THESIS

A STUDY TO PREDICT STORM RUNOFF FROM STORM CHARACTERISTICS AND ANTECEDENT BASIN CONDITIONS

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY Richard H. Hawkins

ENTITLED A STUDY TO PREDICT STORM RUNOFF FROM STORM CHARACTERISTICS AND ANTECEDENT BASIN CONDITIONS

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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RO — Surface runoff, including all overland flow and interflow for the storm in question, in thousandths of areal inches.

$\widehat{RO}$ — Predicted or calculated surface runoff, including all overland flow and interflow for the storm in question, in thousandths of areal inches.

$\underline{V}$ — Storm precipitation, in inches.

Q_{24} — The 24 hour antecedent flow at the Lower Missouri gaging station, in thousandths of areal inches.

I_1 — The one day antecedent rainfall for the watershed, in inches.

i_{30} — The maximum 30 minute rainfall intensity during the storm in question, in inches per hour.

g — The acceleration due to gravity: 32.2 feet per second per second.

c — The rational runoff coefficient, expressed as the decimal fraction of the storm rainfall which becomes storm runoff.

INTRODUCTION

The purposes of this report are twofold. First; to derive, describe, and test a number of different methods for predicting storm runoff from a Colorado Front Range watershed, and second; to relate runoff characteristics to the storm producing it. In short, to both predict and explain the runoff on the watershed in question.

The need for prediction equations in watershed work is urgent. Such equations can be used by both the researcher and the practitioner. In present watershed research the effect of treatment on a watershed is usually measured by paired watersheds--one treated, one untreated. An accurate prediction equation might eliminate the need for a second or control watershed. The effects could be measured directly, comparing observed runoff after treatment with computed runoff representing no treatment. Estimates of storm yield might also be useful for the manipulation of reservoir storage in water supply systems and flood control structures. Further, a prediction equation might show the relative importance of each factor concerned in producing runoff. These factors might then be altered accordingly to control runoff.

It was also hoped that if a sufficiently accurate prediction equation (or system) could be produced for a given watershed, that the constants in a prediction equation (or system) would be functions of the physical characteristics of the watershed. These, for example, might be the gradient of the channel, percent cover, average or mean elevation, or drainage density. If equations of the same form and accuracy could be developed for a number of different watersheds, their characteristics could then be related to the constants. For further studies, the runoff for a given set of conditions could be predicted using standard topographic maps, cover type maps, and soil surveys of the watershed. Thus, it is considered that this study is the first step of a larger study on the effect of watershed variables in runoff prediction.

It is a known fact that rainfall produces runoff. The rainfall, however, usually follows a varied but tortuous path to the stream channel, allowing many losses along the way. For a given storm, a substantial amount of potential storm runoff is lost through vegatative interception. That which is not lost in this fashion reaches the ground surface, to be detained again by the litter. Of the rainfall that reaches the soil mantle, a portion satisfies soil moisture requirements or becomes part of ground water storage. In some cases water may be held temporarily in the soil, and soon enters the channel as surface water. That which is not lost or detained thus far is available for surface runoff, and once the channel is reached, transportive losses occur. The entire process is subject to heavy evaporative losses, from either the soil, the vegetation, or the channel. Thus only a fraction of the rainfall from a storm survives to reach a point of stream flow measurement. In any case, the storm runoff is the difference between the precipitation and the losses incurred.

As the above outline of the hydrologic cycle suggests, losses vary, depending upon the characteristics of the storm producing the rainfall, the soil, the vegetal cover, the topography, and a number of other factors. Many of these are interdependent, difficult to measure, and of varied importance.

Other things being equal, the volume of runoff varies with the volume of rainfall. Also, runoff increases as the intensity of rainfall increases. It follows that runoff increases as the storage potential decreases. In general, as losses decrease, runoff increases.

This study attempts to estimate the effect of three factors (storm volume, storm intensity, and antecedent basin moisture conditions) on the production of storm runoff. This is the equivalent of estimating losses, as that which is lost does not appear as runoff.

The study was conducted on a Colorado Front Range watershed, Missouri Gulch, about 10 miles north of Woodland Park, Colorado. The stream is a minor tributary to the South Platte River, and in light of the ever increasing demand for water on Colorado's Eastern Slope, some research in runoff production from a representative Front Range watershed seems justified.

Review of Literature

The prediction of water yields from a single storm has merited little attention in the literature. More often, interest has centered around monthly, seasonal, or even annual yields. Considerable attention has been devoted to the prediction of peak flows from a storm, mainly for engineering and design purposes. A few of the more pertinent of these studies are reviewed to provide background for this thesis.

A number of methods of relating storm precipitation to storm runoff have been developed. These and several proposed methods will be discussed.

Estimating Peaks

Perhaps the most widely used method of computing peak flows is by means of the rational formula (Williams, 1949):

$$Q = C\ I\ A$$

where I is the storm intensity for the time of concentration in inches per hour, A is the area of the watershed in acres, and Q is the ultimate peak discharge in cubic feet per second. C is the coefficient of runoff, defined as the ratio of the volume of runoff to the volume of precipitation. This method is applicable only to small areas, where the storm can be assumed to cover the entire watershed, and is of long enough duration to allow the runoff to reach its ultimate peak. Typical values of C range from 0.1 to 0.2 for "forested areas" to 0.5 to 0.9 for concrete or bituminous pavement (Hewes and Oglesby, 1957). Much work has been done in an attempt to find accurate and descriptive values of C (Gregory, 1952; Tyler, 1950; Williams, 1949), but it is generally concluded that runoff is equal to rainfall minus losses, not rainfall times a percentage factor (Wisler and Brater, 1949), as the rational formula implies. That is to say, the value of C is not constant.

Another popular formula is the Talbot formula (Society of American Foresters, 1955):

$$A = Ca^{3/4}$$

where A is the required culvert cross sectional area in square feet, a is the area drained in acres, and C is the coefficient whose value depends on the topography. This method, although used by 35 state highway departments in 1951 (Exum, 1951), is also recognized as inadequate.

Many similar formulas have been used for predicting peak flows including the McMath formula (Steel, 1955) and the Burkli-Ziegler formula (Steel, 1955). These are as follows:

McMath $Q = A\ R\ C\ (S/A)^{1/5}$

Burkli-Ziegler $Q = A\ R\ C\ (S/A)^{\frac{1}{4}}$

in which Q is the peak flow in cubic feet per second, A is the area drained in acres, R is the average rate of rainfall in inches per hour, S is the average slope of the watershed in feet per 1000 feet, while C is the rational coefficient of runoff. These formulas have been used primarily in urban situations for the design of sewerage works.

All of the above formulas predict the ultimate peak flow, or the maximum flow that could occur.

Estimating Annual and Seasonal Runoff

Hydrologists have also been called upon to predict seasonal and annual yields. Ogihara (1957) suggested a new formula to express the relationship between annual rainfall and runoff:

$$y^3 - x^3 + ay = 0$$

where y is annual runoff, and x is annual rainfall, while a is a constant. However, he also warns that in most cases annual runoff plotted over annual rainfall approaches a straight line (in contrast to the above formula), and cites reasons:

> Every place on earth has its own climatic conditions.... Precipitation, being of local character, follows a more or less established pattern.... Consequently.... the relationships between annual precipitation and the annual runoff may also vary within a certain limited range, and if so, the relationship between the two can be represented by a linear equation. It is important to recognize, however, the suggestion of the application of a straight line is only an attempt to show this relationship graphically.

In the early 1900's, Dr. J.E. Church of the University of Nevada studied the prediction of seasonal runoff from snowmelt (Stafford, 1959). He attempted to correlate the spring level of Lake Tahoe with the water content of the snow on nearby Mount Rose. His equations predicted the level within ten percent until 1916, when the actual rise exceeded the predicted by 29 percent.

More recently, research was conducted in the Central Rocky Mountains of Colorado to investigate the relation of snowmelt to solar radiation, air temperature, wind, and relative humidity. Correlation analysis determined that the temperature factor alone was at least as good, and in many cases better than a combination of factors. (Garstka et al., 1958).

Estimating Storm Runoff

Multiple Regression: This method has been used to advantage many times for relating peak flows and sediment yields to storm and watershed characteristics. It is summarized by the U.S. Forest Service (1959):

> The method combines the least squares fitting of the best equation to the data and gives a measure of the significance of each of the effects, the probable range in error in the individual effects, and the error in the total effect. The tests of significance give a criterion to judge whether a given individual variable should be retained or dropped from an analysis.... The overall results are expressed in the form of an equation.

An excellent example of the application of the multiple regression approach is a study by Anderson and Trobitz (1949), who said:

> Multiple regression analysis was designed to give estimates of the degree of association between variables, without regard to cause and effect. However, in the application of regression results some degree of cause-effect may sometimes be inferred. In a strict statistical sense such an

> inference is justified for an independent variable only if all other variables correlated with it are either included in the analysis or are known to bear a cause-effect relationship to the independent variable. Such a condition can rarely be attained in practice; however, the reliability of estimates as to association and the possibility of reasoning as to cause are materially increased if the variables are set up on logical grounds and all the variables expected to be important are tested.

In a later work on sediment yields, Anderson (1957) defends the use of multiple regressions in the logarithmic form. It is also noted that the multiple regression method has been found useful by several research workers. The multiple regression will tell two things:

1. "....how the parts and characteristics of the watershed contribute to sediment yields."
2. "....how well we can predict the yield from a watershed by a study of the parts."

The log transformations were used for two chief reasons. First, if one variable is changed, the net effect on sediment yield depends upon the values of each of the other variables. When this is the case, the log form gives the simplest form of the function. Second, the variability of sediment depends upon the magnitude of the variables. When this is true, the log transformation gives a more valid estimate of error over the range of estimated sedimentation.

Finally, Anderson noted that "neglected" variables are not really neglected, but are hidden in other variables and distort the relationships found.

Potter (1955) studied the effect of topographic and rainfall factors on peak runoff in the Allegheny-Cumberland Plateau through multiple regression, and expressed the relationship in the following equation:

$$\text{Log } q = -1.421 + 0.0170\log A - 0.544\log T + 0.929\log P + 0.499\log S$$

where q is the peak rate of runoff in cubic feet per second, A is the area in acres, while T, P, and S were respectively factors describing topography, intensity of precipitation and frequency of storm occurrence. An analysis of covariance showed all the independent variables to be significant beyond the 0.1 percent probability level. Potter concluded that the reliability of estimates could be increased by the careful selection of independent variables.

More recently, an analysis of storm runoff of the Delaware River basin in Kansas by Sharp et al. (1960) by the multiple regression method provided several interesting conclusions:

1. ".... although the multiple regression approach will result in a line of best fit and best estimating equation for hydrologic data, it is not safe to place too much reliance on values estimated by such equations, particularly at levels far removed from the mean, despite high correlation coefficients."

2. ".... some of the more modern statistical procedures may be better tools than the multiple regression approach for evaluating effects of watershed parameters on water yield."

Dimensional Analysis: This is a comparatively recent process, that attempts to determine a function through the use of dimensionless ratios. Although not a method *per se*, it can be used as a helpful device in certain instances. Through a process of judicious selection all variables are grouped into a series of dimensionless terms that are then used in attempts at correlation. Simons et al. (1960), described the use of dimensional analysis in solving problems of flow in alluvial channels, and noted three ways in which dimensional analysis can be helpful:

1. Reduce the number of variables.
2. Make the results applicable regardless of the system of units used.
3. Systematize the research and the analysis of data.

It has been said that dimensional analysis is based on a single premise: That a phenomenon can be expressed by a dimensionally correct equation among the variables (Langhaar, 1951). This premise is both the strength and the weakness of this method. Dimensional analysis can give a partial solution with little work, but does not yield a complete solution. The process also reveals little of the inner workings of the phenomenon.

Dimensional analysis was applied to runoff from a watershed by Erzen (1949), who derived a relationship between rainfall, watershed area, and runoff for three watershed areas in Illinois. The relationship was as follows:

$$Q = g^{\frac{1}{2}}A^{3/4}H^{-1}f(tg^{\frac{1}{2}}A^{-\frac{1}{4}}, \nu^2 g^{-1}A^{-3/2})$$

where Q is the discharge at time t, g is the acceleration of gravity, A is the area of the watershed, H is the areal volume of rainfall, t is the time from the beginning of runoff, and ν is the kinematic viscosity of water. Erzen assumed that all the rainfall fell at one intant, that basin moisture conditions are inconsequential, that all rainfall runs off, and that intensity of rainfall does not have an effect. Despite all this, three watersheds were calibrated, and a close fitting curve derived (see Figure 1). The following substitutions were made:

$Y = Q\, g^{\frac{1}{2}}\, A^{-3/4}\, H^{-1}$ $\quad X = tg^{\frac{1}{2}}\, A^{-\frac{1}{4}}$ $\quad K = \nu^2\, g^{-1}A^{-3/2}$

Then $Y = f(X,K)$

Because the three watersheds were in similar geologic and geomorphic areas, X was assumed to be the same in all three cases studied. It should be noted that if A, ν, and g can be considered as constants for a given watershed, the remaining variables X and Y can be reduced to $Y=K_1\ (Q/H)$, and $X = K_2(t)$.

No mention was made as to the suitability of the technique.

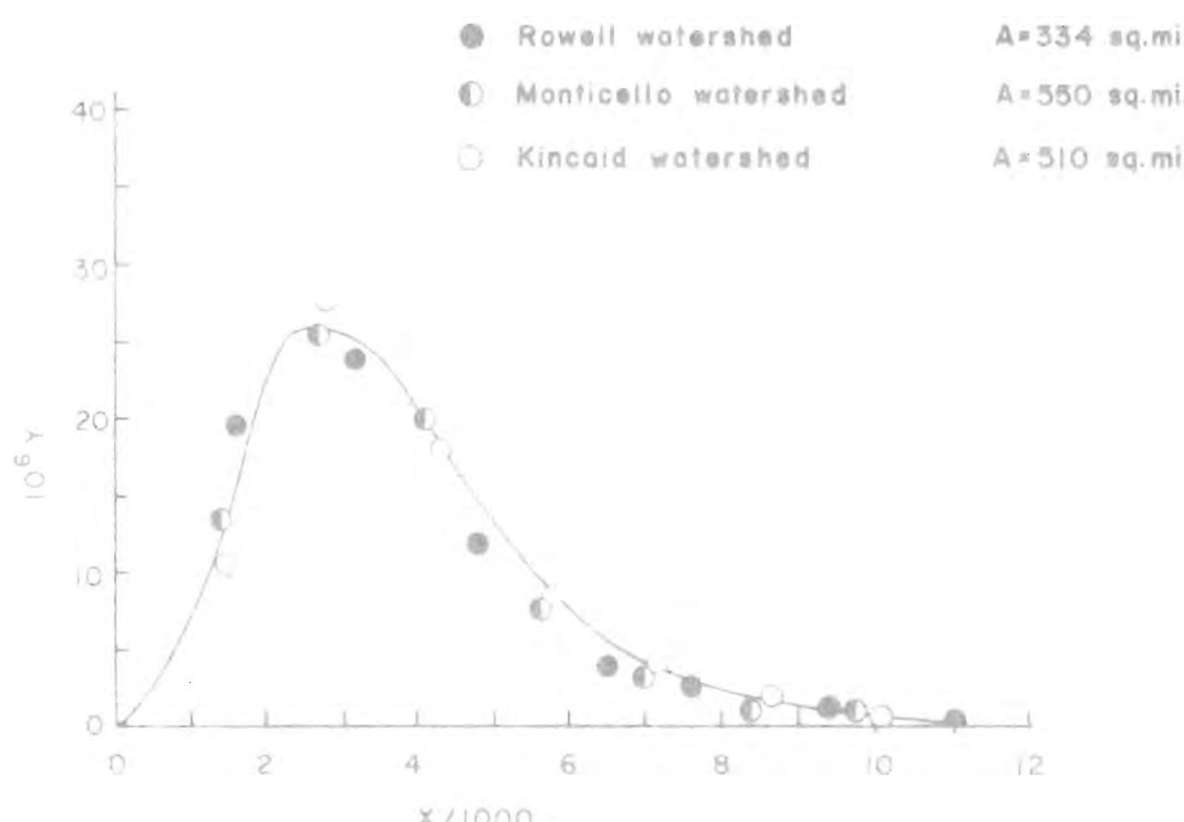
Graphic: Perhaps the most successful and promising method is that of coaxial graphical correlation. The method is described by Ezekiel (1941), and was enlarged upon by Kohler and Linsley (1951). The method might also be called "graphical successive elimination". It has the advantage of having considerable freedom in its final form,

Figure 1

Erzen's Runoff Curve

An application of dimensional analysis

(Erzen, 1951)



and adjustments for various factors are easily seen through graphical means. However, application is both laborious and time consuming.

The method is based on the premise that if an important factor is left out of the correlation it will be evident in the scatter of points on a plot of the relation. That is, the scatter can be explained through the omitted factor (Kohler and Linsley, 1951).

Kohler and Linsley (1951) made an analysis of the storm runoff for the Monocacy River at Jug Bridge, Maryland, and evolved what seemed to be fairly accurate results. (No mathematical criteria of accuracy are provided by this method.) An improvement of the method was made by Miller and Paulhus (1957), and it was postulated that certain of the relationships derived could be used on other small basins in a given region.

Successive Elimination: No previous application of this method to the estimation of storm runoff could be found in the literature, but Ezekiel (1941) covers the subject adequately, and summarizes that ".... (successive elimination) can gradually determine the net association of each factor, but the method is long and laborious." Ezekiel also states that a shorter mathematical method is available which gives the same results. This shorter method is known as multiple regression.

Other Methods Used Estimating Storm Runoff

A number of other methods have been considered. Although they fall outside the scope of this paper, they are of merit from the standpoint of scientific interest.

Infiltration: The infiltration capacity approach has received a great deal of attention in the past, but interest has receded in recent years. This method postulates that the rainfall that does not infiltrate into the soil (rainfall excess) will appear as runoff. The present state of knowledge was summed up by Cook (1946), and some of his more important points are listed below:

1. Only surface runoff can be determined from infiltration data.
2. Runoff must be separately calculated from each complex, and these values summed to obtain the runoff from a multi-complex area.
3. The only rational way to calculate the runoff from a single complex is by the use of infiltration curves.
4. Infiltration data should be accompanied by a full description of the process used in their determination.

Coltharp (1955) applied the infiltration capacity approach to watersheds fairly close to the study area of this paper, and found that only one-tenth of the rainfall excess appeared as runoff. Although the soils are different, the topography and vegetation are somewhat similar to parts of the study area. In the light of this, and item 2 above, the infiltration approach was not used in this paper.

Unit Hydrograph: The unit hydrograph or unitgraph (Sherman, 1932), has been in use for a number of years as a method of predicting storm runoff, and was thought by some to be a panacea for hydrologic problems. The popularity enjoyed by this method may be in part an explanation for a lack of development of other methods. In any case, time has shown it to have notable shortcomings (Barnes, 1959). Often the successful application of the unit hydrograph method calls for an amount of personal judgement for success, and the method falls down on a number of different assumptions. Two of the most important of these assumptions are that the entire watershed is contributing runoff, and the lag time is a fixed period for a given watershed. Informal studies on the nature and amount of data available as well as the characteristics of rainfall and runoff have indicated that the unit hydrograph method is not applicable to this study.

Others: A number of recent efforts center around soil moisture as a key parameter. For a set of agricultural watersheds near Edwardsville, Illinois, Minshall (1960) developed time retention curves for each soil-cover combination, based on antecedent precipitation and season. Then, storm runoff was estimated from the precipitation pattern and the time retention curves. It was concluded that runoff from the most important storms could be estimated with "reasonable accuracy" from the mass rainfall diagram and the time retention curves.

In a northern Mississippi study, surface runoff was strongly correlated with storage opportunity in the upper six inches of soil. The predictions were most accurate for the winter period, and least accurate for the high intensity storms (Thames and Ursic, 1960).

Previous Studies on the Missouri Gulch Watershed

Although the study area was instrumented for twenty years (1939 through 1959), comparatively little has been written on it. Annual Reports of the Rocky Mountain Forest and Range Experiment Station (U.S. Forest Service, 1949, 1950) mention the physical and hydrologic characteristics of the Missouri Gulch watershed. An attempt at relating storm runoff to storm volume and six-day antecedent runoff was published in the 1949 Report, where it was found that volume of precipitation and antecedent flow accounted for 80 percent of the variation in storm runoff, with precipitation alone accounting for more than half.

Rosa (1954) carried out some specialized investigations of runoff on Missouri Gulch, and found from a study of eight storms, that lag time varied from eighteen to thirty-five minutes, with an average of twenty-eight minutes. It was also determined that 50 percent of the storm runoff occurred within about twenty-two minutes of the start of runoff, while storm runoff generally ended about ninety minutes after it began.

Dortignac and Love (1960) described some of the characteristics of infiltration on Missouri Gulch, acknowledging that the aspen sites had the highest infiltration rates. Berndt (1960) made a general study of precipitation and runoff on Missouri Gulch, describing the nature and character of runoff, both on an annual basis and for individual storms. Some of Berndt's conclusions are dealt with more specifically in a description of the study area.

Methods and Materials

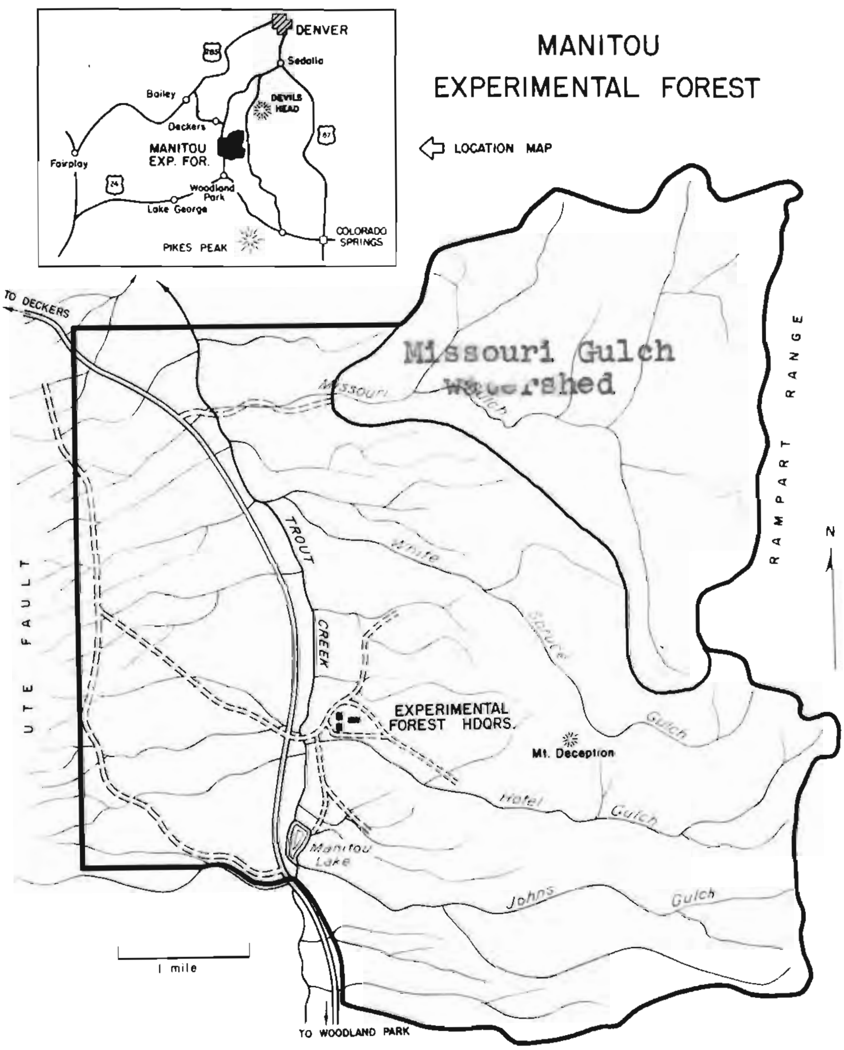
Study Area

General: The study area for this thesis is the Missouri Gulch Watershed, in the Manitou Experimental Forest, located about eight miles north of Woodland Park, Colorado. The watershed is 4600 acres in size, and is located in parts of Douglas, El Paso, and Teller Counties. The Experimental Forest is administered by the U.S. Forest Service, under the direction of the Rocky Mountain Forest and Range Experiment Station, located in Fort Collins. The Experimental Forest and some of its functions are described in some detail by Love (1958), and more detailed descriptions of the watershed follow in this section. The general location of the study area is shown in Figure 2.

History and Present Land Use: Although relatively inaccessible, the watershed has been used in the past for a variety of purposes. It has been grazed for years, and logging and burning have also taken place in parts, while other parts contain lands of overmature timber. There are a number of mine prospecting holes throughout the watershed, but the area is now closed to mining exploration.

The watershed is presently grazed as part of a regular Forest Service allotment, and there is a small

Figure 2


MANITOU
EXPERIMENTAL FOREST
LOCATION MAP
DENVER
Sedalia
Bailey
Deckers
DEVILS HEAD
MANITOU
EXP. FOR.
Fairplay
Woodland Park
Lake George
COLORADO SPRINGS
PIKES PEAK
TO DECKERS
Missouri Gulch
Watershed
Missouri
Gulch
TROUT
CREEK
White
Spruce
Gulch
EXPERIMENTAL
FOREST HDQRS.
Mt. Deception
Hotel
Gulch
Manitou
Lake
Johns
Gulch
UTE FAULT
RAMPART RANGE
N
1 mile
TO WOODLAND PARK

amount of recreational use: fishing in the lower reaches of Missouri Gulch, and some hunting during the fall months. The eastern edge of the watershed coincides with the Rampart Range Road, which is popular during the summer months as a scenic drive from nearby Colorado Springs. No doubt there is some picknicking and other similar recreational use during the summer months.

However, the primary purpose of the watershed is that of research in land use and watershed management. The watershed is thought to be somewhat typical of the Colorado Front Range.

Soils and Vegetation: The soils of the watershed are derived primarily from Pike's Peak granite, with a small area of soils formed from Madison limestone. Soils derived directly from these sources comprise about 66 percent of the total watershed area.

The granite derived soils tend to be acid, infertile, low in organic material, and highly erodible, while extremely porous. Some areas of these soils exist with little or no vegetation, and on slopes which range up to 60 percent. The surface soils are shallow, with loose gravel commonly making up more than 50 percent of the soil.

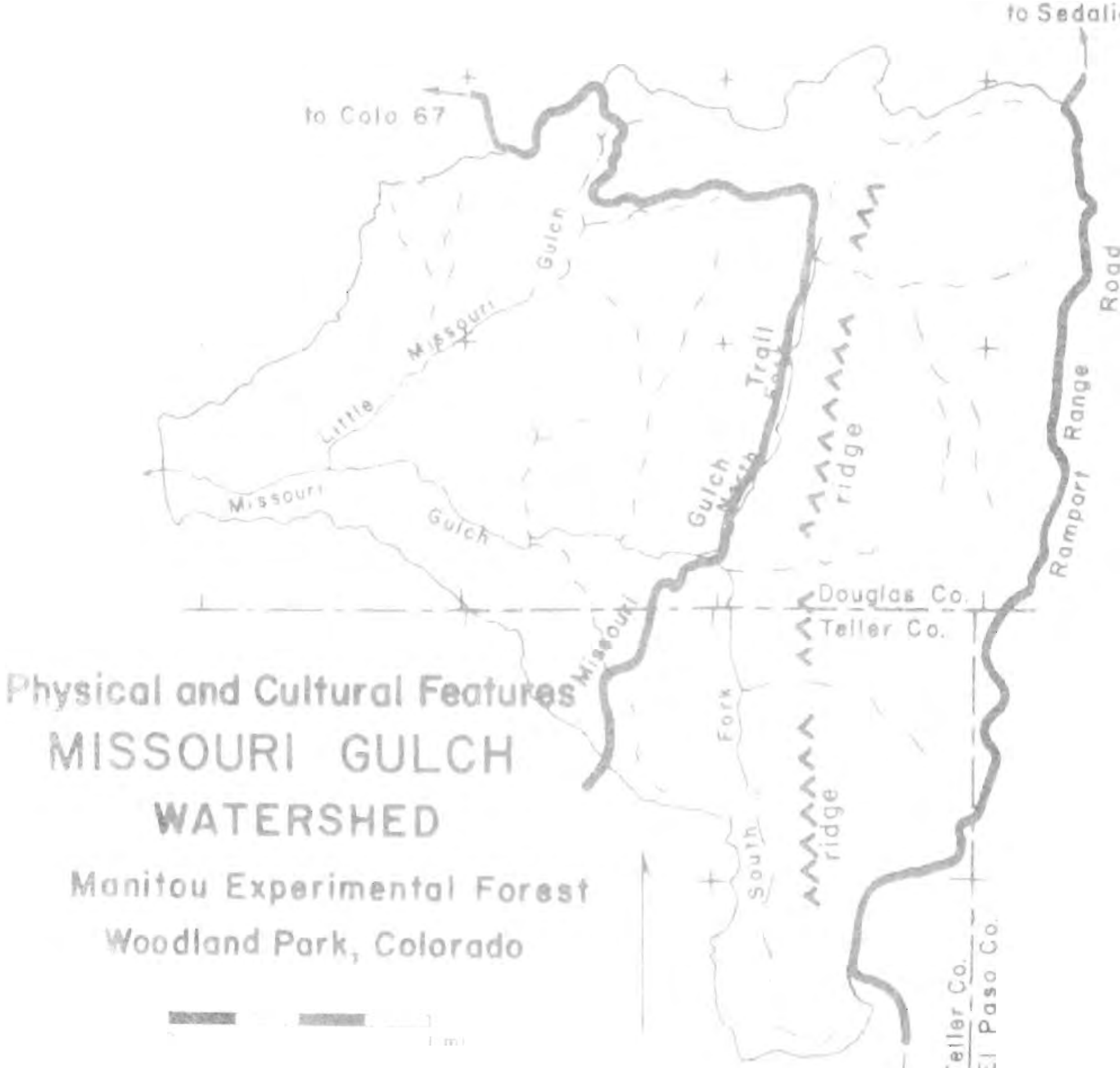
The limestone derived soils, are generally fertile and have excellent moisture relations. They contain a high percentage of calcareous rock, with a substratum of rock fragments with fine soil materials in the fissures. Erosion is not a serious problem on this soil, and gullies usually grass over in a short time (Retzer, 1949).

Alluvial soils occupy about 16 percent of the land area of the watershed, and are found in stream bottoms and alluvial fans. These soils are usually occupied by pure stands of quaking aspen, and exhibit a very high infiltration capacity.

Less than 1 percent of the watershed is in meadows and bogs, while close to 18 percent is exposed rock, mainly bare unweathered granite. Much of this bare rock is concentrated in a sheer rock ridge along the eastern wall of the main valley of the North and South Forks. (See Figure 3)

The distribution of the soils and surface conditions are shown in Figure 4 and Table 1, while a more detailed description of the soils with their relation to vegetation is found in the Appendix.

Figure 3



Source: Pantograph reduction of U.S. Forest Service planimetric map (1:7920), by H.W. Berndt, 1956

Figure 4


Little Missouri Gulch
Missouri Gulch
North Fork
South Fork
Geologic Origin of Soils
MISSOURI GULCH
WATERSHED
Manitou Experimental Forest
Woodland Park, Colorado
0
1 mi.
Source: Pantograph reduction of U.S. Forest Service planimetric map (1:7920), by H.W. Berndt, 1956.
Legend
Pikes Peak granite
Madison limestone

Table 1

DISTRIBUTION OF SOILS AND SURFACE CONDITIONS IN THE MISSOURI GULCH WATERSHED

Soil or Surface Condition	Area (Acres)	Percent Area
Granite Soils		
Edloe gravelly sandy loam	2123	46.1
Stecum gravelly sandy loam	787	17.1
Limestone Soils		
Chubbs stony loam	114	2.5
Alluvial Soils	725	15.8
Meadows and Bogs	26	0.6
Bare Rock	825	17.9
Totals	4600	100.0

Source: Berndt (1960)

Timber covers about 84 percent of the land area of the Missouri Gulch watershed. There is some overmature timber in the South Fork drainage, however much of the watershed is covered with scattered ponderosa pine and Douglas-fir, or small dense lodgepole pine stands, reflecting past logging and burning. The bottoms are generally in either grass or aspen, or a combination of the two. On north exposures ponderosa pine and Douglas-fir predominates, while south facing slopes tend to be free of trees, and the cover consisting mostly of brush and grass. The remainder of the watershed (9%) is bare rock and erosion pavement.

The porosity of the soil mantle is reflected in high infiltration rates. Test results from runs with the Rocky Mountain infiltrometer are shown in Table 2.

Table 2

INFILTRATION RATES FOR THREE COVER TYPES, MISSOURI GULCH WATERSHED

Cover Type	Infiltration Rate* (Inches per hour)
Quaking Aspen	4.30
Mountain brush	3.22
Ponderosa pine	3.14

*Last twenty minutes of a fifty minute run
Source: Berndt (1960)

Figure 5 shows the distribution of native vegetation in Missouri Gulch. The areal extent of the vegetation is summarized in Table 3.

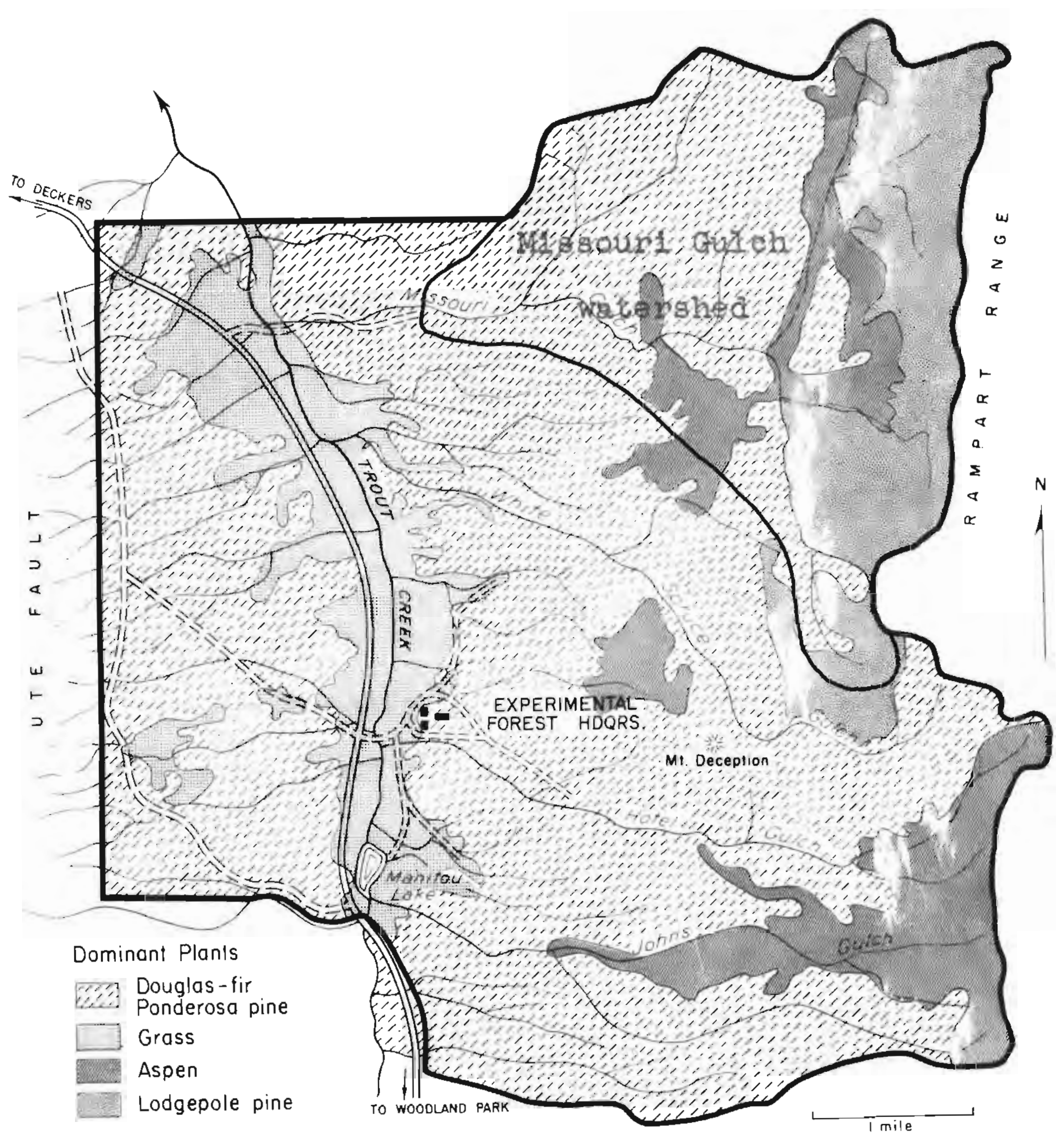
Table 3

EXTENT OF VEGETATION, MISSOURI GULCH WATERSHED

Cover Type	Area (Acres)	Percent Area
Lodgepole pine-Engelmann spruce	1119	24.3
Ponderosa pine-Douglas-fir	1372	29.8
Quaking aspen	392	8.5
Mixture	966	21.0
Brush and grass	352	7.7
Erosion pavement	316	6.9
Bare rock	83	1.8
Totals	4600	100.0

Source: Berndt (1960)

Figure 5
Dominant Plants
Manitou Experimental Forest



<u>Topography</u>: The Missouri Gulch watershed heads at approximately 9400 feet elevation in the Rampart Range, and flows generally westward to its confluence with Trout Creek at about 7500 feet elevation. The waters of Trout Creek join the South Platte river near Deckers, Colorado.

The drainage pattern is a combination of trellis and dendritic. This is thought to be due to a sheer rock ridge in the eastern part of the watershed (See Figure 3), and a combination of erodible soils and steep slopes elsewhere. Because of the presence of this rocky ridge, the eastern part of the watershed is a semi-plateau, being several hundred feet above the main stems of the North and South Forks. This upland is thought to be a remnant of the Rocky Mountain peneplain (Worcester, 1946). The area-elevation curve for the watershed (See Figure 6) reflects the presence of this plateau with an aberration in the curve, which occurs at about 8800 feet elevation.

Slopes in the watershed range from 10 to 60 percent. The maximum elevation in the watershed is 9362 feet, while the minimum is 7700 (at the Lower Missouri Gulch gaging station); the mean elevation is 8676 feet.

Some concept of both the shape and the drainage characteristics of the watershed is illustrated in Figure 7. About 80 percent of the land area is within three miles of the mouth, while no point is greater than 3.72 miles away.

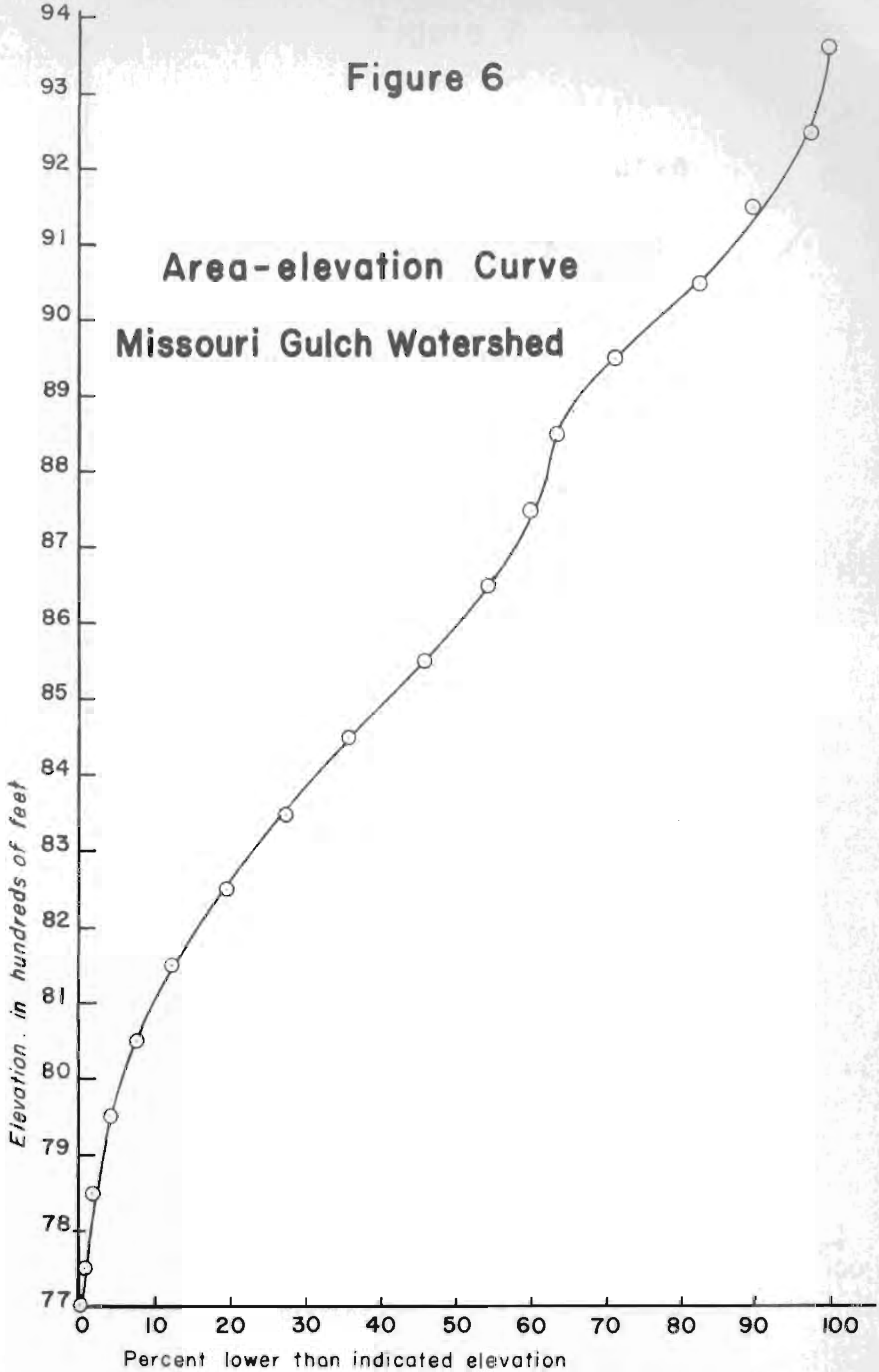
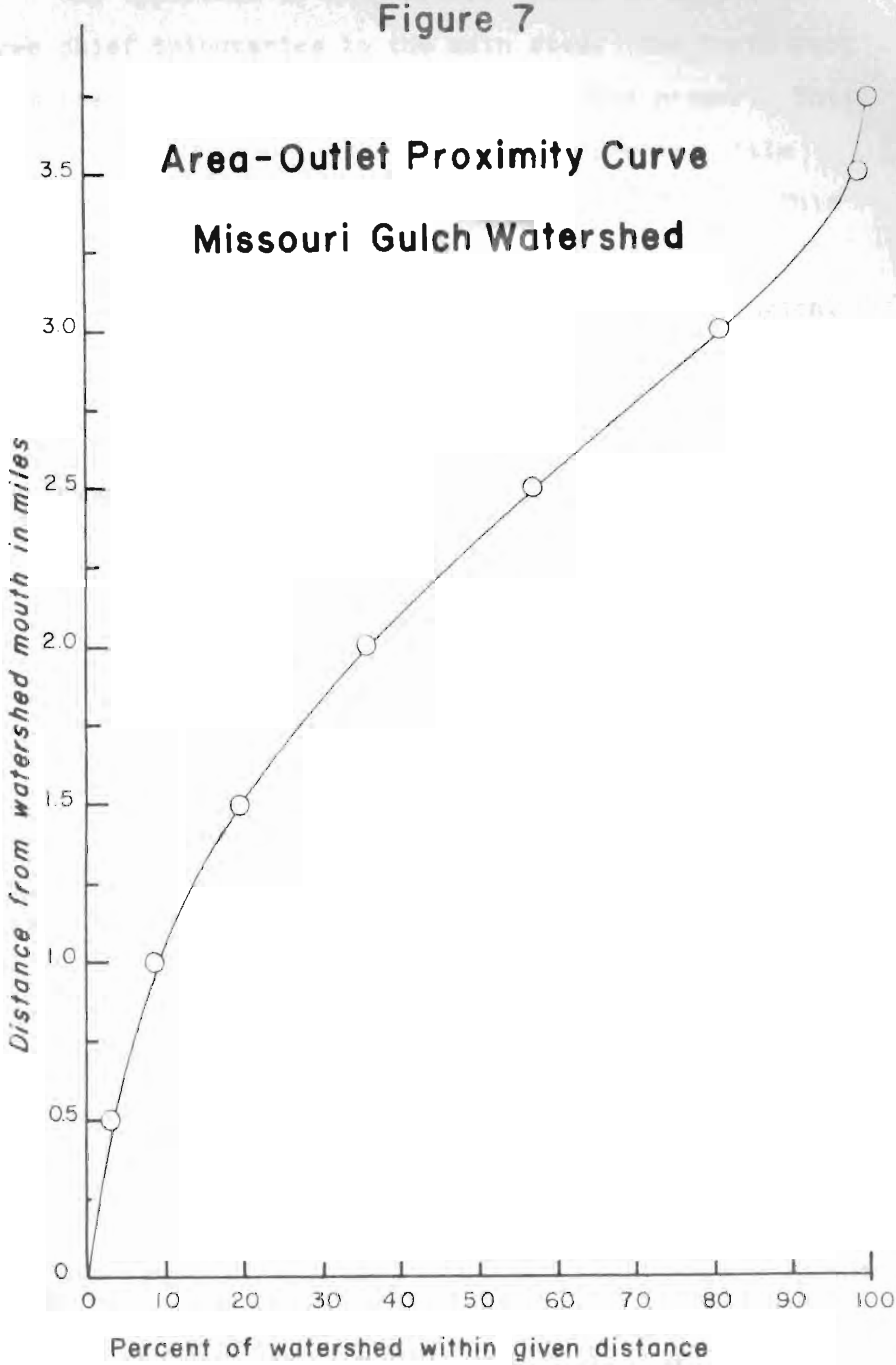


Figure 6
Area-elevation Curve
Missouri Gulch Watershed
Elevation in hundreds of feet
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
0
10
20
30
40
50
60
70
80
90
100
Percent lower than indicated elevation

Figure 7


Area-Outlet Proximity Curve
Missouri Gulch Watershed
Distance from watershed mouth in miles
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
10
20
30
40
50
60
70
80
90
100
Percent of watershed within given distance

The watershed is roughly triangular in shape, with three chief tributaries to the main stem. The North Fork joins the South Fork to form Missouri Gulch proper. This stream is joined about two miles downstream by Little Missouri Gulch, which is the last major tributary. This stream pattern is shown in Figure 3.

Climate and Hydrology: The nearest climatological station to the study area is located at the Experimental Forest headquarters, about 2½ miles from the Lower Missouri Gulch gaging station. This climatological station, at an elevation of 7740 feet, has an average temperature of 40.6°F., and the climate has been described as mild (Love, 1958).

No temperature measurements were taken on the study area. The annual precipitation on the watershed for the period 1940 to 1959 was 18.27 inches (Berndt, 1960). Much of this precipitation comes during the summer months in the form of thunderstorms, yielding rain of high intensity but short duration. Most of the storms studied in this paper are of this type.

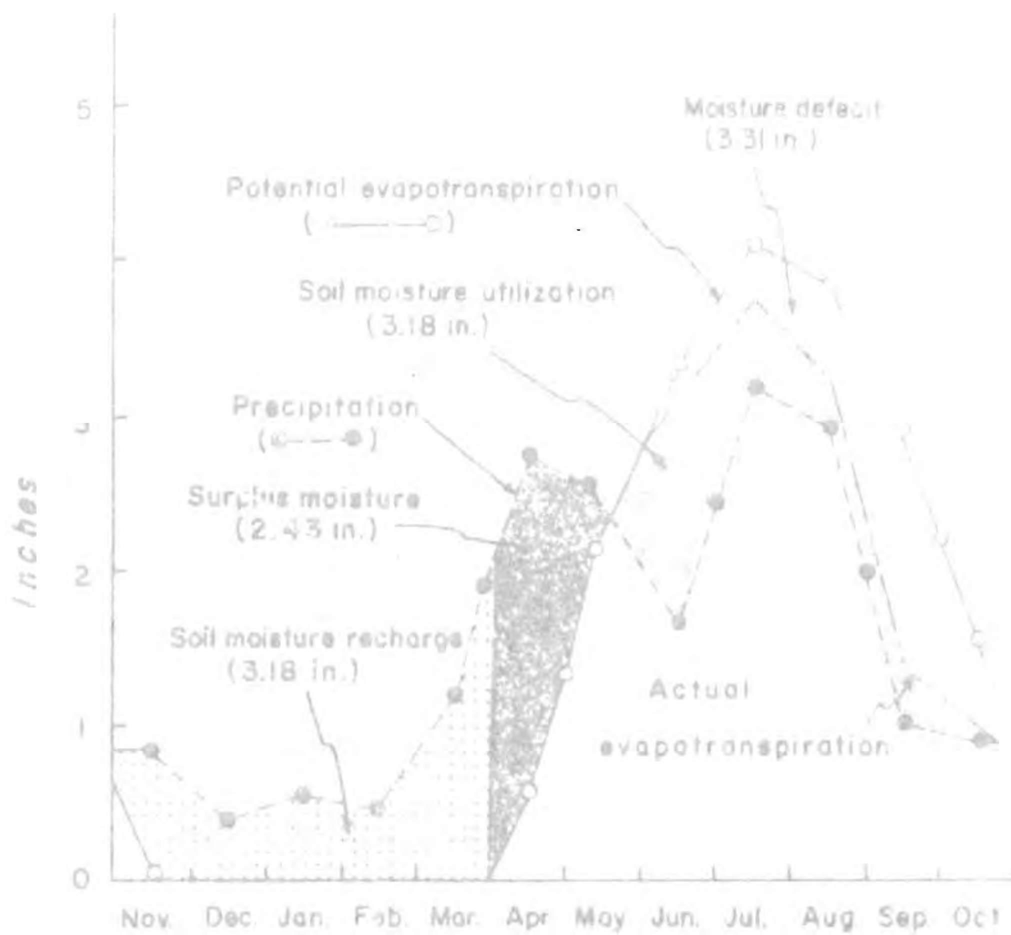
From the headquarters temperature data and the Missouri Gulch rainfall data, an estimate of the water balance was determined by Berndt (1960) for the study area. This is shown in Figure 8. Typically, there is a surplus of moisture in the winter, and a deficiency in the summer, starting about the middle of May.

Figure 8

Water Balance

Missouri Gulch watershed

from Berndt (1960)



The average thunderstorm on Missouri Gulch yields a low percentage of streamflow, frequently less than 1 percent of the storm precipitation. Similarly, on an annual basis, less than 10 percent of the precipitation becomes runoff. More than half the annual runoff comes in May and June, as the result of spring snowmelt, while most of the storm flow comes during the summer months, as the result of thunderstorm activity.

An observer on the watershed during a typical thunderstorm would witness little surface runoff per se. Due to the geologic nature of the watershed, i.e., deep, porous, and uniform subsoil conditions, it is believed that most of the precipitation enters the soil, and becomes interflow, or subsurface flow, and that there is, in fact, very little overland flow. The high infiltration rates (Table 2) suggest this explanation.

Missouri Gulch flows most of the year, but disappears underground in some places during periods of low flow. The North and South Forks dry up in places, but a few pools can usually be found in their courses. Little Missouri Gulch is also a perennial stream, in fact, showing some signs of being a more efficient water producer than the two previously mentioned sub-watersheds.

Instrumentation

Stream Gaging: The stream gaging system in the watershed consists of a two-foot San Dimas flume at the mouth of the watershed (See Figure 9), and two 90° V-notch weirs,

Figure 9. San Dimas flume installed near the mouth of the Missouri Gulch watershed. From Berndt (1960).

Figure 10. 90° V-notch weir installed in North Fork of Missouri Gulch. From Berndt (1960).

installed on the North and South Forks, just above their confluence (See Figure 10).

The San Dimas flume rests on bedrock, and therefore measures the total flow at this point. However, ice collects in the winter, and no accurate record of winter runoff is available. The streamflow records cover the period from 1940 to 1959, and the gage was usually in operation from April 1 to November 1.

The V-notch weirs were installed in 1951 to measure tributary flow. These weirs, however, did not measure total flow, as they were on alluvium rather than bedrock. It is estimated that about 90 percent of the flow was gaged. The water level recorders were operated during the same months as the San Dimas flume. Although the stilling wells froze during the winter, the flow was of sufficient velocity to keep the weir blades free of ice, and staff gage readings were taken periodically to provide an estimate of the flow.

Precipitation Measurements: The watershed was originally provided with a rather dense network of rain gages, including five recording gages and over a dozen standard gages located strategically throughout the watershed. Over the years, some of the standard gages were found to be redundant, and were consequently eliminated from the system. When the Missouri Gulch studies were concluded (September, 1959), only nine standard gages and five recording gages were in operation. However, for the purpose of this study, the precipitation for the 4600 acre watershed was measured by a system of eleven gages, five recording gages and six non-recording (standard) gages.

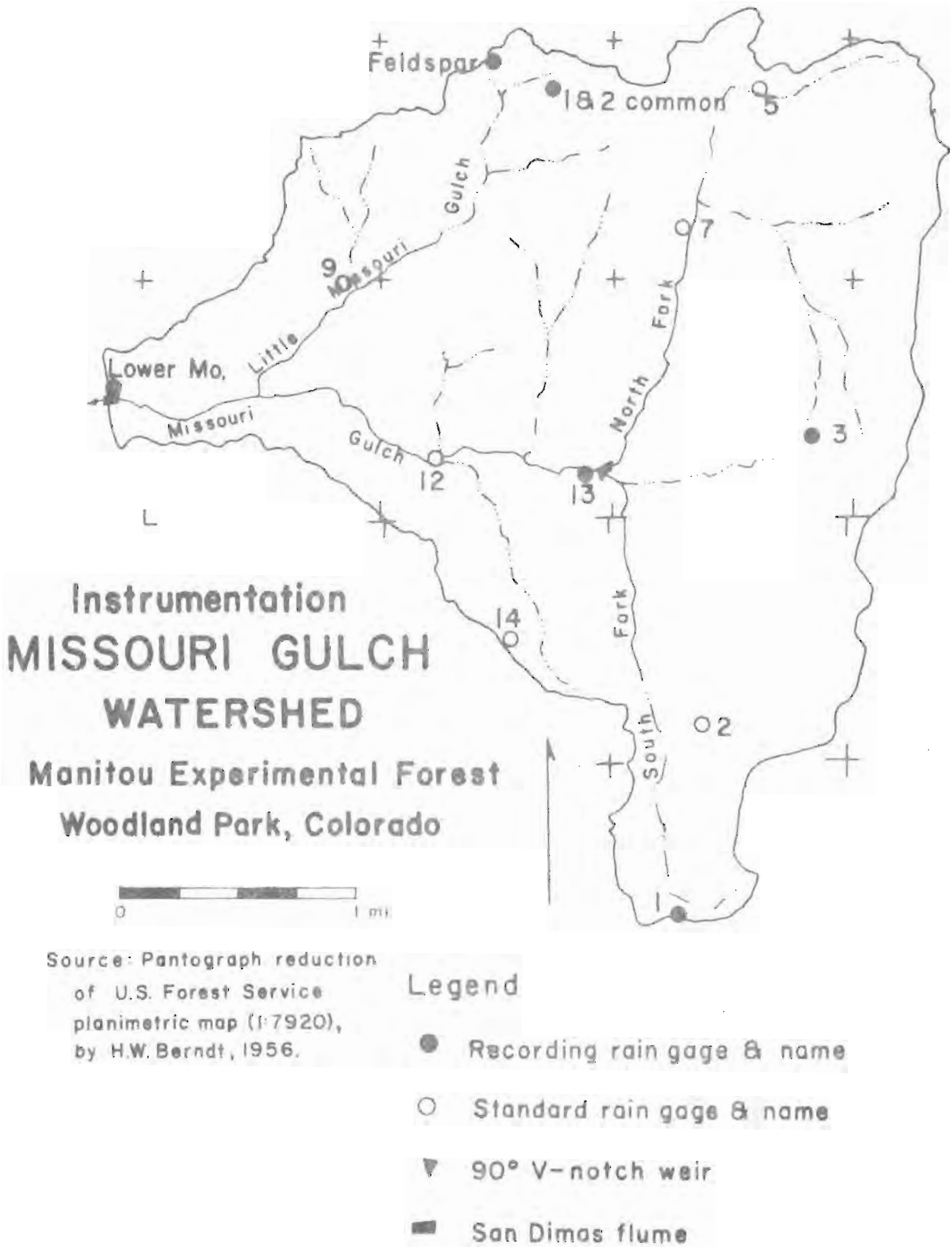
In 1955, one recording gage was moved to a more accessible location, and the station name changed from 1&2 Common to Feldspar.

The location of the various rain gages, as well as the location of the stream gaging station are shown on Figure 11.

Data Reduction

Storm Volumes and Intensities: The individual storm information was taken from the recording rain gage charts and several weekly standard rain gage records. From each of the recording gage charts intensity information and the size of the storm was compiled. A storm is defined as continuous rainfall with no intensity less than 0.05 inches per hour for an hour's duration. The intensity information was averaged using a Thiessen Mean for the gages reporting, and this value was used as the intensity of the storm. Both the maximum twenty-minute and the maximum thirty-minute intensities were computed for each storm (i_{20}, i_{30}), but only the thirty minute intensity was used in the final analysis.

Figure 11


Feldspar
1&2 common
5
Gulch
7
9
10
Missouri
Little
Lower Mo.
Missouri
Gulch
12
13
North
Fork
3
14
Fork
South
2
1
Instrumentation
MISSOURI GULCH
WATERSHED
Manitou Experimental Forest
Woodland Park, Colorado
0
1 mi
Source: Pantograph reduction
of U.S. Forest Service
planimetric map (1:7920),
by H.W. Berndt, 1956.
Legend
Recording rain gage & name
Standard rain gage & name
90° V-notch weir
San Dimas flume

Storm precipitation taken from the recording gage charts was expressed as a percent of the week's total rainfall at that station. These values were then plotted on a map of Missouri Gulch, and lines of equal percentage were drawn (See Appendix). Percentage values were then interpolated for the standard gage stations, and the interpolated percentage was multiplied by weekly rainfall to give the storm rainfall at that station. Then, having the storm rainfall for all selected stations in the watershed, the Thiessen Mean value of the rainfall was determined, and this figure was used as the storm rainfall (V) for the watershed.

<u>Antecedent Precipitation Index</u>: The one day antecedent precipitation (I_1) provided an index of soil moisture. The one day antecedent precipitation was used after preliminary analysis of the two day, five day, and seven day antecedent precipitation. These parameters showed either little value as an index, or a strong correlation with the one day antecedent precipitation. The data for individual storms were computed from the Missouri Gulch recording rain gage charts. In most cases, all stations had records, and only a few times was the information for less than the total number of stations used to represent the entire watershed. The information was averaged using a Thiessen Mean, and the results considered as an antecedent precipitation index; a measure of antecedent basin moisture conditions.

Runoff: The recorder charts at the Lower Missouri gaging station (San Dimas flume) for 20 years were inspected to find hydrographs which would lend themselves easily and accurately to separation. All seemingly usable hydrographs were not used, as some resulted from snow, some had no rainfall associated with them, some had no rainfall records with which to be correlated, and some were thought to be the result of bursting beaver dams.

The hydrographs which were usable in light of the above restrictions were separated from their baseflow by the method of Barnes (1940). This method utilizes three straight lines on the receding limb of a hydrograph on a semi-log plot, and is illustrated in the Appendix. Runoff volumes were then calculated from the records and expressed in thousandths of areal inches (RO).

Others: The twenty-four antecedent runoff (Q_{24}) was taken from the runoff records at Lower Missouri Gulch, and expressed in thousandths of areal inches. The percent runoff (C) was computed from previous computations of the rainfall and runoff. It should be noted that generally less than one percent of the rainfall appeared as runoff.

Examples of all the above calculations are shown in the Appendix, and the completed data are tabulated in a Master Data Sheet, Table 4.

Table 4

MASTER DATA SHEET,
MISSOURI GULCH WATERSHED

Storm Date	RO 0.001 in.	P in.	I_{30} iph	Q_{24} 0.001 in.	I in.	C
7-29-40	4.549	0.66	0.72	3.314	0.07	0.00682
8-22-40	2.066	0.59	0.96	2.249	0.04	0.00349
9-22-40	0.291	0.16	0.26	2.295	0	0.00182
7-26-41	4.579	1.58	1.70	1.871	0.05	0.00290
8-12-41	1.319	0.67	0.59	3.347	0.07	0.00194
9-1-41	3.122	0.63	0.91	9.386	0	0.00496
7-18-44	1.447	1.04	0.55	9.347	0	0.00139
7-20-44	0.923	0.36	0.56	10.683	0.29	0.00256
6-17-46	0.233	0.22	0.28	2.714	0.03	0.00106
7-15-46	1.498	0.66	0.96	3.057	0	0.00224
9-1-46	0.370	0.18	0.15	5.415	0.36	0.00206
7-29-47	2.529	0.41	0.74	5.520	0	0.00632
7-29-51	0.358	0.57	0.81	1.108	0	0.00063
6-16-59	2.900	0.63	0.99	3.222	0.01	0.00461

For symbols, see List of Symbols, p vi.

Analyses of Data

The data obtained in this study were analyzed by four different techniques; two statistical, one graphical, and one semi-graphical. These techniques were, in order of analysis:

1. Multiple Regression Analysis
2. Successive Elimination
3. Empirical Analysis
4. Graphical Coaxial Correlation

In attempting to find a common base with which to compare the accuracy of the four prediction systems, some compromises in statistical semantics were made. The measure of prediction accuracy for an individual sample, is the deviation of the computed value ($\hat{Y}$) from the actual (Y) for that sample. This is

$$Y - \hat{Y}$$

or, in this paper,

$$BO - \widehat{BO}$$

In the statistical methods (Multiple Regression Analysis and Successive Elimination), the standard measure of error from a series of predicted values is the standard error of estimate, $s_{y.x}$, which is

$$s_{y.x} = \sqrt{\frac{\Sigma(Y - \hat{Y})^2}{N}}$$

Another parameter of error in prediction is the average deviation, A.D., which lends itself more easily to interpretation. This is

$$A.D. = \frac{\Sigma|Y - \hat{Y}|}{N}$$

For the two remaining methods, measures of error similar to the standard error of estimate can be computed. The computation of this parameter involves scaling values from a graph or chart. The computed value, although it may be the equivalent of the above outlined $s_{y.x}$, would imply strict statistical analysis if called the standard error of estimate. Thus, for the Graphical Coaxial method and Empirical Analysis, the squared deviations were summed, divided by N, and the square root extracted. This is the Root-Mean-Square value of the deviations, and is used in the following analysis.

Since the prediction equations in the statistical analyses are in logarithmic form, the standard error of estimate is a logarithmic value. The Root-Mean-Square, value of deviations similar to that outlined for the non-statistical methods was computed. An average deviation was also computed for all four techniques.

Multiple Regression Analysis

The data were analyzed by multiple regression. Attempts were made to fit the data to both linear and logarithmic equations, using both I_1 and Q_{24} as expressions of antecedent moisture. The regression equations computed are:

$$(1)\ \widehat{RO} = 0.467\underline{V} + 0.068Q_{24} + 2.549i_{30} - 0.544 \quad R^2 = 0.7546$$

$$(2)\ \widehat{RO} = 0.676\underline{V} + 0.392I_1 + 2.301i_{30} - 0.253 \quad R^2 = 0.7455$$

$$(3)\ \log\widehat{RO} = 0.336\log\underline{V} + 0.525\log Q_{24} + 1.069\log i_{30} + 0.124 \quad R^2 = 0.8634$$

$$(4)\ \log\widehat{RO} = 0.818\log\underline{V} - 0.132\log I_1 + 0.483\log i_{30} + 0.356 \quad R^2 = 0.8226$$

It should be noted that although the logarithmic prediction equations provide a higher R^2, this is only a <u>relative</u> R^2. That is, the squared deviations minimized in the process of least squares fitting were logarithmic deviations, and not arithmetic deviations. Thus, the logarithmic equations will not always provide the best arithmetic fit to the data. However, there is usually little error in the results obtained by assuming that the logarithmic fit will provide the best arithmetic fit also.

Logarithmic equations become meaningless when any of the variables have a value of zero, as the logarithm of zero is minus infinity. Therefore, equation (4) is invalid for all values of $I_1 = 0$, a situation that occurs several times in the data for the fourteen selected storms.

Equation (3), by virtue of its having the highest R^2 was selected as the equation of best fit, and prediction results obtained by it were compared with the other three prediction systems used in the analysis of data. Prediction results obtained by the use of equation (3) are contrasted with other methods in Table 10, and shown graphically in Figure 14.

The actual computation for this method was done by the Computing Center at Colorado State University, Fort Collins.

Successive Elimination

The relation of the independent variables to runoff was determined through the process of successive elimination (Ezekiel and Fox, 1959).

Attempts were made to correlate runoff to different factors in both linear and logarithmic fashions. For the first attempt, in which runoff was correlated to a single independent variable, the following results were obtained:

Table 5

CORRELATION COEFFICIENTS FOR THE
FIRST APPROXIMATION IN SUCCESSIVE ELIMINATION,
MISSOURI GULCH WATERSHED

Factor Correlated to Runoff	Value of R^2
Ψ	0.3234
Q_{24}	0.0087
I_1	0.0609
i_{30}	0.5185
Factor Correlated to log (Runoff)	
$\log \Psi$	0.5823
$\log Q_{24}$	0.1965
$\log i_{30}$	0.6081

From these first results, the logarithmic relation between the thirty minute storm intensity and runoff is the most pronounced. Therefore, for the first approximation or runoff, a log-log relation between intensity and runoff was used. This was:

$$\log \widehat{RO} = 1.255 \log i_{30} + 0.360 \quad r^2 = 0.6081$$

The significance of this relation was tested by an analysis of variance, and was found to be significant beyond the 10% level. A level of 10% was chosen as a criterion of rejection, as the total error of measurement (observation) was considered to be in the neighborhood of 10%.

The deviations ($\log RO - \log \widehat{RO}$) for each storm were computed, and these were correlated with a second independent variable. The results of this attempt are shown in Table 6.

Table 6

CORRELATION COEFFICIENTS FOR THE SECOND APPROXIMATION IN SUCCESSIVE ELIMINATION, MISSOURI GULCH WATERSHED

Factor Correlated to $\log RO - \log \widehat{RO}$	Value of r^2
Q_{24}	0.1157
Ψ	0.0509
I_1	0.0467
$\log Q_{24}$	0.2706
$\log(10\Psi)$	0.0427

The addition of each variable was tested for significance by analysis of variance, and only $\log Q_{24}$ was found to be significant beyond the 10% level. Thus, $\log Q_{24}$ was added as the second independent variable in the prediction equation. The equation was then:

$$\log \hat{RO} = 1.255 \log i_{30} + 0.510 \log Q_{24} + 0.079$$

$$R^2 = 0.7158$$

For the third approximation, the above equation was used to compute the deviation for each storm, and these were correlated to storm rainfall, Ψ. The results are shown below:

Table 7

CORRELATION COEFFICIENTS FOR THE THIRD APPROXIMATION IN SUCCESSIVE ELIMINATION, MISSOURI GULCH WATERSHED

Factor Correlated to $\log RO - \log \hat{RO}$	Value of r^2
Ψ	0.0966
logΨ	0.0324

In testing the addition of the above variables, neither was significant at the 10% level. Therefore, no addition to the prediction equation was made at the third approximation, and the equation computed after the second approximation was accepted. No further analysis was practical, as the supply of variables had been exhausted.

The analysis of variance for the maximum thirty minute rainfall intensity and twenty-four hour antecedent flow is summarized below. Final predicted values of storm runoff for individual storms are shown in Table 10, and shown graphically in Figure 14.

Table 8

ANALYSIS OF VARIANCE FOR ACTUAL RUNOFF
FOR FOURTEEN SELECTED STORMS,
MISSOURI GULCH WATERSHED

Source of Variation	Sum of Squares	df	Mean Square	F
i_{30}	1.580299	1	1.580299	17.702*
Q_{24}	0.279781	1	0.2798781	4.167*
Error	0.738492	12	0.067135	
Total	2.598662	14	0.067135	

*Significant beyond the 10% level

Empirical Analysis

Through a process of grouping terms utilizing the Buckingham-Pi theorem in a fashion similar to dimensional analysis, a series of dimensionless parameters were created, and these were used in attempts at correlation. In a functional equation, this was

$$RO = f(\Psi, Q_{24}, i_{30}, g)$$

or

$$RO = f_2(\Psi, I_1, i_{30}, g).$$

Some problems arose in the analysis, due to the fact that some values of I_1 were zero, and in the process of grouping terms, some terms would be zero or infinity, depending upon whether I_1 was in the numerator or denominator of the term. Therefore, I_1 was dropped from the analysis, and Q_{24} was used as the expression of antecedent moisture.

The grouping of the variables yielded the following dimensionless parameters, or Pi-terms:

$$\Pi_1 = RC/\Psi$$

$$\Pi_2 = Q_{24}/\Psi$$

$$\Pi_3 = i_{30}^2/\Psi g$$

The different Pi-terms for each storm were computed (See Table 9), and the results plotted on log-log paper, using Π_2 as the independent variable, Π_1 as the dependent variable, with Π_3 as the second independent variable which defined families of data on the plot. This plot is shown in Figure 12.

In general, the data seemed to fall into families, with only a few exceptions.

It should be noted in this method of analysis, that Q_{24} is intended only as an index of antecedent basin moisture conditions. As an index, it may reflect not only basin moisture, but other factors as well, primarily channel interception.

This method of runoff prediction proved to be rather accurate for the storms studied. The RMS value of the deviations was 1.14×10^{-3} inches. If one exceptionally poor prediction could be excluded, this could be reduced to 0.34×10^{-3} inches. Some of the storms, due to the nature of the construction of the family lines, showed no error of prediction whatsoever, while other storms showed prediction errors of up to 3.93×10^{-3} inches.

The actual and predicted runoff are shown in Table 10, and illustrated in Figure 14.

Table 9

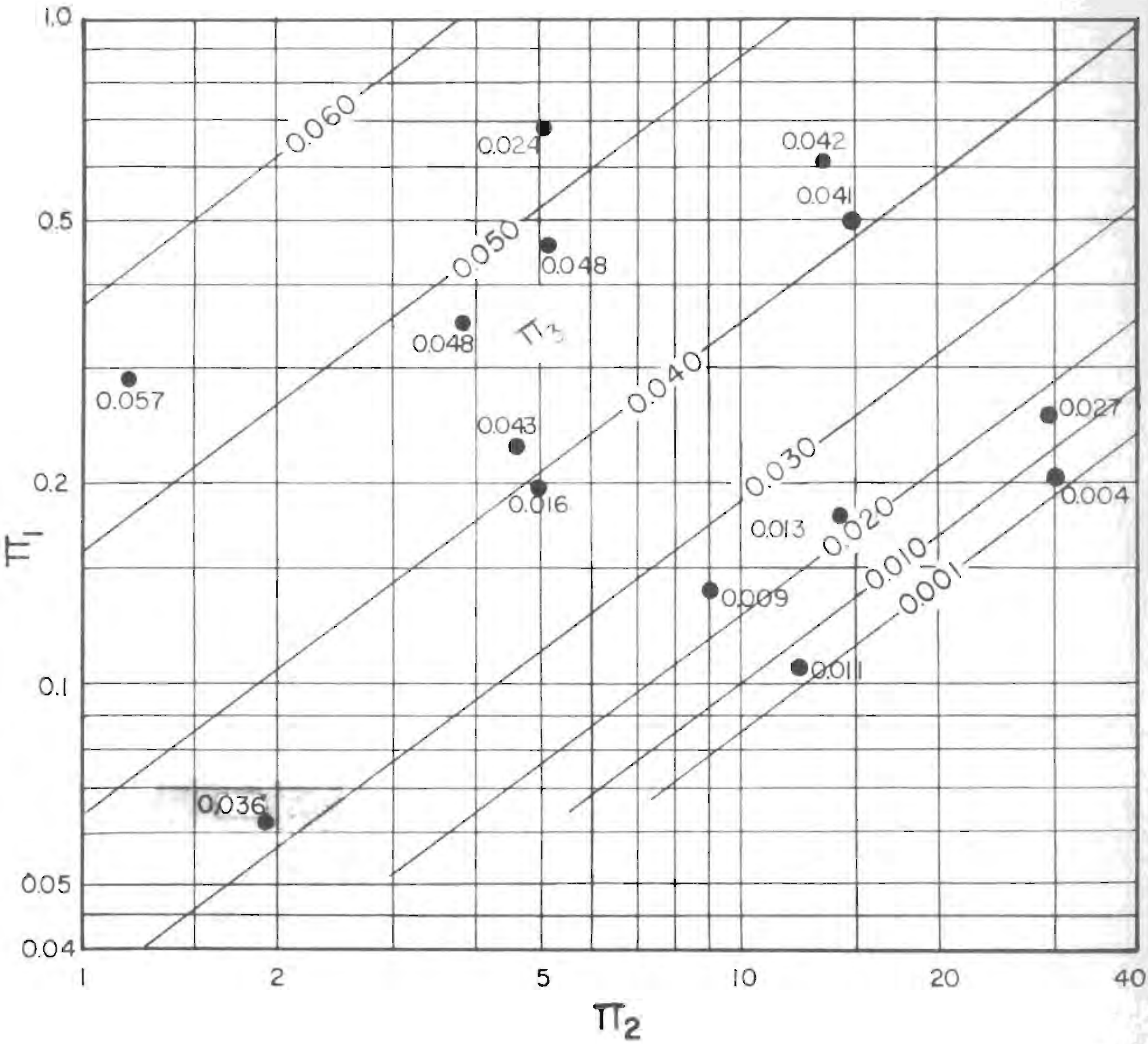
PI-TERMS FOR EMPIRICAL ANALYSIS, MISSOURI GULCH WATERSHED

Storm Date	$(100)\frac{RO}{\Psi}$	$\frac{Q_{24}}{\Psi}$	$\frac{i_{30}^2}{\Psi g}$
7-29-40	0.682	5.021	0.0244
8-22-40	0.349	3.811	0.0481
9-22-40	0.182	14.344	0.0131
7-26-41	0.290	1.184	0.0569
8-12-41	0.194	4.996	0.0162
9-1-41	0.496	14.898	0.0409
7-18-44	0.139	8.988	0.0091
7-20-44	0.256	29.675	0.0271
6-17-46	0.106	12.336	0.0111
7-15-46	0.224	4.632	0.0434
9-1-46	0.206	30.083	0.0039
7-29-47	0.632	13.463	0.0415
7-29-51	0.060	1.944	0.0358
6-16-59	0.461	5.114	0.0484

Figure 12

Empirical Analysis

Plot of Π-terms



$\Pi_1 = 100\,RO/V$ $\quad \Pi_2 = Q_{24}/V$ $\quad \Pi_3 = i_{30}^2/Vg$

Coaxial Graphical Correlation

The relation between the various independent variables and storm runoff was studied using coaxial graphical correlation, as outlined by Kohler and Linsley (1951). The end result of this analysis is shown in Figure 13, which provides a graphical means of storm runoff prediction.

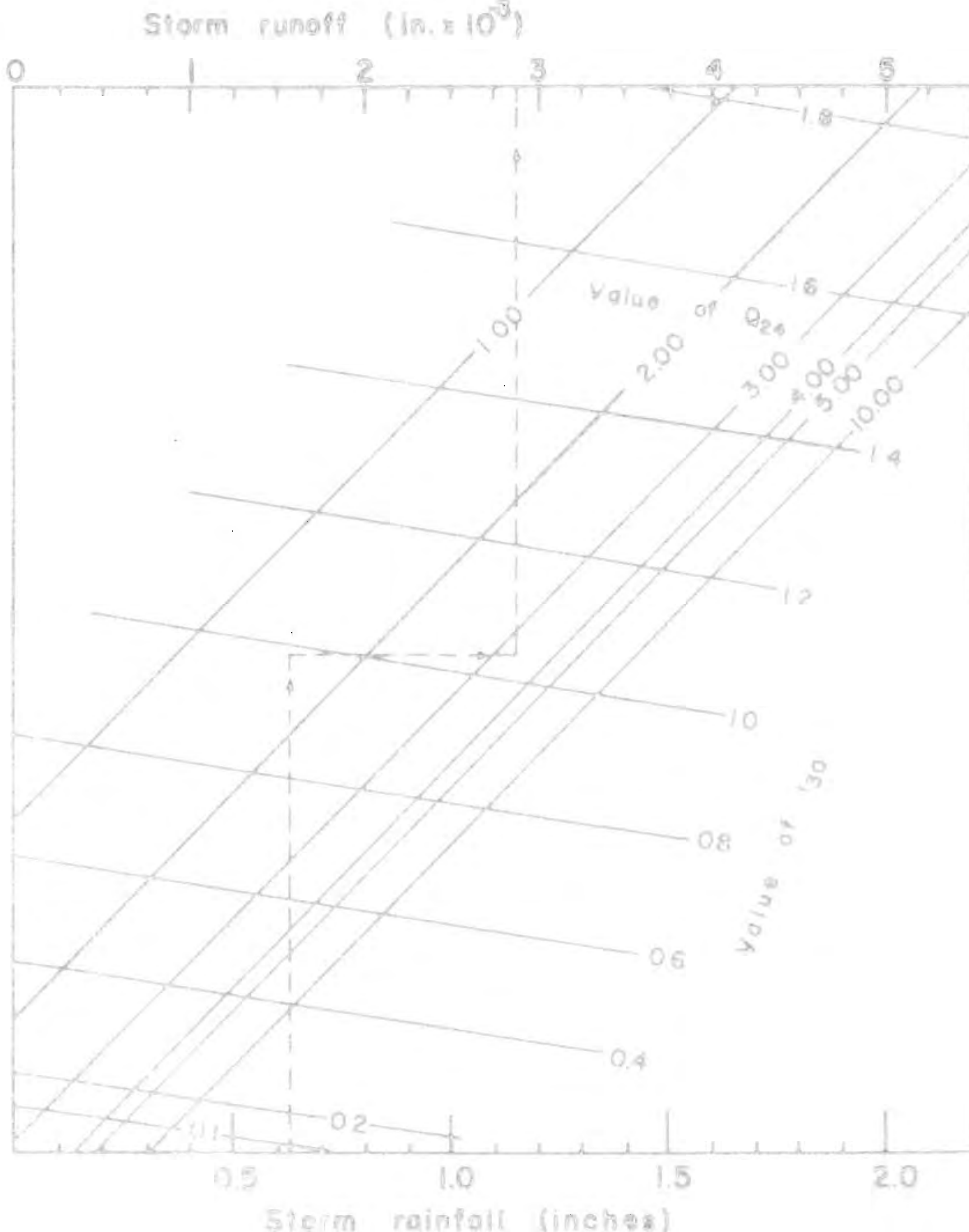
All family lines are straight. This implies a much simpler relationship than probably really exists in nature, but the low number of samples warrants no more intricate assumption.

In the process of constructing the graph, it was noticed that Q_{24} seemed to be a much more significant factor than I_1, and also that Q_{24} seemed to be the biggest single factor accounting for variations in runoff. However, due to the nature of the system, no statistical expression of this relationship was available, and conclusions can only be inferred by the individual constructing the graph and working with the data.

For the four prediction systems studied, the coaxial graph predicted runoff most accurately. The predicted values of runoff as scaled from the coaxial graph are shown in Table 10, and illustrated in Figure 14. The RMS value of the deviations from predicted runoff was 0.89×10^{-3} inches, and the average deviation was 0.45×10^{-3} inches. Most of the prediction error was the result of three particularly poor predictions, their total absolute

Figure 13

Rainfall-runoff relation for Missouri Gulch



error being 5.08×10^{-3} inches, for an average of 1.66×10^{-3} inches. If these occurrences were to be excluded, the average deviation could be reduced to 0.14×10^{-3} inches, or about 300 percent.

The storm of July 16, 1959 is taken as a sample to show the workings of the coaxial graph. From the Master Data Sheet (Table 4), the following information is observed: i_{30} = 0.99 inches per hour, Q_{24} = 3.222×10^{-3} inches, Ψ = 0.63 inch. Entering Figure 13 on the lower axis at Ψ = 0.63, the intercept with i_{30} = 0.99 is located. From this point, proceeding horizontally to Q_{24} = 3.22, a second point is located, and the storm runoff is read from the top axis directly above this point, RO = 2.85×10^{-3} inches. For this storm, the actual runoff was 2.90×10^{-3} inches.

The steps are shown on the Figure by a dashed line.

Figure 14
Predicted vs Actual Runoff
Missouri Gulch Watershed

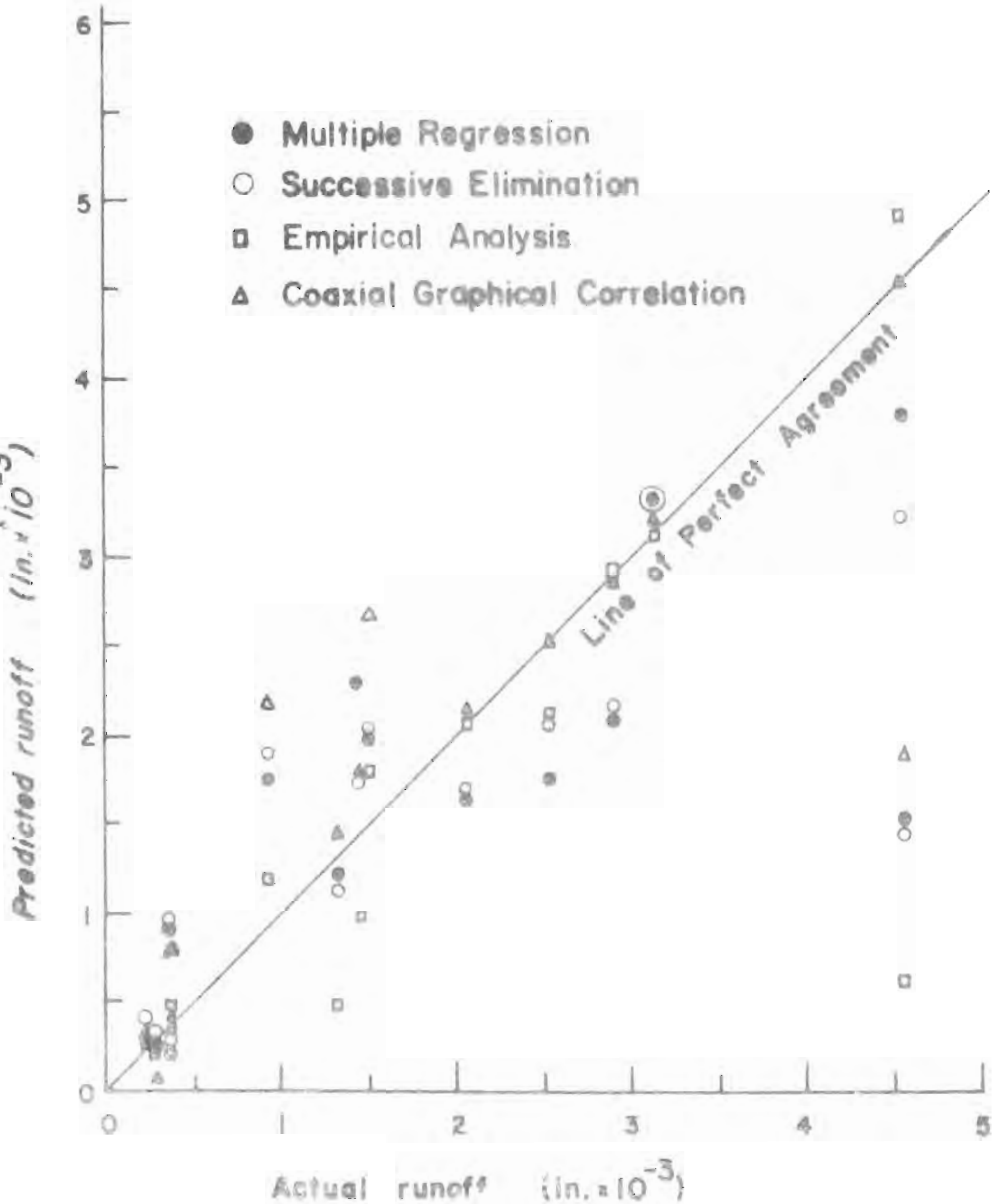


Table 10

PREDICTED VALUES AND DEVIATIONS FOR
DIFFERENT METHODS, FOURTEEN SELECTED STORMS

Storm Date	Actual Runoff in.x10^{-3}	Mult. Regress.		Succ. Elim.		Dimen. Analy.		Graphical	
		Comp.	Dev.	Comp.	Dev.	Comp.	Dev.	Comp.	Dev.
7-29-40	4.549	1.523	3.056	1.462	3.087	0.62	3.93	1.89	2.66
8-22-40	2.066	1.631	0.435	1.721	0.345	2.06	0.01	2.16	0.09
9-22-40	0.291	0.266	0.025	0.340	0.049	0.22	0.07	0.07	0.22
7-26-41	4.579	3.798	0.781	3.224	1.355	4.90	0.32	4.54	0.04
8-12-41	1-319	1.238	0.081	1.146	0.173	0.48	0.84	1.46	0.14
9-1-41	3.122	3.323	0.201	3.335	0.213	3.12	0	3.20	0.08
7-18-44	1.447	2.296	0.849	1.767	0.320	0.97	0.51	1.80	0.35
7-20-44	0.923	1.761	0.838	1.942	1.019	1.19	0.26	2.18	1.26
6-17-46	0.233	0.349	0.116	0.402	0.169	0.26	0.03	0.36	0.13
7-15-46	1.498	1.982	0.484	2.029	0.531	1.78	0.28	2.66	1.16
9-1-46	0.370	0.239	0.131	0.264	0.104	0.32	0.05	0.78	0.41
7-29-47	2.529	1.750	0.779	2.080	0.449	2.11	0.42	2.52	0.01
7-29-51	0.358	0.923	0.565	0.968	0.610	0.46	0.10	0.42	0.06
6-16-59	2.900	2.082	0.818	2.156	0.744	2.90	0	2.87	0.03

	Mult. Regress.	Succ. Elim.	Dimen. Analy.	Graphical
RMS of Deviations	0.96	1.01	1.14	0.89
Average Deviation	0.65	0.65	0.49	0.45

Discussion and Conclusions

The results of this study indicate some interesting facts concerning the hydrology of Missouri Gulch and the ability to estimate storm runoff by means of the procedures studied.

First, it must be concluded that a very small percentage of the storm rainfall became storm runoff. For the storms studied, the percentage of storm runoff (RO/V) averaged about 0.3 percent, with a maximum of about 0.7 percent. Since the percentage of storm runoff is "C" from the rational formula (Q = C I A), great errors in flood peak prediction might result in using the rational formula on watersheds similar to Missouri Gulch. The casual observer, or field engineer might estimate a "C" value to be in the neighborhood of 0.30, or about 100 times its real value. Consequent structures would then be overdesigned by a factor of 10,000 percent. The value of "C" for the storms studied seemed to be independent of the size of the storm.

In attempting to explain this low storm yield, investigations were made as to the possibility of the entire runoff being the result of channel interception alone. According to Berndt (1960), there are 6.1 miles of "live" channels in the Missouri Gulch watershed. If the average width of these channels is assumed to be 1½ feet, the total surface area of the streams would be

$$\frac{(6.1)\ (1.5)\ (5280)}{43560} = 1.1 \text{ acres.}$$

As a percentage of the total area of the watershed, this amounts to

$$\frac{(1.1)\ (100)}{4600} = 0.024 \text{ percent}$$

Since about twelve times as much runs off, channel interception could account for only 1/12 of the total storm runoff. Thus, the question is still unanswered: why is the runoff so low, and what is its source?

Some of the loss to streamflow may be explained through vegetative interception. Johnson (1942), found on studies elsewhere at Manitou Experimental Forest that about 0.03 to 0.05 inches of precipitation was required to saturate the forest canopy during a storm. For the small storms studied, interception losses of this magnitude would be a fairly large percentage of the total rainfall, leaving very little available for streamflow. On the larger storms, however, this becomes insignificant in light of the accuracy of the measurements and the size of the storms.

The extremely porous nature of the soils allows very little overland flow. Since none of the storms studied exhibited intensities greater than the infiltration rates given in Table 2, it is possible that there was no surface runoff during these storms. The depth of soils allows deep seepage and the opportunity for the water to flow down through the soil, rather than across the soil to stream channels.

That runoff which did occur might be the result of rainfall and runoff on the bare rocky ridge (See Figure 3), and on the service roads. Since a portion of the Missouri Gulch Trail is adjacent to stream channels, and the aforementioned ridge runs parallel and close to the North and South Forks, this possibility is suggested.

The method of Coaxial Graphical Correlation seems to provide the best prediction results, as it exhibited the lowest RMS value of the deviations, and the lowest average deviation. Conclusions as to which method provided the second best fit, etc., are dependent upon which parameter is chosen as a measure of accuracy. Empirical analysis provides the second lowest average deviation, but the multiple regression provided the second lowest RMS value of the deviations. The rankings are tabulated in Table 11:

Table 11

PREDICTION ACCURACY FOR FOUR TECHNIQUES.
FOURTEEN SELECTED STORMS,
MISSOURI GULCH WATERSHED

Rank	Measure of Accuracy			
	RMS of Deviations		Average Deviation	
1	Graph. Coax.	(0.89)	Graph. Coax.	(0.45)
2	Mult. Regress.	(0.96)	Empir. Analy.	(0.49)
3	Succ. Elimin.	(1.01)	Succ. Elimin.	(0.65)
4	Empir. Analy.	(1.14)	Mult. Regress.	(0.65)

It should be noted that a good deal of the error in each of the techniques is incorporated in one exceptionally poor prediction (Storm of July 29, 1940).

The definite effect of each of the independent variables upon runoff was not determined conclusively. The multiple regression seemed to indicate that the thirty minute intensity (i_{30}) is the most important single factor producing runoff. Successive elimination encourages the same conclusion, while work with the coaxial-graphical system encouraged the author to judge either twenty-four hour antecedent flow (Q_{24}) or storm precipitation (Ψ) as the most important factor. In no case was the one day antecedent precipitation (I_1) found to be of great importance in the prediction of runoff.

In contrasting the methods of multiple regression and successive elimination, generally similar results are obtained. In this case, the exponents of the independent variables should be the same. Inspection of the two prediction equations shows this to be approximately the case. Differences are accounted for by the facts that: 1) Five place logarithms were used in the multiple regression analysis, while only three places were used in successive elimination; and (2) Exponential values of the independent variables were calculated with a log-log slide rule in the approximation steps in successive elimination. The significance of these errors is subject to question, but in light of the accuracy of the measurements, these small errors provide little distortion.

A number of tacit assumptions made in this type of study can also be challenged. As the data encompassed a period of twenty years, it must be assumed that watershed conditions were unchanged during the period of study. This is not necessarily the case, as no doubt there was some vegetative change over the twenty years, and channel conditions cannot be assumed to remain constant for such a long period. Vegetative changes could include either an increase of vegetation and its by-products, or a decrease due to drouth and/or grazing. Channel obstructions may have periodically been accumulated and swept out by spring floods, and different conditions may have been present for the different storms studied.

In computing the storm precipitation it was necessary to assume that the storms were distributed evenly over the watershed, both in time and in amount. Informal studies indicated that both of these assumptions were seldom matched by field conditions. Variations in these conditions may have affected storm runoff considerably.

Also, the analysis was hampered by the small range of data, and in some cases, poor records from which to obtain data. The intensity calculations in particular, were subject to error, as thirty minutes on some recorder charts represented 0.03 inch, which is about the same as the width of the pen trace on the record, and not much more than the pencil point used to extract the information.

Finally, although some of the techniques studied herein provide seemingly accurate prediction results, these results should not be taken at face value, as no independent population was set aside at the beginning of the study to check the results. That is; the data should fit the prediction systems, as the data were used to derive the systems. That the prediction systems provide accurate answers is not an indication that the relationships presented are valid, as no independent check on the systems has been provided.

This study has provided conclusions of only the most general nature, and leaves many questions unanswered. Certainly additional studies on the disposition of precipitation on watersheds similar to Missouri Gulch would be necessary before definite conclusions explaining the low yield of the watershed could be stated. Similarly, the prediction techniques studied were hampered in their efficiency by the small number of samples which they utilized. It is not assumed that conclusive statements concerning the techniques studied can be drawn on fourteen samples alone.

Summary

This study was conducted in an effort to explain the runoff phenomenon on the Missouri Gulch watershed, and to determine a suitable method for predicting storm runoff in terms of rainfall characteristics and antecedent basin moisture conditions.

The study area is a part of Manitou Experimental Forest, eight miles north of Woodland Park, Colorado. The study watershed has steep slopes, scattered vegetation, and deep granitic soils. The basic data used; i.e., rainfall and runoff records were obtained through the cooperation with the Rocky Mountain Forest and Range Experiment Station, with headquarters in Fort Collins, Colorado.

Values of storm runoff, storm precipitation, storm intensity, twenty-four hour antecedent flow, and one day antecedent precipitation were obtained for fourteen storms, and used in attempts to establish a runoff prediction system through the following techniques:

1. Multiple Regression Analysis
2. Successive Elimination
3. Empirical Analysis
4. Graphical Coaxial Correlation

The study indicates that less than one percent of storm rainfall on Missouri Gulch becomes storm runoff. Losses to runoff cannot be explained through vegetative interception, nor can storm runoff be accounted for

entirely through channel interception. It was postulated that losses to storm runoff could be explained in terms of the nature of the predominant soil mantle on the watershed.

The findings indicated that the coaxial graphical correlation method provided the most accurate runoff predictions, and that the three remaining methods varied in accuracy, depending upon the measure of accuracy used. No conclusive statements could be made as to the suitability of the techniques due to the low number of samples, and the lack of an independent population for checking the prediction systems.

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APPENDIX A.

SAMPLE CALCULATIONS AND EXAMPLES OF REDUCTION OF DATA

Appendix A.

Sample Calculations Storm of July 10, 1949

Rainfall Computations (Ψ): All rainfall in inches

Gage	Storm Rainfall from records	Storm Rainfall computed	Weekly rain from records	percent of week's rain in storm
1		1.65	2.85	58*
2		1.35	2.76	49*
3	0.80		2.98	27
5		0.43	1.88	23*
7		0.81	2.20	37*
9		0.63	1.96	32*
12		0.83	1.97	42*
23	1.16		2.09	56
14		0.97	1.98	49*
LMG	0.24		2.07	12
1&2 Comm.	0.92		1.86	49

*Interpolated value

By Thiessen Mean, Ψ = 0.8643, say 0.86.

Intensity Computations (i_{30}):

Gage	Thiessen factor(f)	Thirty min. Station rainfall (inches)(P_{30})	(P_{30})(f)
1	N O R E C O R D		
3	0.544	0.65	0.3536
13	S T O P P E D C L O C K		
LMG	0.150	0.15	0.0225
1&2 Comm.	0.306	0.47	0.1438
	1.000		0.5199

$$i_{30} = \frac{0.5199}{30/60} = 1.0398 \text{ say } 1.04 \text{ inches per hour}$$

Antecedent Precipitation Computations (I_1):

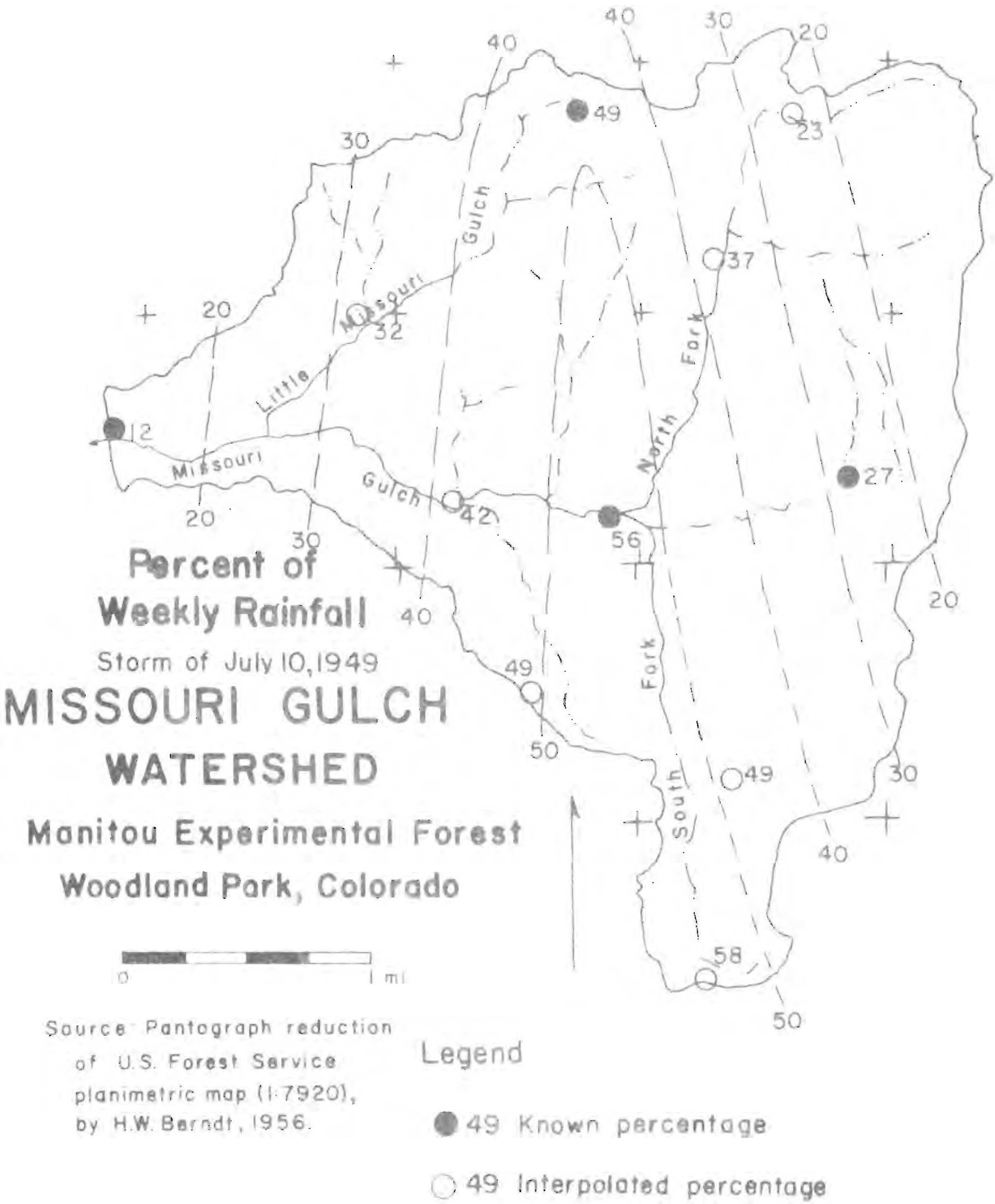
Gage	Thiessen Mean Factor(f)	Station Rainfall (inches)(I_1)	(f)(I_1)
3	0.544	0	0
LMG	0.150	0	0
1&2 Comm.	0.306	0.04	0.012
	1.000		0.012

I_1 = 0.01 inch

Thiessen Mean Factors for Various Situations

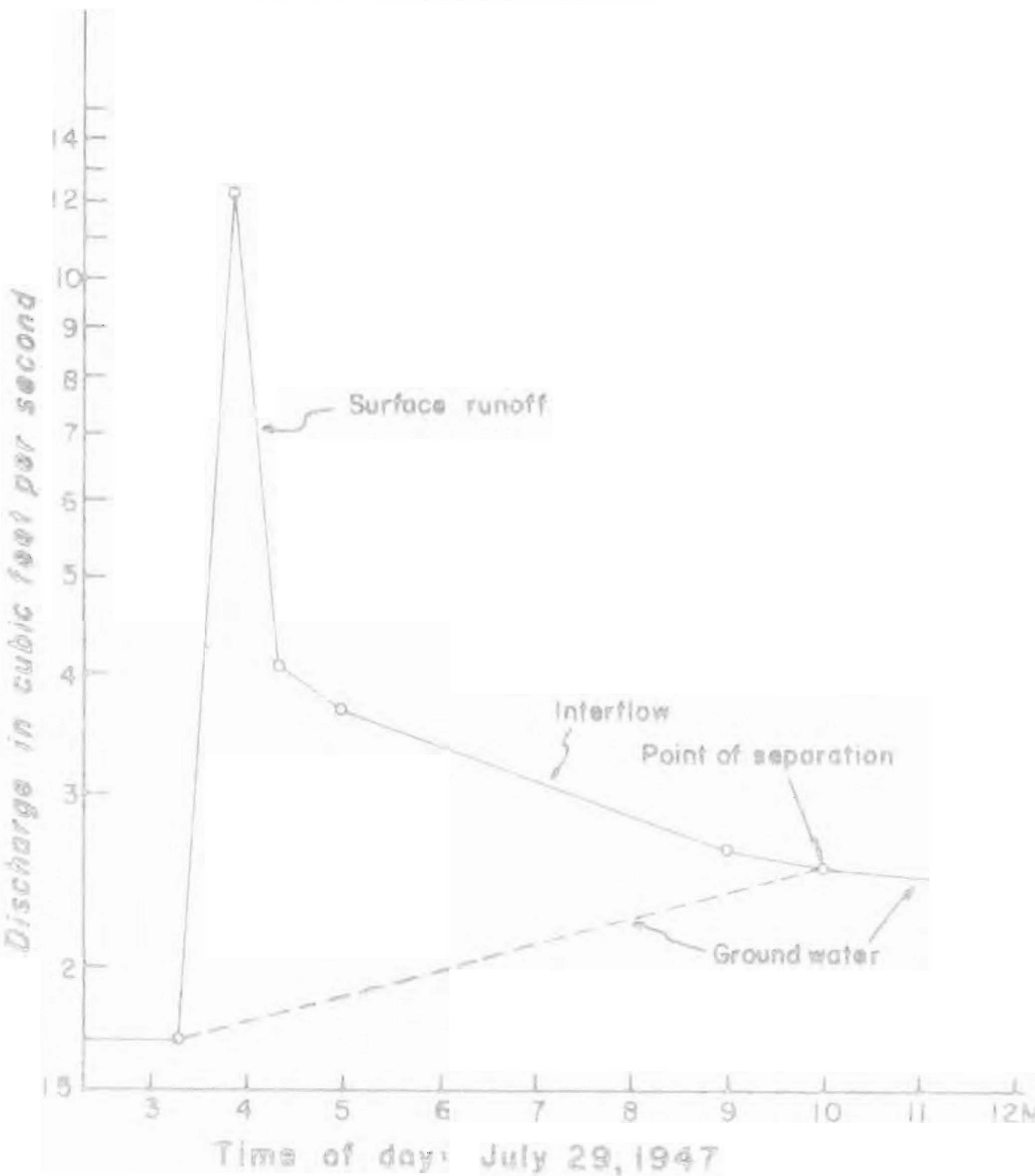
Missouri Gulch Watershed

<u>Gage</u>	Thiessen Mean Factors				
1	0.031	0.031	0.086		
2	0.011	0.011			
3	0.147	0.147	0.289	0.279	0.544
5	0.103	0.103			
7	0.126	0.126			
9	0.135	0.135			
12	0.083	0.083			
13	0.109	0.109	0.308	0.371	
14	0.045	0.045			
1&2comm.	0.071			0.247	0.306
L. Mo.	0.039	0.039	0.095	0.103	0.150
Feld.		0.065	0.222		
Totals	1.000	1.000	1.000	1.000	1.000


Percent of Weekly Rainfall
Storm of July 10, 1949
MISSOURI GULCH WATERSHED
Manitou Experimental Forest
Woodland Park, Colorado
0
1 mi
Source: Pantograph reduction of U.S. Forest Service planimetric map (1:7920), by H.W. Berndt, 1956.
Legend
49 Known percentage
49 Interpolated percentage
Missouri Gulch
Little Missouri
Missouri Gulch
North Fork
South Fork
49
23
37
32
12
27
42
56
49
49
58
40
30
20
50

Example of Hydrograph Separation

Storm of July 29, 1947



APPENDIX B.

SOILS AND VEGETATION INFORMATION

APPENDIX B

SOILS AND VEGETATION (From Berndt, 1960)

Soils are derived mainly from Pikes Peak granite and Madison limestone, with alluvial fills in the drainageways. Edloe and Stecum* gravelly sandy loams, derived from granite, are the most extensive soils of the area.

Edloe gravelly sandy loam, developed on moist north and east exposures and at higher elevations on all exposures, has light brown to grayish surface soils of loose gravelly texture under well developed 1- to 2-inch litter layers. Surface soils rarely extend below 15 inches. Parent material is a loamy gravel with high sand content, resulting from disintegrating bedrock.

Vegetation types associated with the Edloe gravelly sandy loam are lodgepole pine, Engelmann spruce, ponderosa pine, Douglas-fir, and aspen.

Lodgepole pine and Engelmann spruce trees occur either pure or mixed in dense stands at the highest elevations. Where lodgepole pine occurs in pure stands, it is the result of past fires. The sparse understory is made up of low shrubs, some native grasses, and low-growing annuals.

Ponderosa pine and Douglas-fir trees occur in pure or mixed stands. North exposures support moderate to dense stands of Douglas-fir, with scattered ponderosa

*Soil names are tentative and are subject to final correlation.

pine. These exposures are well protected by dense ground litter and understory. A mixture of ponderosa pine, Douglas-fir, and quaking aspen is found along drainage-ways and on other intermediate sites. These stands have a light to moderate cover of understory vegetation.

Stecum gravelly sandy loam, developed on dry south and southwest exposures, has a pale brown surface soil of loose open gravelly loam, overlain with a thin litter of needles or grass residue. In some areas, the surface is an exposed erosion pavement. Surface soils are rarely deeper than 10 inches. The parent material is a light brown loamy gravel; the gravels are sharply angular and can be dug from the rotting granite bedrock.

Cover types associated with the Stecum gravelly sandy loam are ponderosa pine, Douglas-fir, and on south exposures, brush-grass. Some areas are covered with an erosion pavement.

Ponderosa pine and Douglas-fir grow in relatively open stands, with a sparse understory of mountainmahogany, Arizona fescue, and mountain muhly.

Brush-grass consists of mountainmahogany, mountain muhly, and Arizona fescue, and generally occurs on south exposures. Fair to poor site protection is afforded by the ground cover and litter.

Erosion pavement occurs on south slopes. These slopes support extremely poor stands of ponderosa pine, mountain brush, or native bunchgrass, or are barren.

Where vegetation occurs it affords less than 30 percent ground cover. Inadequate cover and litter have resulted in the formation of an erosion pavement on the soil surface. Immediately below the pavement, finer soil particles are found.

Both the Edloe and Stecum gravelly sandy loams are shallow, coarse, low in organic matter, and relatively infertile. Surface soils are slightly acid but become basic with depth.

Chubbs stony loam, a very fertile soil, derived from Madison limestone, is found only in the lower part of the watershed. The reddish- or grayish-brown surface soils are loose loams or stony loams with well developed soft granular structure, extending 8 to 15 inches deep. The soil is calcareous and contains a high percentage of rock fragments. Subsoil, when present, is a reddish- or grayish-brown heavy loam or clay loam, with granular structure, containing a high percentage of fragmented rock. The parent material is a deep layer consisting of 80 to 90 percent fragmented limestone rock, with loose loam sifted between the fragments.

On Missouri Gulch watershed, ponderosa pine and Douglas-fir are the cover types associated with Chubbs stony loam.

Soils developed from recently deposited alluvium occur in stream beds and on alluvial fans. The surface soils are brown or dark brown, sandy or gravelly loams, 10 to 18 inches thick. They have weak granular structure and are loose when moist but compact when dry. The profiles generally lack a defined subsoil. The parent materials are brown gravels or loamy gravels, often highly stratified. Quaking aspen, in virtually pure stands, generally grows on these soils. The sites are well protected with litter, a dense understory of aspen and conifer reproduction, low shrubs, native bunchgrasses, and numerous annual forbs.

Wet meadows and bog soils have developed from alluvial deposits on small, isolated flood plains through the watershed. Surface soils are dark gray to black gravelly or sandy loams, high in organic matter, and peaty in places. They extend to a depth of 24 inches and are highly stratified. No B-horizon has developed. Parent material is a coarse-textured, stratified gravel or loamy gravel. This layer is mottled or streaked with rust-brown and is characteristically poorly drained.

Exposed parent rock, generally unweathered granite, occurs on the steepest slopes where there has been little opportunity for soil development. The bulk of this area lies in the east wall of the north and south fork drainages.