DRAINAGE AREA AS A HYDROLOGIC FACTOR ON THE GLACIATED CANADIAN PRAIRIES

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SUMMARY

On the Canadian Prairies glaciation has created a great deal of depressional storage in most watersheds. The amount of runoff required to fill the available storage each year is a function of previous runoff and climatic conditions; hence areas which contribute to runoff at a downstream point one year may not contribute in another. Consequently, the drainage boundaries of these watersheds change periodically.

This paper describes the problem and discusses some of its applications to hydrological investigations.

RÉSUMÉ

Dans la région des prairies de l'ouest du Canada, la période glaciaire a beaucoup contribué à la condition des réservoirs qui se forment dans les dépressions, et que cette condition existe dans la plupart des versants. La quantité de l'ecoulement exigée pour ramplir, à la capacité, ce reservoir en question, est une fonction d'un écoulement précédant ainsi que des conditions climatiques. C'est par suite de cela que les régions qui contribuent, disons cette année, a un écoulement dans un endroit d'aval, ne contribueront pas, peut-être, aussi considérablement à l'avenir. Parconséquent, les bornes du drainage de ces versants changent périodiquement.

Cette étude décrit ce problème et discute quelques-unes de ses applications par des investigations hydrologiques.

The Problem

Introduction

Drainage area is usually regarded as the most obvious and readily available factor in a hydrologic study of a basin. Accordingly, formulas and graphs have been developed to determine the runoff characteristics of an area using drainage area as the common denominator. However, the drainage area of streams in regions subjected to glacial transformation and deposition is often difficult to determine. On the Canadian Prairies, for instance, great fluctuations of the drainage basin boundaries have been observed in dry and wet years and in different seasons of the year. The objects of this paper are to describe this problem of fluctuating drainage areas and to suggest some of its ramifications.

Description of the Area

To fully comprehend how the area of a drainage basin on the Canadian Prairies may fluctuate, it is imperative that the effect glaciation has had on the drainage pattern be appreciated. Since the region was once covered by a continental ice sheet, the present surface deposits are chiefly of glacial origin. This glacial drift is distributed irregularly in most areas and lacustrine and morainic deposits may be found in the same basin. Morainic country is characterized by gently undulating to strongly rolling topography with numerous undrained or partially drained depressions and marshy areas. Generally, the interior drainage system is inadequate and is characterized by a lack of well-developed drainage channels. Under normal climatic conditions the smaller depressions contain water for a few months each spring. During prolonged dry periods even the large depressions and the lakes disappear. On the other hand, a cycle of wet years with subsequent above-normal precipitation fills the depressions to overflowing and produces high groundwater levels. This produces conditions favourable to a high runoff and portions of a drainage basin which may be unproductive in dry years overflow and contribute materially to flows on the main stream.

Figure 1 shows an aerial mosaic of a typical drainage basin on the Canadian Prairies under wet conditions. It may be seen that the myriads of depressions and the sloughs are all filled and connect to adjacent sloughs and eventually the main stream. In contrast, a mosaic of the same area is shown in Figure 2 as it would appear in dry years. Only the larger sloughs have any water in them at all. The drainage area contributing to flows at point "A" is only about 20 percent of the contributing area shown in Figure 1.

Figure 1
Aerial mosaic of a typical
drainage basin on the Canadian Prairies
under very wet conditions

Figure 2
Aerial mosaic of a typical
drainage basin on the Canadian Prairies
under dry conditions

Drainage Area and Runoff Volume

The recorded runoff volume at a gauging station is usually expressed in terms of the average depth in inches over the basin above that station, or in acre-feet per square mile based on an assumed drainage area. This assumed drainage area is usually considered constant. In many glaciated areas such a method yields a distorted picture of the runoff from a unit area. A different drainage area to suit the climatic conditions of a particular period should be used if a true comparison is desired, or if correlations with other streams are to be attempted. The variation of drainage boundaries is peculiar to each individual basin and is likely a function of the available surface storage, precipitation and evaporation.

The actual effect of the varying size of a watershed on the total runoff volume is difficult to evaluate. If many of the depressions in a basin are filled to overflowing at the time of runoff, the runoff from the area draining into these depressions will contribute to flows on the main stream. If on the other hand, the depressions are only partly full at the time of runoff, only a small percentage will contribute to the volume downstream. In summary, depression storage will effectively reduce the rate and the total volume of surface runoff.

Drainage Area and Flood Peaks

Flood peaks are affected by varying drainage area in a slightly different manner than runoff volume. Let us consider a watershed that has numerous depressions. In many years, the flood peaks will be produced by that portion of the basin which has little natural storage. There will be a temporary storage and time lag for all runoff originating upstream from the depressional area; consequently, this runoff will have only a slight effect on the flood peak produced by the watershed as a whole. It should be realized, however, that the runoff from a "sloughy" area may provide a large base flow on which a high runoff from other portions of the watershed can be superimposed. In a flood study, it may be reasonable to assign a weight to such an area for the purpose of reducing it to the size of an equivalent area similar to the rest of the contributing portion of the basin.

In the case of extreme floods, a slightly different situation exists. The maximum probable flood would be expected to originate from the "gross" drainage area diminished only slightly by the natural storage. Drainage area terms are defined on page 7.

Pertinent Data

Factors Affecting Drainage Area

The factors which cause the boundaries of a watershed to fluctuate are analogous in many ways to the factors which contribute to the variability in water yield. Precipitation, temperature, storm intensity and the physiography of the watershed are some of the more important factors to be considered. A brief discussion of some of these variables follows.

A. The natural surface storage is a physiographical factor which is peculiar to each watershed or portion of a watershed. It usually takes the form of closed drainages which range in size from small depressions to large marshes and flats. Depressional storage has been briefly considered in Chapter II of the text "Applied Hydrology", by Linsley, Kohler and Paulhus. It is stated therein that in order to understand the sequence of events which takes place after the beginning of surface runoff, the following facts must be recognized:

1. "Each depression has its own capacity or maximum depth.
2. As each depression is filled to capacity, further inflow is balanced by outflow plus infiltration and evaporation.
3. Depressions of various sizes are both superimposed and interconnected. In other words, every large depression encompasses many interconnected smaller ones.
4. Each depression, until such time as it is filled has a definite drainage area of its own."

The manner in which the water surface of many depressions fluctuate by seasons and by years on the Canadian Prairies may be realized by reference to work carried out by Ducks Unlimited of Canada. Over a period of years they have studied bodies of water in Eastern Saskatchewan which are typical of the Prairies as a whole. The table which follows summarizes some of their observations.

Average Observed and Estimated Water Surface Areas of Lakes and Sloughs in Eastern Saskatchewan

Year	1952	1953	1954	1955	1956	Yearly Average
Water area in the month of May, acres per sq. mi.	16.4	14.2	11.2	16.2	19.7	15.5
Water area in late summer acres per sq. mi.	5.5	8.6	10.7	9.2	8.1	8.5
Ratio of area in late summer to month of May percent	35	60	95	57	41	55

B. Soil and topography are factors which greatly affect infiltration; infiltration in turn influences the surface runoff and the rate at which depressional storage is filled. It is characteristic of glaciated areas that light, shallow soil mantles predominate in the areas of rolling topography and heavy lacustrine deposits are usually associated with flat to gently undulating plains. Furthermore, the subsoil in glaciated regions is frequently an impervious boulder clay which impedes groundwater flow.

C. Precipitation and evaporation behave antithetically but must be considered together as being the most significant variables affecting the limits of a drainage basin.

The actual effect of precipitation will be determined by its seasonal distribution and must be considered in two parts, namely: that precipitation which produces the runoff and that precipitation which is antecedent. It would appear that the effective antecedent precipitation should be found by weighting the monthly precipitation for several years previous, the weight decreasing as one goes backwards in time.

Evaporation is a factor which also affects antecedent conditions. High evaporation may minimize the effect of high antecedent precipitation and vice versa.

D. Intensity of rainstorms and rate of warm-up in the spring obviously influence the amount of infiltration and subsequently the volume of surface runoff which replenishes the depressional storage.

E. Other factors such as vegetation, area under cultivation, cultivation practices and type of crops grown may all indirectly affect the contributing drainage area of a watershed any year. However, the average effect of such factors is believed to be less significant than those discussed above.

Drainage Area Definitions

The drainage area definitions used in this paper are as outlined hereunder.

The gross drainage area of a watershed is that plane area enclosed within its divide which through natural and artificial processes would entirely contribute runoff to the main stream in extremely wet years.

The net drainage area is that portion of the watershed which contributes water to the runoff on the main stream in any particular year. It is not a constant and may fluctuate each year.

Net wet drainage area for a watershed is the average of the net drainage area for that watershed arbitrarily determined for years of much above normal precipitation, by observation, judgement and analysis of detailed drainage maps.

Net dry drainage area for a watershed is the average of the net drainage areas for that watershed arbitrarily determined for years of much below normal precipitation, by observation, judgement and analysis of detailed drainage maps.

The definitions listed above have been illustrated in Figure 3, a detailed map of the Assiniboine River basin above Sturgis, Saskatchewan on which the boundaries of the gross, net wet and net dry areas are delineated. The influence of depressional topography on the location of these boundaries may be noted.

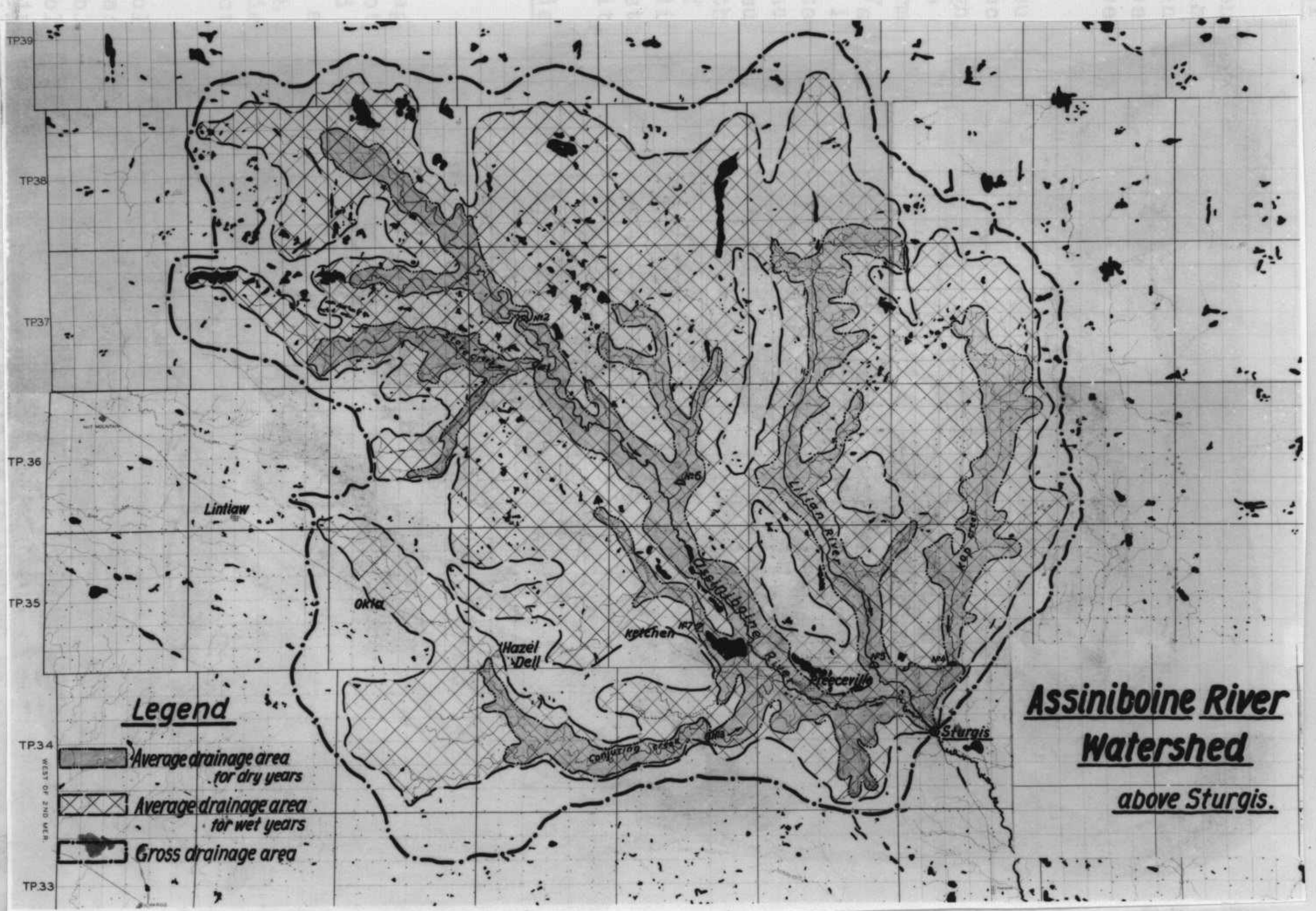

Figure 3
Assiniboine River Watershed above Sturgis, Saskatchewan
showing gross, net wet, and net dry drainage areas

Drainage Area Determination

General

Some of the complexities which hinder the determination of the contributing area of a drainage basin have been mentioned. It should be pointed out that no simple and practical solution to the problem can be found without additional field observation. However, several methods have been considered which warrent further consideration. These possibilities will be outlined in this section.

Linsley, Kohler and Paulhus, in their book "Applied Hydrology" have suggested a general formula which may be adaptable to the problem of fluctuating drainage boundaries to determine the productiveness of "sloughy" portions of a basin during a runoff. They have expressed the volume of water in depression storage V_s at any time throughout a storm in terms of the accumulated rainfall excess P_e by an equation of the type $V_s = S_d(1 - e^{-kP_e})$ where S_d is the total depression storage capacity and k is a constant. It is likely impractical to apply this equation to watersheds where detailed topographical maps are not available unless regional coefficients can be developed by field measurements to indicate a measure of the available depressional storage. Then too, in its present form that equation does not account for the effect of antecedent precipitation, runoff and evaporation. It is pointed out in the above-mentioned book that little is known of actual variations in depression storage but it is suggested that the rate at which such storage is depleted probably recedes logarithmically with time.

Methods for Consideration

1. Precipitation-Evaporation Analysis

It has been stated that the factors which greatly influence the drainage boundaries in most years are precipitation and evaporation but that other lesser factors play a part. When attempting to find a practical method to determine these boundaries with the limited basic data available it is axiomatic that the number of variables should be kept to a minimum giving emphasis to major factors. Thus, it is believed that from a consideration of precipitation and evaporation alone it may be possible to predict the contributing drainage area of a basin each year.

The simplest form of relationship between two independent variables, say precipitation and evaporation, and the dependent variable drainage area, would be a three-dimensional graph. The independent variables would be located on the 'X' and 'Y' axes and the dependent variable shown by contour lines, probably spaced logarithmically. The relative 'weight' to be applied to each independent variable and the location of the contour lines would be influenced by observed and recorded data in known dry and wet years.

2. Runoff-Climatic Index Variables

An additional possibility to determine a contributing drainage area relationship from meteorological information would be to utilize one of the conventional graphical methods for correlating such information to water yield. For instance, a coaxial method for relating the variables precipitation producing the runoff, antecedent precipitation and evaporation and rate of snowmelt or intensity, might be contemplated to arrive at a contributing-drainage-area-as-a-percent-of-gross-drainage-area-curve.

Applications

General

Frequently it is necessary to determine the annual runoff at a point on a stream where there is no recorded data. The problem is either to determine the runoff distribution of upstream tributary basins from a main stream recording station or to use that data to find the missing information on a neighboring stream. For that determination it is common practice to account for drainage basin characteristics and different meteorological conditions but to convert the recorded data to the basin in question by a constant drainage area ratio. However, in watersheds containing much depressional storage this ratio may not be constant and may vary each year as the size of the drainage areas vary since these drainage area fluctuations will probably not be proportional on separate basins.

Runoff-Drainage Area Analysis

In the following a method is proposed for determining the runoff on a basin having no records from a basin having records assuming that climatic conditions are the same on both basins; call these basins A and B. This system may be considered in three steps: first, determine the contributing drainage areas each year of basinA; secondly, determine the contributing drainage areas each year of basin B from those determined for basin A; thirdly, find the runoff each year for basin B by multiplying the recorded runoff on basin A by the ratio of the drainage areas on basins B to A. Figures 4 and 5 have been prepared to illustrate this method.

Figure 4 is a schematic diagram of an arrangement for determining the yearly contributing drainage area on a stream from the corresponding yearly runoff with the aid of a climatic index. This climatic index, derived from precipitation, evaporation, etc, in conjunction with the runoff would be, in effect, a means of measuring the residual storage of the basin.

Figure 5 shows the relationship of the drainage area at a point in one watershed (say the point where the recorded runoff data is available) with the drainage area on other watersheds. In this example, the Assiniboine River basin at Sturgis, Saskatchewan and seven of its main tributary basins were considered. The dry, wet and gross drainage areas of each basin were first determined from aerial photographs and detailed survey and soil maps. Then the Assiniboine River drainage areas at Sturgis, as a percent of the gross drainage area were plotted against the corresponding drainage areas of the tributaries. The resulting graph, Figure 5, reveals that each tributary basin has its own characteristic relationship as regards contributing drainage area. It is reasonable to assume that the relative runoff contribution from each basin varies with the contributing drainage area of that basin. It should be noted in the accompanying table that these are adjacent basins, all of comparable size, all with the same general topographic characteristics and all with the same climatic conditions. The fact that each basin shows a different relationship indicates different natural storage characteristics of each basin.

HYDROLOGICAL AND PHYSIOGRAPHICAL DATA
ASSINIBOINE R. ABOVE STURGIS, SASKATCHEWAN

Stream	Drainage Area			Length	Drainage Density			Soil	Recorded Data		
See Fig. 3	Gross Sq.mi.	Av. for wet Years sq.mi.	Av. for dry Years sq.mi.	Main Stream miles	Gross D.A. mi/mi^2	Wet D.A. mi/mi^2	Dry D.A. mi/mi^2		Yearly Runoff 1916-55 ac.ft.	Yearly Precipitation 1916-55 inches	Yearly Evaporation 1921-50
Assiniboine River Above Sturgis	960	665	170	60.0	0.63	0.90	1.85		Av. 65,200	16.33	27.14
									Max. 208,100	29.6	39.9
									Min. 2,700	8.8	19.4
Trib. No. 1	71	39	14	17.0	0.64	1.16	2.32	loam			
No. 2	109	69	17	27.0	0.46	0.73	2.10	loam			
No. 3	135	66	12	29.5	0.59	1.05	2.16	loam			
No. 4	103	73	24	22.5	0.55	0.78	1.60	Clay loam & loam			
No. 5	170	126	35	27.0	0.65	0.88	1.69	Sand loam & loam			
No. 6	100	89	11	18.5	0.69	0.77	3.36	loam			
No. 7	88	68	4.5	20.0	0.90	1.17	2.67	loam			

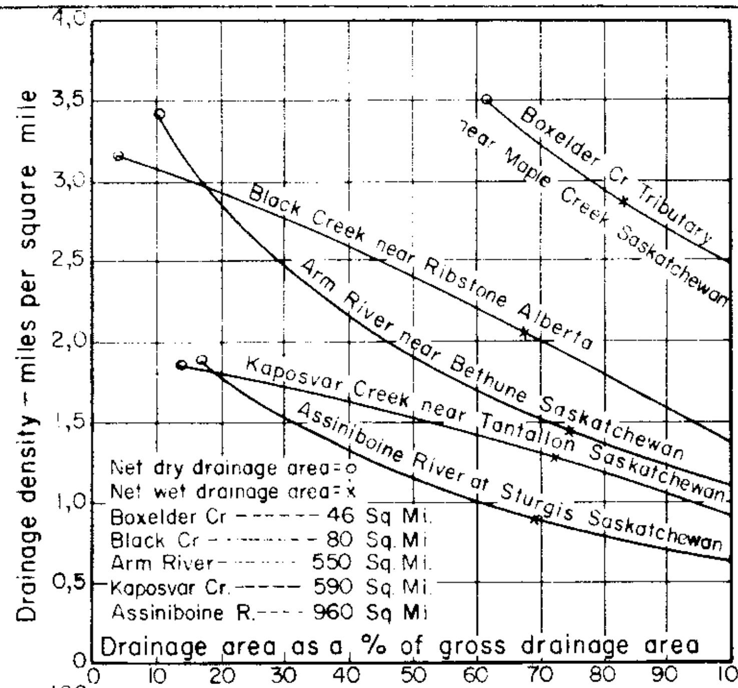

Figure 6

Drainage density—drainage area relationship of some typical watersheds on the Canadian Prairies

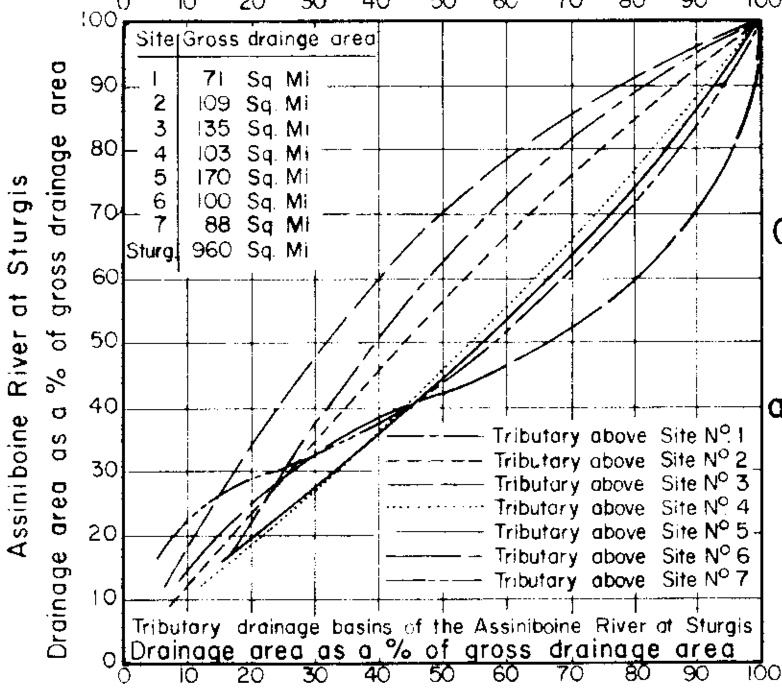

Figure 5

General drainage area relationship of the Assiniboine River above Sturgis, Saskatchewan and its major tributary basins

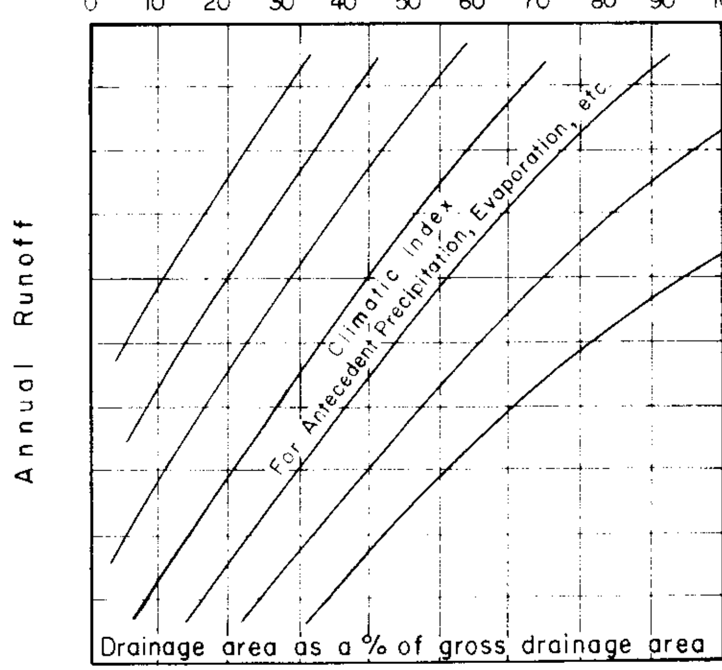

Figure 4

Schematic diagram of a runoff-drainage area relationship for a watershed on the Canadian Prairies

Prepared by ________ Drawn by: [illegible]	
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Drainage Density

The drainage density of a basin is an expression of the average length of streams per unit area. It is usually expressed in the form of the ratio $\Sigma L/A$ where ΣL is the total length of streams in the basin and A is the drainage area. Of course, the absolute value of the drainage density depends upon the detail of the map from which the term ΣL is determined. The reciprocal of this factor $A/\Sigma L$ is the average distance between streams and $A/2\Sigma L$ is a measure of the average length of overland flow for the basin. Ordinarily, the ratio of the time of overland flow to the total time of travel to the outlet is assumed to be very small and the direct effect of drainage density is considered insignificant except in connection with flood flows. However, if the variation of drainage density with the contributing area of a basin is plotted as in Figure 6, it will be realized that the time of overland flow for some basins is not a very small item and when the drainage area of a basin fluctuates, drainage density should be considered as a pertinent basin characteristic.

Figure 6 shows the drainage density-drainage area plot of a number of typical watersheds on the Canadian Prairies. The variation of this watershed factor is seen to be peculiar to each basin; it will have application where the characteristics of different basins are being compared.

Correlations to Determine Missing Flow Data

It often happens that attempts to correlate the runoff data on neighboring streams yields poor results. However, if the annual contributing drainage area is first determined and the data then plotted as runoff per square mile, considerable improvement may be obtained in those basins where varying drainage areas are dominant.

Review

The following conclusions may be drawn from this paper:

1. The contributing drainage area of watersheds in many glaciated regions varies by seasons and by years.

2. The fluctuating effect of drainage areas should be considered in any hydrologic study in regions having appreciable depressional storage.

3. It should be possible to estimate the contributing drainage area of a watershed each year from an analysis of available information, that is, aerial surveys and topographical maps, supplemented by meteorological and hydrometric data.

4. Application of the varying drainage area concept will permit more accurate determination of missing stream flow data in most glaciated regions.

5. This paper represents an initial attempt to stimulate interest in the problem of varying drainage areas. Additional basic field data is required in this field.

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