Hdrological interpretation of basin morphology
John. D. Fox

HYDROLOGICAL INTERPRETATION OF BASIN MORPHOLOGY

by

John D. Fox

IWR-95

August 1978

HYDROLOGIC INTERPRETATION OF BASIN MORPHOLOGY

Completion Report
OWRT Agreement No. 14-31-0001-5002
OWRT Project A-049-ALAS

by

John D. Fox
Assistant Professor of Land Resources

Institute of Water Resources
University of Alaska
Fairbanks, Alaska 99701

The work upon which this completion report is based was supported by funds provided by the U. S. Department of the Interior, Office of Water Research and Technology as authorized under the Water Resources Research Act of 1964, Public Law 88-379, as amended.

IWR-95 August 1978

ACKNOWLEDGMENTS

The author wishes to thank Patricia Werner, Robert Carlson, Linda Dwight, Sheila Finch, and Mary Hayes for their assistance in the preparation of this report.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	ii
INTRODUCTION	1
OBJECTIVES	2
RESEARCH RESULTS	2
Review of Quantitative Geomorphological Methods	2
Identification of Important Parameters	4
Geomorphological Analyses	8
DISSEMINATION OF RESEARCH RESULTS	9
TRAINING	10
COLLABORATION	10
LITERATURE CITED	11

INTRODUCTION

Hydrologic processes in a particular basin are governed by three groups of factors: input regimes of mass and energy, the nature of mass and energy transfer and transformation, and the biophysical characteristics of the basin. This third group provides the structural or morphological framework in which hydrologic processes are taking place and, as such, contributes significantly to the uniqueness of specific basin response.

While much work has been done in quantitative geomorphology in the past decade, little direct incorporation of such indices into hydrologic models has occurred. Perhaps this reflects a preoccupation with form on the part of geomorphologists and with physical process on the part of the hydrologist. Yet, a better understanding of relationships between form and function in hydrology would help resolve such persistent problems as flow estimation from ungaged streams, flood frequency analysis with sparse data, generalizing results from intensely studied experimental watersheds, and assessment of areal variability of hydrologic parameters. Considering Alaska's size and diverse environments, these problems take on additional significance.

A growing percentage of Alaska's water resource will be enveloped or at least intersected in the next decade by the expanding social and economic institutional activities of man. These activities will be intensive and extensive and will extend from population centers across miles of wilderness. Considering the size and diversity of Alaska's water environment, use of hydrologic models for water resource management becomes an attractive if not certain alternative. Successful use of models however, is predicated on availability of representative data and adequate knowledge of hydrologic processes. In an area as vast as Alaska, an efficient means of extrapolating results of an intensive localized investigation is needed. Existing information must be used to the fullest extent. Establishing relationships between land form and hydrologic processes will enable more relevant interpretation and application of research results to current management problems.

OBJECTIVES

The objectives of this project were to:

1. Review existing methods of quantitative geomorphology with particular emphasis on hillslope profile and channel network analyses.

2. Identify those parameters or expressions useful in relating hillslope form and channel patterns to hydrologic processes.

3. Perform certain geomorphological analyses for selected Alaskan basins, and

4. Recommend possible designs for watershed models that couple hydrologic processes with factors of basin form.

RESEARCH RESULTS

1. Review of quantitative geomorphological methods

Use of more sophisticated quantitative land form analyses in geomorphology (Doornkamp and King, 1971; Chorley, 1971) and a recent emphasis on soil moisture dynamics and streamflow in hydrology has set the stage for more meaningful incorporation of basic land form parameters into physics-based watershed models.

Pitty's (1969) work on hillslope analysis demonstrated the potential usefulness of quantitative landform description. The experience of Pitty, and Doornkamp and King suggest slope-profile analysis to be more hydrologically meaningful than random point samples of slope angle. However, most geomorphologic studies are concerned with slope development as brought about by physical, chemical and biological processes, or in other words, how process affects form. Hillslope evolution models have been proposed to explain these relationships (Scheideggar, 1961; Ahnert, 1970; Caine, 1971) which at least infer subsequent effect of form on process. Melton (1960) reported on intra-valley variation in slope angles as related to microclimate, Young and Mutchler (1969) investigated the effect of slope shape on erosion and runoff, and Schumm and Lusby (1963) reported seasonal variation in infiltration capacities and runoff from hillslopes.

The hydrologist's concern with basin geometry and form has been demonstrated by attempts to estimate runoff using multiple linear regression (Thomas and Benson, 1970; Mustonen, 1967), principal component analysis (Wallis, 1965; Mojica, 1971), and conceptual hydrologic models (Holtan and Lopez, 1971; Crawford and Linsley, 1966). Limited success of such studies may result from assumptions of simple linear relationships between variables, lumping of hydrologically distinct subsystems into a single computational unit, and inadequate specification or representation of basin morphology (Calver, Kirkby, and Weyman, 1971).

As basin area increases, the channel network will play an increasingly significant role in storm runoff regimen. However, classical analyses of channel networks, such as Horton's laws of drainage composition, are more useful as comparative indices than in establishing functional relationships between morphology and hydrology. Rogers (1972), however, reported close correspondence between channel length frequency distribution and hydrograph shape for a number of watershed and rainfall patterns. Separation of stream network into exterior and interior link lengths and their associated drainage areas (Smart, 1972) has obvious implications with respect to convergent and divergent subsurface water flow lines. Blyth and Roda (1973) report variations in drainage densities are most significant in first order basins and Kirkby and Chorley (1967) concluded stream hydrographs reflected the influence of drainage density and not vice versa.

Recent work in soil moisture-groundwater flow theory as well as field and laboratory studies have a direct bearing on hydrologic interpretations of geomorphological features. Flow equations describing two-dimensional, saturated-unsaturated moisture movement were solved for the steady-state case by Jeppson (1969) for a number of slope profile configurations. Amerman (1970) presented solutions for unsteady, two-dimensional, saturated-unsaturated flow for a sloping porous media. The effect of slope angle however, was not investigated. Recent papers by Freeze (1972a, 1972b) imply significant control by topography on soil-water, groundwater, streamflow relationships. Field studies by Hewlett (1961), Whipkey (1965), Dunne and Black (1970), and Weyman (1970) support the theoretical analyses and serve as the foundation for the variable source area concept of streamflow production (Hewlett and Hibbert, 1965), or the Dynamic Watershed concept proposed by the Tennessee Valley Authority (TVA, 1965). Other studies demonstrating the importance of slope in controlling subsurface water flow include Richards, Gardner, and Ogata (1956), Wilcox (1957), Nixon and Lawless (1960) and Schmid and Luthin (1965).

2. <u>Identification of important parameters</u>

Predicated on the above review, geomorphological parameters or descriptive indices were selected which were directly relevant to the hydrologic functioning of watersheds in Alaska. Discussion of these characteristics is divided into sections relating to parameters of area, hillslopes, and channels.

Parameters of area: Area is the most obvious category of geomorphological parameters having a direct influence on basin hydrology. Past hydrologic efforts have concentrated on total basin area since a direct relationship exists between total flow volume (Q) and basin area (A_t)

$$Q = (P - ET - \Delta S) k A_t \qquad \text{Eq. 1}$$

where P is precipitation, ET is evapotranspiration and ΔS the change in storage for some specified time period and k is a constant converting area-depth units to those of volume. Often, the watershed is divided into sub-areas of similar characteristics (i.e. P, ET, ΔS) to improve estimates of Q over some time period. Although the basis for subdivision (i.e. soil type, vegetation, flow lines, etc.) may be more important hydrologically than the calculated area itself, the significance of the latter is in estimating the net effect of basin heterogeneity on runoff from the whole watershed. Thus, the significance of some hillslope parameter, such as azimuth, lies not only in its effect on energy input and partitioning on that slope, but also in the percentage of the total basin area having slopes of that azimuth. Recognizing the heterogeneous nature of basin features, equation 1 can be rewritten such that

$$Q = k \sum_{i=1}^{n} (P_i - ET_i - \Delta S_i) A_i/A_t \qquad \text{Eq. 2}$$

where A_i/A_t is the decimal fraction of the total area characterized by a particular set of water balance values and n is the number of subareas identified.

There remains one specific expression of area that needs to be mentioned. This is the "contributing area" or "source area." This area is usually defined as that portion of the whole watershed contributing to streamflow in some specified time period. Ideally the contributing area is equal to the total basin area for annual considerations.

Perhaps a more typical interpretation is that area contributing directly to storm flow. This area may shrink and expand seasonally as soil moisture and stream lengths fluctuate. Contributing areas are normally thought of as riparian zones, areas of high antecedent moisture content, and impervious areas contiguous with stream channels. If we assume the runoff-rainfall (or snowmelt) ratio for contributing areas is 1, then the basin runoff coefficient for storm flow (Q_s) might be defined as the ratio of contribution area (A_c) to total basin area (A_t) is such that

$$Q_s = P \cdot k \cdot A_c \qquad \text{Eq. 3}$$

and now the contributing area can be defined as

$$A_c = \frac{Q_s}{k \cdot P} \qquad \text{Eq. 4}$$

where P is rainfall or snowmelt rate expressed in area-depth units. The Hortonian runoff model assumes only surface or overland flow as contributing to storm runoff and thus one-half the reciprocal of the drainage density would give the average maximum length of overland flow or the average distance between drainage divides and channels. This approach may be fruitless for all but the most impervious of watershed surfaces. However, in light of the current emphasis on subsurface movement of water, the average length of subsurface flow might be useful.

Assuming saturated conditions and unit hydraulic gradient, the average length of flow for a specified period, t, would be simply the hydraulic conductivity, K, times t. This value could be interpreted as the width of the subsurface contributing area, W_{cs}.

$$W_{cs} = K \cdot t \qquad \text{Eq. 5}$$

The width of the overland flow contributing area, W_{co}, would be

$$W_{co} = v \cdot t \qquad \text{Eq. 6}$$

where v, the overland flow velocity, would be a function of depth of flow, surface slope and roughness. Contributing area is then calculated from the product of the width, as estimated above, and the length (L), as estimated from twice the total length of channels in the watershed or subarea (this implies symmetry of contributing area about the stream channels). Thus

$$A_{cs} = W_{cs} \cdot L \qquad \text{Eq. 7}$$

$$A_{co} = W_{co} \cdot L \qquad \text{Eq. 8}$$

where A_{cs} is the subsurface contributing area and A_{co} is the surface or overland flow contributing area. Where surface soils are heavily vegetated and infiltration capacities are high, overland flow may occur only from near-saturated areas as "exfiltration" or seepage. In such cases A_{cs} and A_{co} are approximately equal. In any event, the total contributing area A_c might be expressed as

$$A_c = \max\,(A_{cs}, A_{co}) \qquad \text{Eq. 9}$$

Hillslope Parameters: The parameters descriptive of watershed hillslope and important in effecting hydrologic processes are slope steepness (s), slope orientation (a), and slope length (l). A specific combination of slope steepness and length will determine the relative relief, but some specification of either maximum, minimum or mean elevation is needed to complete the description.

Hillslope processes are particularly important in upland watersheds where extensive aquifers often do not exist as in valley fill deposits. The processes most affected are energy input and water flow. Energy input, in turn, dominates the regime of snowmelt, soil freezing and thawing, and evapotranspiration. At high latitudes the variation of this input is strongly related to slope steepness and orientation. The instantaneous variation in hydrologic processes due to inputs are compounded by longer term effects on soil temperature and moisture regimes. The short-term net effect of slope and aspect on streamflow may be further complicated by the cloud cover characteristics of the region, particularly during snowmelt periods. The contrast of energy input on different slopes will be diminished under cloudy skies since most of the solar input is diffuse radiation. This effect might be expressed as

$$R_s = R_h \left[\frac{R_{oh} + (R_{os} - R_{oh})(1-C)^n}{R_{oh}} \right] \qquad \text{Eq. 10}$$

where R_s and R_h are amounts of solar radiation received on sloping and horizontal surfaces respectively; R_{os} and R_{oh} are the potential amounts of solar radiation, neglecting atmospheric effects, for sloping and horizontal surfaces, respectively; C is sky cover in tenths and n an empirical exponent.

For the whole watershed the expression of average slope steepness and azimuth may be of less value than information on the distribution of basin area in slope steepness and azimuth categories.

Overland water flow velocity is affected as discussed previously, by slope steepness. Subsurface flow will be most notably affected by slope when moisture contents are high and soils are shallow. Although under saturated conditions the matrix potential gradient may be zero in a plane parallel to the slope, a downslope hydraulic head gradient may still exist due to the gradient in gravitational potential, which is equal to the sine of the slope angle. Therefore, as long as water is removed from the bottom of the slope as streamflow or seepage, unsaturated flow down the slope can continue to feed a transient zone of saturation as demonstrated by Hewlett (1961) and Nutter (1975).

Slope length is most significant for investigations of overland flow and erosion. Additional significance of slope length is the implication of storage capacity. However, this factor may be adequately reflected by the area and slope steepness parameters.

Channel parameters: Parameters descriptive of watershed channel network also significant in calculation of hydrologic processes are total length of channels, drainage density, channel slope, hydraulic radius and roughness. Other indices of channel length may also be important. Morisawa (1968) reports the following:

$$\frac{\text{Thalweg length}}{\text{valley length}},$$

$$\frac{\text{channel length}}{\text{length of meander belt axis}},$$

$$\frac{\text{stream length}}{\text{valley length}} .$$

Also of importance is the surface area of lakes, ponds and marshy or boggy areas along the streamcourse.

In any attempts to subdivide watersheds for the purpose of water-balance and streamflow modeling, consideration might well be given to the topographic distinction between those land areas draining directly to a channel versus those portions of a subarea (i.e. elevation zone) draining directly to the land area of the adjacent subarea.

Rogers (1972) showed that a frequency distribution of the path length to the basin outflow point displays similarity to the basin hydrograph. Such an analysis may be appropriate for rain events, but for snowmelt generated runoff, some combination of aspect, elevation and path length might be more appropriate.

3. Geomorphological analyses

Initially plans included taking measurements of selected geomorphic indices for non-glacial Alaskan streams for which flow records were available. Delineation by physiographic province was also considered desirable. Unfortunately, the above criteria resulted in so few streams that little hope of statistical validity was foreseen for the multiple regression approach to the problem.

As an alternative, a watershed model was conceived that explicity incorporated many of the significant geomorphological parameters discussed above. The approach was then to vary the selected parameters and observe the response of simulated streamflow. This change in strategy necessitated considerable work in developing an appropriate model. Time and funding for the project reported here did not allow completion of this task and the subsequent analysis such that frozen soils, permafrost, and other northern phenomenon could be programmed to interact appropriately with the geomorphic parameters. Also, only the hillslope characteristics of small, low-order watersheds have been incorporated to date.

Preliminary testing of the model indicated the importance of aspect, area-elevation distribution, and latitude for snowmelt generated runoff events. The area-elevation relationship is also important under rainfall conditions when a precipitation-elevation relationship is used in the model. Increasing drainage density directly in the model accelerates runoff, as would be expected. However, actual differences in drainage density between basins is probably indicative of some other, more fundamental difference. One would expect that a particularly high drainage density might reflect either an increased input to the system or a reduced storage and/or transport capacity. Thus, changing drainage density only in the model had little effect on flow compared to the effects of changing soil depths, soil type, or precipitation which, in the final analysis may be the cause of increased drainage densities. Since there is no casual link in the current model between soils and drainage density, such compound effects could not be investigated. Further work is needed to investigate the usefullness of using simulation experiments to derive simplified empirical relations between parameters of basin form and key indices of streamflow regime.

4. Recommendations for watershed model design

Review of geomorphological indices and experiments with initial models indicated key features that should be incorporated into hydrologic models, particularly in northern regions. They are:

a. Division of the area to be modeled into elevation zones.
b. A precipitation-elevation function and temperature-elevation relationships.
c. Incorporation of the effects of slope, aspect and latitude on snowmelt and evapotranspiration.
d. Specification of those portions of each elevation zone drained by a channel.
e. Identification of the interrelationship between soil depth, hydraulic properties and channel length.
f. A channel routing technique that incorporates the channel length and pattern (sinuosity, meander characteristics, etc.)
g. Incorporation of soil temperature and a freezing-thawing algorithm.

DISSEMINATION OF RESEARCH RESULTS

Although all results of this study were not conclusive, at least one scientific journal article and a technical report are anticipated. Reports will be distributed to relevant state and federal agencies.

Personal communications related to this project have already been made with several state and federal agencies.

TRAINING

At the time of this project no qualified graduate students were available. However, results of the project, as well as techniques used, have served to improve classroom materials and laboratory exercises in our Watershed Science course.

COLLABORATION

Alaska Department of Environmental Conservation collaborated by making topographic maps and river mileage measurements available for use in this study.

LITERATURE CITED

Ahnert, F. 1970. A comparison of theoretical slope models with slopes in the field. Zeitchr. Geomorph. Supplementband 9. pp. 88-101.

Amerman, C. C. 1970. Finite difference solutions of unsteady two-dimensional partially saturated porous media flow. Ph.D. Thesis. Purdue University, Lafayette.

Blyth, K., and K. C. Roda 1973. A stream length study. Water Resources Research. 9(5):1454-1461.

Caine, N. 1971. A conceptual model for alpine slope process study. Arctic and Alpine Research. 3(4):319-329.

Calver, A., M. J. Kirkby, and D. R. Weyman. 1971. Modelling hillslope and channel flows. Pages 197-218 in R. J. Chorley, ed. Spatial analysis in geomorphology. Metheun & Co., London.

Chorley, R. J., ed. 1971. Spatial analysis in geomorphology. Metheun and Co., London. 393 pp.

Crawford, N. H., and R. K. Linsley. 1966. Digital simulation in hydrology: Stanford Watershed Model IV. Dept. of Civil Engineering. Stanford University, Stanford, CA. Technical Report 39. 210 pp.

Doornkamp, J. C., and C. A. M. King. 1971. Numerical analysis in geomorphology: an introduction. Edward Arnold, Ltd., London. 372 pp.

Dunne, T., and R. Black (1970). Partial area contributions to storm runoff in a small New England watershed. Water Resources Research. 6(5): 1296-1311.

Freeze, R. A. 1972a. Role of subsurface flow in generating surface runoff. 1. Base flow contributions to channel flow. Water Resources Research. 8(3): 609-623.

Freeze, R. A. 1972b. Role of subsurface flow in generating surface runoff. 2. Upstream source areas. Water Resources Research. 8(5): 1272-1283.

Hewlett, J. 1961. Soil moisture as a source of base flow from steep mountain watersheds. Southeastern Forest Experiment Station, U.S. Forest Service. Station Paper 132.

Hewlett, J., and A. Hibbert. 1965 . Factors affecting the response of small watersheds to precipitation in humid areas in Sopper and Lull, eds., International Symposium on Forest Hydrology. Pergamon Press.

Holtan, H. N., and N. C. Lopez. 1971. USDAHL-70 model of watershed hydrology. Agricultural Research Service, U. S. Dept. of Agriculture. Technical Bulletin 1435. 84 pp.

Jeppson, R. J. 1969. Numerical solution of the steady-state two dimensional flow system resulting from infiltration on a watershed. Utah Water Research Laboratory, Logan. Report PRNG-59c-1.

Kirkby, M. J., and R. J. Chorley. 1967. Throughflow, overland flow and erosion. Bulletin of the International Association of Scientific Hydrology. 12:5-21.

Melton, M. A. 1960. Intravalley variation in slope angles related to microclimate and erosional environment. Bulletin of the Geological Society of America. 71:133-144.

Mojica, I. 1971. Effects of changes in land use on the streamflow of the Reventazon River, Costa Rica. Unpublished. Ph.D. Dissertation. University of Washington, Seattle. 185 pp.

Morisawa, M. 1968. Streams, their dynamics and morphology. McGraw-Hill Book Co., New York. 175 pp.

Mustonen, S. E. 1967. Effects of climatological and basin characteristics on annual runoff. Water Resources Research. 3(1):123-130.

Nixon, P., and G. Lawless. 1960. Translocation of moisture with time in unsaturated soil profiles. Journal of Geophysical Research. 65:655-661.

Nutter, W. 1975. Moisture and energy conditions in a draining soil mass. Report for Office of Water Research and Technology, U. S. Dept. of Interior. University of Georgia, Athens. Technical Completion Report A-025-GA.

Pitty, A. F. 1969. A scheme for hillslope analysis/1. initial considerations and calculations. Occasional papers in geography. Univ. of Hull Publications, Yorkshire, England. No. 9. 76 pp.

Richards, L. A., W. R. Gardner, and G. Ogata. 1956. Physical processes determining water loss from soil. Proceedings of the Soil Science Society of America. 20:310-314.

Rogers, W. F. 1972. New concept in hydrograph analysis. Water Resources Research. 8(4):973-981.

Scheideggar, A. E. 1961. Mathematical models of slope development. Bulletin of the Geological Society of America. 72:37-49.

Schmid, P., and J. Luthin. 1965. The drainage of sloping lands. Journal of Geophysical Research. 69:1525-1529.

Schumm, S. A., and G. C. Lusby. 1963. Seasonal variation of infiltration capacity and runoff on hillslopes in Western Colorado. Journal of Geophysical Research. 68:3655-3666.

Smart, J. S. 1972. Quantitative characterization of channel network structure. Water Resources Research. 8(6):1487-1496.

Tennessee Valley Authority. 1965. Area-stream factor correlation. Bulletin of the International Association of Scientific Hydrology. 10(2):22-37.

Thomas, D. M.. and M. A. Benson. 1970. Generalization of streamflow characteristics from drainage basin characteristics. U.S. Geological Survey. Water Supply Paper 1975.

Wallis, J. R. 1965. Multivariate statistical methods in hydrology - a comparison using data of known functional relationship. Water Resources Research. 1(4):447-461.

Weyman, D. R. 1970. Throughflow on hillslopes and its relation to the stream hydrograph. Bulletin of the International Association of Scientific Hydrology. 15(3):25-33.

Whipkey, R. F. 1965. Subsurface stormflow from forested slopes. Bulletin of the International Association of Scientific Hydrology. 10:74-85.

Wilcox, J. C. 1957. Rate of soil drainage following an irrigation. 1. Nature of soil drainage curves. Canadian Journal of Soil Science. 39(2):107-118.

Young, R. A., and C. K. Mutchler. 1969. Effect of slope shape on erosion and runoff. Transactions of the American Society of Agricultural Engineers. 12:231-233.