similarly, in the case of subregion A, eq. (2), composed of linear terms, has an R^2 value only slightly lower than eq. (14), which uses a Taylor series. The logarithmic equation (9) and the Taylor series equation (15), for subregion B, explain nearly the same amount of variance, with the latter having the higher value of R^2. Using R^2 as the index for selecting prediction equations dictates that eqs. (9) and (14), representing subregions A and B, respectively, would be used for estimating specific yield in the region of this study.

Comparison of the two selected subregional equations (9) and (14), reveals that ΔH and Lat. are common to both equations. The high significance of $H_{.50}$ in eq. (9) but complete lack of this parameter in eq. (14) can be partly explained by the low variability of median elevation in subregion A. The absence of slope as a variable in the equation for subregion B is difficult to explain. Although longitude and latitude are significant variables in eq. (9), only latitude appears in eq. (14). It is understandable that specific yield would not be a function of longitude in subregion A, as nearly all basins are located on the Continental Divide. The negative sign on the regression coefficient for the term $\Delta H_1 \times \sigma$ in eq. (14) is not consistent with hydrologic reasoning. This anomaly can be attributed to the interrelation between σ and ΔH_1 of the previous term. Factoring out $\frac{\Delta H_1}{L}$, which is common to both terms, and substituting average values for σ and ΔH_1 shows the net relation with the dependent variable to be positive. Thus, envisioning the two terms as a whole is more tenable.

Many of the variables excluded from these equations are highly correlated with those selected by the computer for inclusion in the relationship. For example, ΔH_2 could easily be substituted for ΔH_1 in eq. (9) with little decrease in explained variance. Many of the parameters obtained from the hypsometric curves are highly correlated among themselves.

Basin area is found to be substantially correlated with basin length. Thus, a prediction equation can easily be synthesized in which lift is represented by the combined effect of ΔH and A. As one would expect, area is inversely proportional to specific yield in this case. If one wishes to reduce the work of obtaining data for estimating specific yield, the above approach would be useful. However, a reduction in explained variance would be expected.

It is noteworthy that percentage vegetal cover is not significantly correlated with specific yield. One might expect this parameter to explain some of the nonhomogeneity between basins with differing amounts of vegetation. Apparently the amount of vegetation on an areal basis does not significantly affect specific yield in the basins for which such data were available.

2. Conclusions.

a. In meteorologically homogeneous mountainous regions, satisfactory prediction equations for specific yield can be obtained without passing through intermediate meteorologic and hydrologic processes.

b. Many of the physiographic parameters studied are correlated among themselves.

c. Parameters obtainable from hypsometric curves can explain a substantial portion of the variability in specific yield.

d. Basin elevation, slope, and rise are the most significant parameters.

BIBLIOGRAPHY

1. Plan to develop technology for increasing water yield from atmospheric sources: Office of Atmospheric Water Resources, Bureau of Reclamation, United States Department of the Interior, November 1966.
2. Gilman, Donald L.; Hibbs, James R.; and Paul L. Laskin; Weather and climate modification: U.S. Weather Bureau, July 10, 1965.
3. Saline water conversion, 1963 report: United States Department of the Interior, Office of Saline Water.
4. Weather and climate modification, 1966 report: The National Academy of Sciences - National Research Council.
5. Stinson, J. Robert, Project skywater - - The Bureau of Reclamation's atmospheric water resources program: Paper presented at the 35th Annual Meeting of the Western Snow Conference, Boise, Idaho, April 20, 1967.
6. Schaefer, V. J., The production of ice crystals in a cloud of supercooled water droplets: Science 104, pp. 457-459, 1946.
7. McDonald, James E., Physics of cloud modification: Advances in Geophysics, Vol. 5, pp. 223-303, Academic Press, 1958.
8. Bollay, E. and Associates, Park range atmospheric water resources program, phase 1: A water resources technical publication, Research Report No. 5, United States Department of the Interior, Bureau of Reclamation.
9. Schlaifer, R., Probability and statistics for business decisions: McGraw-Hill, 1959.
10. Mood, Alexander M. and Graybill, Franklin A., Introduction to the theory of statistics: McGraw-Hill, 1963.
11. Hess, Seymour L., Introduction to theoretical meteorology: Holt, Rinehart and Winston, Inc., 1959.
12. Bollay, E. and Associates, Park range atmospheric water resources program, phase II, part A: Interim Report prepared for the Bureau of Reclamation, November 15, 1966.
13. Fletcher, N. H., The physics of rainclouds: Cambridge University Press, 1962.
14. Puchalik, J., Memorandum, Civil Engineering Department, Colorado State University.
15. Ludlam, F., Artificial snowfall from mountain clouds: Tellus 7, pp. 277-290, 1955.
16. MacCready, P. B., Jr. and R. F. Skutt, Cloud buoyancy increase due to seeding: Journal of Applied Meteorology, Vol. 6, No. 1, pp. 207-210, February 1967.
17. Linsley, R. K., The relation between rainfall intensity and topography in Northern California: Research Report No. 1, Department of Civil Engineering, Stanford University, June 1956.
18. Russler, B. H. and W. C. Spreen, Topographically adjusted normal isohyetal maps for western Colorado: Tech. Paper No. 4, Division of Climatological and Hydrologic Services, Weather Bureau, U. S. Department of Commerce, August 1947.
19. Spreen, W. C., A determination of the effect of topography upon precipitation: Transactions of the American Geophysical Union, Vol. 2, No. 2, pp. 285-290, 1947.
20. Lee, R., Evaluation of solar beam irradiation as a climatic parameter of mountain watersheds: Hydrology Paper No. 2, Colorado State University, Fort Collins, Colorado, August 1963.
21. Julian, Robert W., Water yield-physiographic relationship in Colorado headwaters: M. S. Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado, December 1966.
22. Barrett, W. C. and C. H. Milligan, Consumptive water use and requirements in the Colorado River area of Utah: Special Report No. 8, Agricultural Experiment Station, Utah State Agricultural College, March 1953.
23. Blaney, H. F. and W. D. Criddle, Consumptive use and irrigation water requirements of crops in Colorado: Soil Conservation Service, U. S. Department of Agriculture, August 1949.
24. Colorado Water Conservation Board, Report of irrigation practices, Laramie River: July 1941.
25. Engineering Advisory Committee to the Upper Colorado River Basin Compact Commission, Final Report: November 29, 1948.
26. Smith, R. J., Water resources inventory for water division number 4 - State of Wyoming: 1965.
27. Voelker and Hunter, Value of water for irrigation in the Roaring Fork Basin of Colorado: Bureau of Agriculture Economics, U. S. Department of Agriculture, Washington, D. C., May 1950.
28. Chow, V. T., Handbook of Applied Hydrology: New York, McGraw-Hill, 1964.

Key Words: Water Yield, High Mountain Watersheds, Physiography

Abstract: A statistical method is presented that permits the estimation of yield of high mountain watersheds in terms of physiographic characteristics evaluated from maps. The method is advantageous because it does not require the knowledge of the climatic or hydrologic characteristics of the basin or of the region. The method is, however, limited to regions of reasonable climatic and hydrologic homogeneity. The applicability of the method is illustrated for several regions in the Upper Colorado River Basin. A coefficient of determination as high as 77 percent is obtained in the best case. In the worst result the coefficient falls below 50 percent. The estimate of specific yield is valuable for many applications. It provides, in particular, a means of deciding upon the suitability of basins to weather modification programs.

Reference: Julian, Robert W., Yevjevich, Vujica, and Morel-Seytoux, Hubert J., Colorado State University Hydrology Paper No. 22 (August 1967,)"Prediction of Water Yield in High Mountain Watersheds Based on Physiography."

Key Words: Water Yield, High Mountain Watersheds, Physiography

Abstract: A statistical method is presented that permits the estimation of yield of high mountain watersheds in terms of physiographic characteristics evaluated from maps. The method is advantageous because it does not require the knowledge of the climatic or hydrologic characteristics of the basin or of the region. The method is, however, limited to regions of reasonable climatic and hydrologic homogeneity. The applicability of the method is illustrated for several regions in the Upper Colorado River Basin. A coefficient of determination as high as 77 percent is obtained in the best case. In the worst result the coefficient falls below 50 percent. The estimate of specific yield is valuable for many applications. It provides, in particular, a means of deciding upon the suitability of basins to weather modification programs.

Reference: Julian, Robert W., Yevjevich, Vujica, and Morel-Seytoux, Hubert J., Colorado State University Hydrology Paper No. 22 (August 1967,)"Prediction of Water Yield in High Mountain Watersheds Based on Physiography."

Key Words: Water Yield, High Mountain Watersheds, Physiography

Abstract: A statistical method is presented that permits the estimation of yield of high mountain watersheds in terms of physiographic characteristics evaluated from maps. The method is advantageous because it does not require the knowledge of the climatic or hydrologic characteristics of the basin or of the region. The method is, however, limited to regions of reasonable climatic and hydrologic homogeneity. The applicability of the method is illustrated for several regions in the Upper Colorado River Basin. A coefficient of determination as high as 77 percent is obtained in the best case. In the worst result the coefficient falls below 50 percent. The estimate of specific yield is valuable for many applications. It provides, in particular, a means of deciding upon the suitability of basins to weather modification programs.

Reference: Julian, Robert W., Yevjevich, Vujica, and Morel-Seytoux, Hubert J., Colorado State University Hydrology Paper No. 22 (August 1967,)"Prediction of Water Yield in High Mountain Watersheds Based on Physiography."

Key Words: Water Yield, High Mountain Watersheds, Physiography

Abstract: A statistical method is presented that permits the estimation of yield of high mountain watersheds in terms of physiographic characteristics evaluated from maps. The method is advantageous because it does not require the knowledge of the climatic or hydrologic characteristics of the basin or of the region. The method is, however, limited to regions of reasonable climatic and hydrologic homogeneity. The applicability of the method is illustrated for several regions in the Upper Colorado River Basin. A coefficient of determination as high as 77 percent is obtained in the best case. In the worst result the coefficient falls below 50 percent. The estimate of specific yield is valuable for many applications. It provides, in particular, a means of deciding upon the suitability of basins to weather modification programs.

Reference: Julian, Robert W., Yevjevich, Vujica, and Morel-Seytoux, Hubert J., Colorado State University Hydrology Paper No. 22 (August 1967,)"Prediction of Water Yield in High Mountain Watersheds Based on Physiography."