PHYSIOGRAPHIC CHARACTERISTICS AND THE RUNOFF PATTERN

by

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Don M. Gray

SYNOPSIS

The influence of several geomorphic characteristics of a watershed as, drainage area size, length and slope of the main stream, general land slope and channel geometry on the time distribution of surface runoff is discussed. The presentation emphasizes the interrelationships between certain geomorphic properties of a watershed and demonstrates the use of the factors for synthesizing unit graphs for ungaged areas.

Consideration is also given to the effect of such factors as climate, topography, and vegetation that determine the characteristics of hydrographs from melting snow.

SURFACE RUNOFF — RAINFALL

A hydrograph of a stream is the graphical representation of the instantaneous discharge rate with time. It represents the integrated effect of all physical characteristics of the basin and their modifying influence on the translation and storage of a rainfall-excess volume which falls on the drainage area. The factors which are involved are numerous. Some exert a major influence on the shape of the runoff pattern whereas others are of negligible consequence.

Hydrograph synthesis for ungaged watersheds is generally accomplished using expressions which relate geometric properties of the hydrograph with easily-measured basin parameters. Because the time-distribution of runoff is influenced by both basin and storm characteristics, the development of such expressions can be successfully accomplished only after some restriction is placed on the latter variable.

Use of the unit graph concept presented by Sherman in 1932 has expedited certain of these correlations and, in addition, permits the investigator to evaluate the effect of pertinent geomorphic factors of the basin on hydrograph shape. Herein, a unit graph is defined as:

A discharge hydrograph resulting from one inch of direct (surface) runoff generated uniformly over the tributary area, at a uniform rate, during a specified period of time.

Much controversy has arisen among hydrologists concerning the validity of the unit graph for synthesizing flood hydrographs. Some workers discredit the concept because the assumptions (1) that the rainfall intensity is uniform over the entire basin, (2) that there is non-variance in outflow response with different intensity rains or the velocity of flow is constant and (3) that storage and outflow are linearly related, impose conditions which are either seldom realized in the field or which can be shown to be mathematically incorrect.

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Other investigators accept the concept because they have found it to be a practical workable, hydrologic tool (Mitchell, 1948).

The writer wishes to clarify that it is not the intent of this paper to evaluate the applicability of the unit graph theory, but, to use the concept to demonstrate the effect of watershed characteristics on hydrograph shape.

General

As previously indicated, all factors which affect the travel-time: area distribution of a watershed also influence the shape of the hydrograph. Clark (1945), Dooge (1956), Nash (1958) and others have shown the applicability of synthesizing hydrographs by routing instantaneous inputs (runoff volumes) applied to different time-area shapes through different amounts of storage.

An insight as to the influence of certain geomorphic factors on hydrograph properties can be obtained from review of several expressions used for peak discharge determinations and unit graph synthesis. Several of these expressions are given in Table 1. Using the results given in Table 1 as a guide, the dominant factors may be summarized as,

1. Drainage – area size and shape,
2. Density and distribution of water courses,
3. Overland slope or general land slope,
4. Size, length, slope and condition of stream channels, and
5. Depressional storage and pondage due to surface channel obstructions forming natural detentions.
Table 1. Summary of expressions relating geomorphic properties of a watershed and the runoff pattern

<table>
<thead>
<tr>
<th>Method</th>
<th>Peak Discharge ( q )</th>
<th>Storm Duration ( t_R )</th>
<th>Time Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rational</td>
<td>( q = CkA )</td>
<td>( t_R = t_c )</td>
<td>( t_c = 0.0078(\sqrt{L^3/H})^{0.770} ) (Kirpich, 1940)</td>
</tr>
<tr>
<td>Kinnison (1945)</td>
<td>( q = (0.000368^{2.4+124})A^{0.95/4.04}L^{0.7} ) - Minor Floods</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Conservation Service (1957)</td>
<td>( q = 484AV/P_R )</td>
<td>( t_R = t_L/5.5 )</td>
<td>( P_R = t_R^2 + t_L )</td>
</tr>
<tr>
<td>Snyder (1938)</td>
<td>( q = 640C_PA/t_L )</td>
<td>( t_R = t_L/5.5 )</td>
<td>( t_L = C(LC)^{0.3} )</td>
</tr>
<tr>
<td>Hickok, Keppel and Rafferty (1959)</td>
<td>( q = cV/t_L )</td>
<td>( t_R )</td>
<td>( t_L = 23(\sqrt{L_{sa}+\bar{W}<em>{sa}}/S</em>{sa}/\bar{D})^{0.65} )</td>
</tr>
<tr>
<td>Clark (1945)</td>
<td>( 0 + (1-x) k \frac{dO}{dt} )</td>
<td>( t_R = 0 )</td>
<td>( k = bL\sqrt{A}/\sqrt{S} ) (Linsley, 1945)</td>
</tr>
<tr>
<td>Gray (1962)</td>
<td>( g = C(\delta)\frac{m}{e^{-\delta/\Gamma(m)}} )</td>
<td>( t_R &lt; 1/4P_R )</td>
<td>( P_R/\delta = b(L/\sqrt{S_c})^n )</td>
</tr>
</tbody>
</table>

1 See Table 2 for nomenclature of symbols
Table 2. Nomenclature of symbols used in Table 1.

<table>
<thead>
<tr>
<th>Method</th>
<th>Symbol Designation and Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rational</td>
<td>C — runoff coefficient</td>
</tr>
<tr>
<td></td>
<td>i — rainfall intensity (in/hr)</td>
</tr>
<tr>
<td></td>
<td>A — drainage basin size (acres)</td>
</tr>
<tr>
<td></td>
<td>t_c — time of concentration (min)</td>
</tr>
<tr>
<td></td>
<td>L — maximum length of flow (ft)</td>
</tr>
<tr>
<td></td>
<td>H — difference in elevation between remote point and outlet (ft)</td>
</tr>
<tr>
<td>Kinnison</td>
<td>s — median altitude of basin above outlet (ft)</td>
</tr>
<tr>
<td></td>
<td>A — drainage basin size (sq. miles)</td>
</tr>
<tr>
<td></td>
<td>a — percent of total area in lake, ponds or reservoirs</td>
</tr>
<tr>
<td></td>
<td>L — average distance water must travel to outlet (miles)</td>
</tr>
<tr>
<td>Soil Conservation Service</td>
<td>A — drainage basin size (sq. miles)</td>
</tr>
<tr>
<td></td>
<td>V — volume of surface runoff (in)</td>
</tr>
<tr>
<td></td>
<td>P_R — period of rise of hydrograph (hr)</td>
</tr>
<tr>
<td></td>
<td>t_L — lag time (center of mass of excess precipitation to peak of hydrograph) (hr)</td>
</tr>
<tr>
<td></td>
<td>t_c — time of concentration (hr)</td>
</tr>
<tr>
<td>Snyder</td>
<td>C_p — coefficient to take account of flood wave and storage effect in basin — (0.56–0.69)</td>
</tr>
<tr>
<td></td>
<td>A — drainage basin size (sq. miles)</td>
</tr>
<tr>
<td></td>
<td>t_L — lag time (hr)</td>
</tr>
<tr>
<td></td>
<td>C_i — coefficient to account for slopes and storage (ave. value = 2)</td>
</tr>
<tr>
<td></td>
<td>L — length of basin (miles)</td>
</tr>
<tr>
<td></td>
<td>L_CA — length from gaging station to center of area (miles)</td>
</tr>
<tr>
<td>Hickok, Keppel and Rafferty</td>
<td>V — volume of surface runoff (acre-ft)</td>
</tr>
<tr>
<td></td>
<td>t_L — lag time (min) — time from center of mass of limited block of intense rainfall to peak of hydrograph</td>
</tr>
<tr>
<td></td>
<td>L_oo — length from outlet of watershed to center of gravity of source area (ft)</td>
</tr>
<tr>
<td></td>
<td>W_oo — average width of source area (ft)</td>
</tr>
<tr>
<td></td>
<td>S_oo — average land slope of source area (ft)</td>
</tr>
<tr>
<td></td>
<td>DD — drainage density (ft of channel/Acre)</td>
</tr>
<tr>
<td></td>
<td>Source Area — that half of watershed having highest average landslope</td>
</tr>
</tbody>
</table>
Table 2. Nomenclature of symbols used in Table 1. (Cont’d).

<table>
<thead>
<tr>
<th>Method</th>
<th>Symbol Designation and Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clark</td>
<td>O – outflow rate</td>
</tr>
<tr>
<td></td>
<td>x – coefficient which gives discharge as weighted average of inflow and outflow</td>
</tr>
<tr>
<td></td>
<td>k – storage constant</td>
</tr>
<tr>
<td></td>
<td>t – time</td>
</tr>
<tr>
<td></td>
<td>I – inflow rate</td>
</tr>
<tr>
<td></td>
<td>b – coefficient</td>
</tr>
<tr>
<td></td>
<td>L – length of the main stream</td>
</tr>
<tr>
<td></td>
<td>A – drainage basin size</td>
</tr>
<tr>
<td></td>
<td>S – mean slope of the basin</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Symbol Designation and Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>C – volumetric runoff coefficient</td>
</tr>
<tr>
<td>m, s – parameters of two parameter gamma distribution whose magnitude are a function of basin characteristics</td>
</tr>
<tr>
<td>e – base of natural logarithms</td>
</tr>
<tr>
<td>Γ – gamma function</td>
</tr>
<tr>
<td>P – period of rise</td>
</tr>
<tr>
<td>L – length of the main stream</td>
</tr>
<tr>
<td>S – average channel slope of the main stream</td>
</tr>
<tr>
<td>b, n – coefficient and exponent evaluated experimentally</td>
</tr>
</tbody>
</table>

Dimensional Analysis

Prior to discussing the effects of individual factors on hydrograph shape, it is informative to consider the overall relationship between the variables by the classical approach of dimensional analysis. This approach, based entirely on an analysis of the dimensions of the primary quantities, has proven a useful tool in modern day fluid mechanics.

The basic quantities involved in predicting the discharge rate at any time produced by a given rainfall excess rate of given duration uniformly-distributed over a watershed are,

1. Discharge, q \( \propto L^3T^{-1} \)  
2. Time, t \( \propto T \)  
3. Excess precipitation intensity, i \( \propto LT^{-1} \)  
4. All pertinent lengths, \( \ell \propto L \)  
5. All pertinent widths, w \( \propto L \)  
6. All pertinent depths, d \( \propto L \)  
7. Channel roughness, n  
8. Fluid density, \( \rho \propto ML^{-3} \)  
9. Fluid viscosity, \( \mu \propto ML^{-1}T^{-1} \)  
10. Acceleration of gravity, g \( \propto LT^{-2} \)

\( \propto \) means dimensionally equal to, M – mass, L – time and T – time
A general functional equation may be established between the variables as follows,

$$q = \phi(t, i, \ell, w, d, n, \rho, \mu, g)$$  \hspace{1cm} 1.

According to the Buckingham Pi theorem, the 10 variables, expressed in 3 dimensions, may be reduced to a set of 7 dimensionless products (Murphy, 1950). One combination of products which may be selected is:

$$\frac{q}{l^2} = \phi\left(\frac{\ell}{gt^2}, \frac{\rho \ell^2}{\mu t}, \frac{l}{\ell}, \frac{d}{l}, w, n\right)$$  \hspace{1cm} 2.

Consider the two dimensionless terms, $\ell/\sqrt{gt^2}$ and $\rho \ell^2/\mu t$, in the argument of Eqn. 2. Essentially these terms are forms of the Froude number and Reynolds number, respectively, which are well known to hydraulicians. If it is assumed that inertial forces predominate in governing flow from a watershed, the various scale ratios for identically, geometrically-similar watersheds of areas, $A$ and $a$, respectively can be established as,

- **Geometric Ratio** = $(A/a)^{0.5} = n$  \hspace{1cm} 3.
- **Time Ratio** = $(t_A/t_a) = \sqrt{n}$  \hspace{1cm} 4.
- **Intensity Ratio** = $(i_A/i_a) = \sqrt{n}$  \hspace{1cm} 5.
- **Discharge Ratio** = $(q_A/q_a) = n^{2.5}$  \hspace{1cm} 6.

In the foregoing analysis, to obtain the discharge ratio of $n^{2.5}$, it is assumed that the other components are scaled according to Eqn. 3, 4 and 5. In unit graphs, since the volume of rainfall excess must be one inch the discharge ratio for unit graphs from different-sized areas becomes $n^{1.5}$. If the intensity scale is taken equal to unity, or both watersheds receive the same excess rainfall intensity, then the discharge ratio becomes $n^2$. In effect, this latter result simply infers that, for a constant excess rainfall rate, discharge is proportional to the area of watershed contributing to flow.

The above analysis provides some insight of the effect of area on discharge for given conditions. This approach has been used successfully by McCarthy to develop relationships between slope, properties of the area-elevation graph, stream pattern and the lag and peak discharge for 12-hr unit graphs for watersheds in the Connecticut River Basin. Mamisao (1952), used similar criteria to construct a distorted physical model of a small Iowa watershed. Rainfall patterns measured on the prototype were appropriately scaled and applied to the model using a rainfall simulator. The results of this study indicated reasonable agreement in the shape of the hydrograph obtained from model and prototype and, illustrates the potential use of models for hydrologic investigations.

**Drainage - Area Size and Shape**

As indicated previously, the peak discharge of a hydrograph is directly related to drainage basin area. But as the size of the basin increases, the time-base of the hydrograph increases. It follows therefrom that, for a given rainfall excess, the peak ordinate, when expressed in units of cfs/sq. mile will likewise decrease with area.

Drainage-area shape is instrumental in governing the rate at which water is supplied to the main stream as it proceeds to the outlet. It is, therefore, a significant feature which influences the period of rise. For example, a semicircular basin in which the flow con-
verges from all points to the outlet will define a hydrograph with a shorter time to peak than one produced on a long narrow basin of equal area. Langbein and others (1947) summarize the effect as follows:

A drainage basin whose drainage tributaries are compactly organized so that water from all parts of the basin has a comparatively short distance to travel will discharge its runoff more quickly and reach greater flood crests than one in which the larger part of the basin is remote from the outlet.

Density and Distribution of Water Courses

The pattern and arrangement of the natural stream channels determine the efficiency of the drainage system. Other factors being constant, the time required for water to flow a given distance is directly proportional to length. Since a well-defined system reduces the distance water must move in overland flow, the corresponding reduction in time involved is reflected by an outflow hydrograph having a short, pronounced concentration of runoff.

Slope of Valley Sides or General Land Slope

The general land slope has a complex relationship to the surface runoff phenomena because of its influence on infiltration, soil moisture content and vegetative growth. The influence of land slope on hydrograph shape is manifested in the time of concentration of the runoff volumes to defined stream channels. On large watersheds, the time involved in overland flow is usually small in comparison with the time of flow in the stream channel. Conversely, on smaller areas, the overland flow regime may exert a dominating effect on the time relationships and the peak of the hydrograph.

The velocity of overland flow is not readily computed because of the variations in types of flow that may exist along the paths of transit. Overland flow over smooth slopes may range from purely laminar to purely turbulent. Horton (1935, 1945) describes an additional type of flow, subdivided flow, in which flow is subdivided by grass or vegetal matter so as to produce a condition where the velocity is practically uniform over the depth of flow. Under this flow condition, resistance is very great.

Theoretical and empirical considerations of the overland flow regime were expressed by Butler (1957) in the following relationship:

\[ q = ay^bSL^c \]

where \( q \) = rate of outflow per unit width,
\( y \) = average depth of surface storage
\( SL \) = land slope, and
\( a, b \) and \( c \) = coefficient and exponents which vary with Reynolds number, raindrop impact and roughness.

When laminar flow conditions exist throughout the flow distance the values of \( b \) and \( c \) are 3.0 and 1.0 respectively. For turbulent flow they are \( 2/3 \) and \( 1/2 \) respectively. Equation 7 indicates that as the general land slope increases, the velocity of overland flow increases. This effect reduces the time to peak of the hydrograph.
**Slope of Main Stream**

After reaching the main drainageway, the time necessary for a flood wave to pass the outlet is related to the length and slope of the waterway. The velocity of water, \( v \), in an open channel may be expressed in the general form,

\[
v = AR^mS^a_c \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 8.
\]

where \( A \) = constant whose magnitude depends on primarily the roughness of the channel,

\( R \) = hydraulic radius,

\( S_c \) = channel slope, and

\( m \) and \( n \) = exponents.

It follows from Eqn. 8 that the time, \( t \), required for a particle of water to move a given distance, \( L \), in a channel is inversely related to some power of the slope. According to Manning, the values of the exponents are respectively, \( m = 2/3 \) and \( n = \frac{1}{2} \). Dooge (1956) shows that in loose boundary hydraulics, however, roughness and slope are not independent, and that the velocity relationship depends on the size of the bed material. He indicates that, for a channel in equilibrium, the travel time varies inversely with the cube root of the channel slope.

Since the recession limb represents the withdrawal of water from channel storage, the effect of channel slope should be influential in that portion of the hydrograph. With increased channel slope, the slope of the recession limb increases, and the base time of hydrograph decreases.

**Interrelationships of Watershed Characteristics**

In the preceding paragraphs, an attempt has been made to point out the relative influence of certain geomorphic properties on the time-distribution of surface runoff volumes. Those factors discussed affect primarily the time of travel or translation of water from the watershed to the gaging station.

Techniques used in hydrograph synthesis for ungaged basins depend for their success on empirical expressions which relate this watershed characteristics to hydrograph shape. The development of such expressions can be expediated and simplified if consideration is given to the interrelationship of different watershed characteristics. If this is done, the number of variables to be considered may be reduced.

The writer, in a study reported elsewhere (1961), conducted a study of the geomorphic properties of 47 small watersheds in the United States. These watersheds, located in the states of Iowa, Missouri, Nebraska, North Carolina, Ohio and Wisconsin, varied in size from 0.23 to 33.00 sq. miles. A summary of the findings of this study is reported herein.

In 1945, Horton suggested that the development of morphological characteristics depends on three main factors: surface resistivity to sheet erosion, runoff intensity, and ground slope. Since these factors vary with soil and bedrock conditions, vegetative cover, and climatic conditions, watersheds in different regions would be expected to exhibit wide differences in the degree of development of their drainage systems. Miller (1953) explained the differences in the morphological character of watersheds attributable to lithological differences by comparing an area of sandy soil underlain by porous and permeable sandstone with an area of dense clayey soils underlain by dense shale:

Maturely dissected topography would be expected to vary in the following ways: in sandstone areas streams of a given order should be longer and their drainage basins
larger; drainage density should be less, slopes should be longer and possibly gentler than in the shale areas. Furthermore, in a dolomite area the characteristics would be expected to differ from those in either of the areas described above.

For homogeneous watersheds, the laws of stream numbers, stream lengths, and stream slopes proposed by Horton (1945) and, the law of stream areas proposed by Schumm (1956) indicate that these variables are related to stream order. Accordingly, for watersheds within the same physiographic region, these laws suggest that the stream lengths, stream slopes and stream areas can be related in the form of simple power equations.

Figures 2, 3 and 4 show the relationships between the length of the main stream, watershed area, length to center of area and the slope of the main channel for the watersheds studied by the writer. In the study, no attempt was made to categorize the watersheds according to stream order because of limitations imposed by the topographic information.

The pertinent conclusions found in the study are summarized as follows:

1. The length of the main stream, $L$, drainage-basin area, $A$, and length to center of area $L_{ca}$, are highly related.
2. When consideration is given to physiographic region, the slope of the main stream, $S_c$, can be inversely related as a simple power equation to either of the parameters, $L$, $L_{ca}$ and $A$.
3. The general geometric shape of watersheds is between ovoid and pear shape.

If one applies these results to the expressions given for lag time and time of concentration listed in Table 1, it is obvious that many of these equations could probably be simplified to give the relationship between the dependent variable and a single independent variable, for example, drainage-basin area.

**Pondage and Detention Storage**

In prismatic channels, a flood wave moves with nearly pure translation or with little change in shape. However, in natural channels, the wave is generally attenuated by channel storage. That is, the crest of the wave is reduced and its time base is lengthened. The amount of attenuation caused by channel storage depends on the geometry and roughness of the channel. It is somewhat less than that incurred by complete reservoir or lake action.

Several flood routing methods have been developed which can be used to determine the extent of modification of a flood wave when it passes through a channel or a reservoir. The common procedure used in channel routing is to divide the length of stream into a series of reaches then route the flood through the successive reaches. The amount of work involved in this procedure can be reduced if the lag and route method is used. Clark (1945) found that for practical purposes the modification of a flood wave could be estimated by translating the initial flood wave a time equal to the travel time of the reach then routing it through an amount of reservoir storage.
FIG. 1 WATERSHED CHARACTERISTICS

FIG. 2 RELATION OF LENGTH OF MAIN STREAM, L, AND WATERSHED AREA, A.

FIG. 3 RELATION OF LENGTH TO CENTER OF AREA, L_cA, AND LENGTH OF MAIN STREAM, L.

FIG. 4 RELATION OF SLOPE OF THE MAIN STREAM, S_c, AND LENGTH OF THE MAIN STREAM, L, FOR WATERSHEDS WITHIN SELECTED REGIONAL GROUPINGS.
This method was used to synthesize the instantaneous unit graph for a watershed from its time-area distribution.

Since storage must first be filled, then emptied its delaying and modifying effects on surface runoff volumes are very important to hydrograph shape. Minor variations in the rates of generation of runoff on a watershed caused by differences in rainfall intensities and areal distribution of a rain over the basin are evened out by storage. Sherman (1932) summarizes the effect on the unit graph of differences in storage caused by differences in topography as follows:

Topography with steep slopes and few pondage pockets gives a unit graph with a high sharp peak and short time period. A flat country with large pondage pockets gives a graph with a flat rounded peak and a long time period.

Channel Storage:

To illustrate some of the effects of channel storage on the runoff pattern, the writer has plotted the observed hydrographs collected on two experimental watersheds located in Hastings, Nebraska for the storm of June 7-8, 1953 (see Fig. 6). These watersheds, W3 and W11, drain areas of 485 acres and 3519 acres respectively. Rainfall records collected from 12 rain gages located within the watersheds indicated the storm was fairly uniformly distributed over both watersheds. The average depth of precipitation was calculated as 1.70 inches. Both watersheds yielded approximately the same depths of surface runoff.

It can be observed in Fig. 6 that the rising limb of the hydrograph for W11 exhibits a pronounced "flattening-out" at times, 1-2½ hr after the beginning of rainfall, at a discharge rate of approximately 300 cfs. This change in slope of the rising limb can be attributed to two factors, (1) a decrease in rainfall intensity and (2) out-of-bank flow. In this hydrograph, the rainfall intensity effect has tended to accentuate the flattening of the curve. Observations of other hydrographs for the watershed have shown this property of the hydrograph for relatively uniform storm patterns.

From the rating curve for W11 it was found that the stage corresponding to a discharge of 300 cfs is 4.25 ft. By review of the cross-section detail given in Fig. 5 it can be noted that this stage is approximately the depth of the incised channel. When the discharge rate exceeds approximately 300 cfs out-of-bank flow occurs and correspondingly, the velocity, stage-storage and storage-discharge relations of the stream change markedly and abruptly from those conditions which existed with in-channel flow. As pointed out by Johnstone and Cross (1949) flooded overbank areas generally produce a detention-basin effect which is characterized by a reduction in peak discharge and a more slowly rising limb of the hydrograph. That is, the rate of increase in discharge with runoff volume is slower.
FIG. 5 PLAN AND TYPICAL CHANNEL SECTION OF HASTINGS, NEBRASKA, WATERSHEDS

FIG. 6 STORM HYDROGRAPHS FOR WATERSHEDS W3 AND W11, HASTINGS, NEBRASKA, JUNE 7-8, 1953.
The above discussion points out some obvious errors which may result in the shape of "out-of-bank" flood hydrographs derived by superimposing a series of "in-channel" unit graphs. It is important in application of the unit graph concept to recognize that overbank flow alters the flow regime and that it is necessary to route the flood through appropriate amounts of channel storage to account for this change.

Inasmuch as the recession limb represents primarily the withdrawal of water from the channel system, the area enclosed by that portion of the hydrograph is representative of the volume of channel storage when inflow ceases. For comparison, the writer computed the relative percentages of the total surface runoff volumes enclosed within the recessions of the hydrographs for W11 and W3. These values were 42 percent and 34 percent, respectively. In effect, the larger volumes of channel storage tend to lengthen the time base of a hydrograph.

Overland or Reservoir Storage:

In the physiographic region of the Canadian Prairies, in which the relief of the area is poorly developed, most large watersheds contain within their topographic divide a large number of small catchments or sloughs. These sloughs, by their reservoir action tend to modulate the peak discharges from their drainage areas and thus reduce the flood peaks on the main drainage basin.

One of the major problems encountered by hydrologists in analyzing flow records from these basins is that of delineating the area of the watershed contributing during a storm. For most storms, surface runoff which originates within the drainage basin of a slough is completely entrapped by the slough and is ineffectual in contributing to the main stream. In effect, the total drainage area of the large basin is reduced by the sum of the areas draining to each small catchment (as shown by hatched area in Fig. 7). As the magnitude of the storm runoff increases a progressively larger number of the small sloughs become connected through waterways and contribute to flow on the main stream. Thus, the effective size of the drainage basin increases.

To date, no entirely satisfactory method has been found to evaluate quantitatively the relative influence of overland detention and depressional storage to the flood hydrograph. Further study of this problem would appear to be warranted.

![Fig. 7. Schematic Relief Map of Prairie Watershed](image-url)
Summary

In the preceding paragraphs, the effects of certain basin characteristics on the time distribution of surface runoff have been discussed. It must be remembered however that the hydrograph represents the integrated effect of all factors as they modify the storm runoff. The final shape of the time-distribution pattern will reflect the influence of those factors which predominate on the basin at the time of the storm.

SNOWMELT

For a given watershed, the time distribution of runoff from snowmelt water differs in shape from that caused by rainfall. The single factor which makes the runoff pattern different is the difference in rates of generation of the excess volumes. In rain flood problems, it is customary to study situations in which direct runoff volumes are generated very rapidly. By comparison, the rate at which runoff is generated from snowmelt is sluggish. In fact, in certain cases, because of the comparatively low rates of snowmelt, subsurface flow can be very important to flood hydrographs.

Either unit graphs, or storage routing methods may be used to synthesize the time distribution of runoff from snow covered areas (U.S. Dept. of Commerce, 1956). In application of the unit graph technique, conventional rain-fall type unit graphs may be used for rain or snow events, however, special “long-tailed” unit graphs must be developed to distribute runoff originating totally from snowmelt. Probably, storage routing is the most amendable procedure to derive the time distribution of runoff from snow. By this method, the total water excess is divided to two (or more) components and routed separately. The major limitations in application of the method are those of determining the proper lag and storage characteristics of the component parts. In addition to travel time from the basin, time lag in the snowpack must also be considered. Time lag in the snowpack depends on the time required to warm the pack, the time required to satisfy the storage requirements of the pack, and the time required for water to move through the pack.

Factors Affecting Snowmelt

Inasmuch as the time distribution of runoff from snowmelt is very dependent on the manner of generation of the excess volumes further discussions of this phenomenon are warranted. The effect of climatic, vegetative, and topographic factors as they influence the snowmelt process and their effects on hydrograph shape are discussed briefly in subsequent paragraphs.

Climatic Factors:

In order for snow to melt, heat must be supplied from some source. Under natural conditions, the primary sources of heat include (1) net radiation, (2) conduction and convective transfer of sensible heat from the air, (3) conduction from the underlying soil and (4) heat supplied by incident rainfall. All meteorological factors which influence the net heat supply and heat transfer affect the rate of melting of snow. The most important of these factors include: air and snow temperature, vapor pressures of air and snow, solar radiation intensity, albedo of snow, and wind velocity and turbulence.

From a theoretical point of view, it would appear logical to compute snow melt from meteorological data by applying the energy budget approach. Several equations which permit this calculation are given in the literature. Needless to say, however, the application of these equations to estimate snow melt from natural basins is very complicated because of the effects of topography on solar radiation, wind, temperature, etc. and the
variations in the thermal quality and distribution of the snow over the basin. In addition, few watersheds, if any, are adequately instrumented to provide measurements of all the parameters needed for these calculations.

In general, the limitations imposed by the scarcity of data and the complexities of natural basins are such that, in practical application, resort is made to evaluating snowmelt from empirical expressions. Air temperature is naturally one of the more important indices of snow melt which can be easily measured and thus is used frequently in such expressions. Perhaps the most common empirical approach for estimation of snowmelt is the day degree method. By this method, the cumulative snowmelt for given snowpacks is related to the cumulative day degrees above freezing temperature. Once these plots have been derived, snowmelt runoff from the watershed can be determined for different periods by multiplying the area of watershed contributing to flow by the slope of curve, the day degree factor. Experimental observations have shown that the degree day factor may vary from 0.06 - 0.15 in/day degree. Variation in this factor can be attributed to the inability of temperature alone to reflect the influence of all factors influencing snowmelt and to differences in the land and storage properties of the snowpack at different periods in the melt cycle.

Several investigators have reported studies of the use of temperature data to estimate snowmelt. Bruce (1962), reported a comparison of snowmelt computations by the energy balance approach and day-degree method for a basin in Quebec. His findings indicated that the degree-day method underestimates the melt on high melt rate days and overestimates the melt on days of small amounts of melt as determined by the basin equation approach (energy balance). Rosa (1956) suggested that in forested areas, snowmelt can be estimated from temperature data if consideration is given to the separate effects of topography and vegetation. McKay (1963) in a study of snowmelt on the Canadian Prairies reported similar conclusions. He found that fairly good estimates of the average snowmelt could be obtained from measurements of the daily maximum temperature and a threshold temperature (variable temperature base defined as the air temperature above which melting tends to occur and below which melting is not likely to occur). These results are applicable to areas included within the few degrees of latitude in which the study was conducted. They may not be applicable in areas which are climatically dissimilar, or where slope, aspect and forest are significant to the energy balance of the snowpack. Other studies have indicated that in cases where most of the snowmelt passes to ground storage and appears as discharge from ground water flow that temperature provides a better index of flow than any other factor. Generally, under these conditions, flow is regulated by freezing and thawing of the soil surface.

Probably a better meteorological parameter than temperature to estimate snowmelt is solar radiation. Witherspoon & Ayers (1958) in their study of snowmelt from two small watersheds in Ontario found that the hydrographs from these watersheds took the shape of the solar radiation histogram.

Topographic Factors:

Topographic factors of a basin such as slope, aspect and elevation affect such meteorological variables as wind, solar radiation, temperature, etc, and thereby influence the depletion of snow amounts on a basin. For example, basins with southern aspects receive more sunshine per unit area than those with northern aspects, Croft (1946) in his studies reported cases in which the water content of snow on northern slopes in some years was greater than five times that of nearby southern slopes although the two exposures had received approximately the same depths of snow. Surface air temperatures at any time are an inverse function of elevation. Therefore, the snowmelt rate can be expected to decrease with elevation.
In mountainous areas, melting occurs as a snow line which moves up the mountain as melting progresses. This line defines one boundary of the watershed area contributing to flow. The other boundary is the outer isotherm of melting temperature. Because of the effect of elevation on the process, the area of the watershed which contributes to flow decreases in areal extent as the melt season progresses. Seldom, does more than 20–30 percent of a mountainous basin contribute at a given time. This tends to produce hydrographs with low rounded peaks and slowly ascending and descending limbs.

In flat areas, such as the Prairies, the snowmelt process is quite different from that experienced in mountainous areas. Due to the flat topography and lack of forest cover, melting occurs rather simultaneously over a watershed. Also, because the snowpack is generally shallow, rapid changes in the albedo of a watershed occur as melting progresses. These factors produce high melt rates which result in high, sharp, flood peaks similar to rains which last only relatively short time. Most of the runoff from watersheds in this region occurs as surface runoff because the ground is generally frozen at the time of melting.

Vegetative Factors:

The vegetative cover of a watershed influences both snow catch and retention characteristics of the basin. In forested watersheds, depending on the type, density, and stand of trees, large amounts of snow may be intercepted. On these areas, where there is wind movement, snow is collected and trapped in clearings. During the melt period, the shade effect of the trees reduces the amount of insolation received by the clearings and melt is delayed. In contrast, observations have shown that on cut and burnt forested areas snowmelt starts earlier and produces flashier types of hydrographs.

On the prairies, the conservation practice of strip cropping influences the retention and depletion characteristics of snow on watersheds. Fields left in summer fallow are black and smooth. These areas do not catch snow readily, and their slight catches tend to be quickly lost by melting and/or evaporation. Adjacent fields in stubble retain much greater catches of snow. The rate of snowmelt from these strips is slower than from the fallow and, in fact much of the melt may be retained as soil moisture.

Table 3 summarizes the effects of forest and depleted rangelands under different management conditions on the peak flow rates of surface volumes of spring runoff. (U.S. Forest Service 1959).

<table>
<thead>
<tr>
<th>Cover Type</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Very Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>0.8</td>
<td>1.5</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Forest (old Burn)</td>
<td>2.5</td>
<td>3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brush</td>
<td>1.0</td>
<td>1.5</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Grass</td>
<td>1.0</td>
<td>2.5</td>
<td>6.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Summary

The shape of the snowmelt hydrograph of a watershed depends on both the snowmelt process and watershed characteristics. Because of the complexity and the interrelationships of the many factors involved in the transition of water, in the form of snow, to its
PHYSIOGRAPHIC CHARACTERISTICS

appearance as streamflow, no completely integrated solution for evaluating the runoff pattern from snowmelt volumes has been developed. Probably, the heat-budget approach offers the greatest potential for determining the melt rate of snow. The success of this method depends on the precision with which the components of the energy-balance equations can be evaluated.

Before the complex problem of snowmelt-runoff relations can be resolved, some knowledge of the time variation of the infiltration capacity of an initially frozen soil under different conditions, for example, depth of snowpack, must be obtained. Until such times when a complete understanding of the physical processes become known, predictions of the time-distribution of runoff from snowmelt will depend for their success on empirical relationships established between pertinent variables.

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