Geomorphologic Characteristics of Fourteen Indiana Watersheds Obtained from a Computer Data Bank of Stream Networks

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Abstract

Twenty-eight geomorphologic properties were obtained for each of 14 Indiana watersheds. These properties are based on Strahler's stream ordering system and on Shreve's stream link magnitude system. The laws of the stream numbers and of the stream lengths, in general, were found to be valid. The bifurcation ratio has a nearly constant value of about 4.5, almost equal to the ideal network value. The mean first-order stream length ranges from 0.08 to 0.13 miles, a comparatively low value due to the detail of the maps used. The drainage area is strongly correlated to the stream length and is inversely related to the watershed slope. Weaker correlations exist between the drainage area and the drainage density and between the drainage area and the texture ratio.

Basic Geomorphologic Parameters

There are two classifications of stream networks which are widely used. The Strahler ordering system assigns the order one to every unbranched fingertip tributary segment. Two first-order streams unite to form a second-order segment. A third-order segment is formed by junction of two second-order streams, but may be joined by additional first- or second-order segments. If two unequal channels unite to form a segment its assigned order is the same as the larger order of the two upstream segments. In Shreve's link magnitude system all exterior links are assigned the magnitude of one. The junction of any two links increases the magnitude of the resulting downstream link, the magnitude of which is the sum of the magnitudes of the two upstream links.

Based on these two systems, numerous drainage basin characteristic parameters were derived. The interrelationships between these parameters and other basin characteristics calculated directly from the stream network data form the structure shown schematically in Figure 1. This structure consists of three major parts based on the Strahler stream ordering system, the Shreve link-magnitude system and the direct measurements from drainage basins, respectively. The major function of Strahler's stream ordering system is the assignment of an order to each stream segment. The order of a basin, U_B, is defined as the order of the largest segment which it contains.

The basic function of Shreve's link-magnitude system is the assignment of a magnitude to each link. The magnitude of a basin, M_B, is defined as the magnitude of the largest link which it contains.

In the third part, direct measurements from basin maps are used to estimate the geomorphologic parameters. Four parameters describe the most important characteristics of basins. They are: the drainage

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area, the basin perimeter, the basin length and the basin slope. The basin length is defined as the maximum straight line distance between a point on the basin perimeter and the stream mouth. The basin slope is defined as the total relief, or the difference between the highest contour and the elevation of the basin mouth, divided by the main stream length. The primary basin parameters are the number of streams of a given order, N_u, the length of a stream of a given order, L_u, the bifurcation ratio R_B, the number of links of a given magnitude N_m and the link length of a given magnitude.

The secondary basin parameters were derived from the three major parts of the geomorphic parameter structure. They are the texture

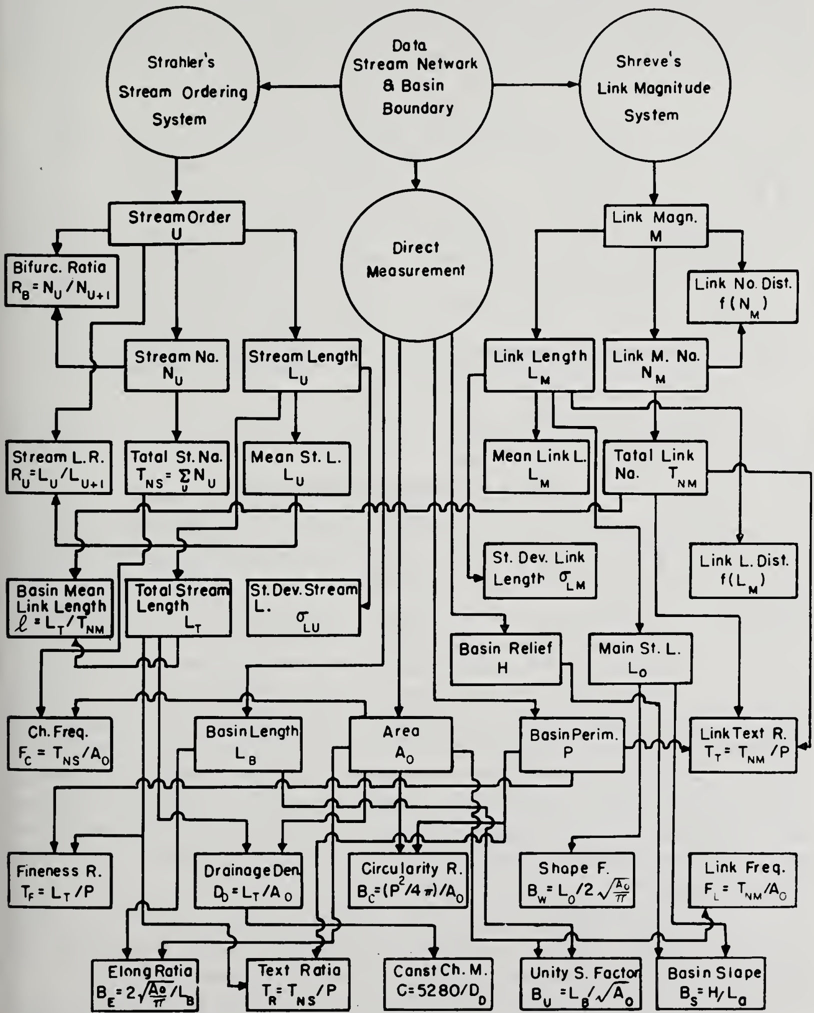

FIGURE 1. *Interrelated scheme of geomorphologic parameters.*

ratio, the link-texture ratio, the fineness ratio, the drainage density, the constant of channel maintenance, the channel frequency, the channel link frequency, the circularity ratio, the elongation ratio, the watershed shape ratio, and the unity shape factor. Working definitions of the primary and secondary basin parameters were given by Coffman *et al.* (1) and are shown schematically in Figure 1.

Data Acquisition

The coordinates of stream junctions and sources and of the boundaries of the 14 Indiana watersheds listed in Table 1 with areas varying between 3 and 220 square miles were obtained from the Purdue University Atlas of County Drainage Maps (2). These coordinates were stored on magnetic tapes (3). These data were processed using the W.A.T.E.R. System Computer Program for Stream Network Analysis (1).

TABLE 1. *Watersheds for geomorphologic analysis.*

Watershed No.	Watershed Name	Watershed No.	Watershed Name
1	Lawrence Cr. at Ft. Benjamin Harrison	24	Buck Cr. at Muncie
2	Bear Cr. near Trevlac	35	Salamonie River at Portland
3	Bean Blossom Cr. at Bean Blossom	37	Bice Ditch near South Marion
10	Big Blue River at Carthage	39	Little Cicero Cr. near Arcadia
16	Hinkle Cr. near Cicero	42	Wildcat Cr. near Jerome
19	Brush Cr. near Nebraska	43	Slough Cr. near Collegeville
22	Cicero Cr. at Noblesville	44	Little Indian Cr. near Royal Center

Analysis of Geomorphologic Data

Horton proposed that the stream numbers and the steam lengths vary with the stream orders in a geometric progression. Accordingly, the plot of the data on semi-logarithmic paper, should result in an approximately straight line. The stream numbers and the mean stream lengths are plotted versus the stream orders for 12 basins as shown in Figure 2. The plots are approximately straight lines with the exception of the stream length plots of Bean Blossom Creek (WS3), Little Cicero Creek (WS39), Wildcat Creek (WS42), Slough Creek (WS43) and Little Indian Creek (WS44) which are of the "incomplete" type networks. These incomplete networks contained only two streams of the second highest order, the minimum number to form the highest order streams which, in turn, were very short. In general, the law of the stream numbers is obeyed much more strongly than that of the stream lengths.

The average first order stream length ranges from 0.08 to 0.20 miles in Indiana small watersheds. These small values are due to the great detail with which the drainage maps were drawn.

The bifurcation ratio, R_b, provides some measure of a stream segment's tendency to divide. Coates (4) measured some basins in southern Indiana and found bifurcation ratios for first-order to second-order streams ranging from 4.0 to 5.1. Shreve (5) reported that: "For a given number of first-order streams in network, the most probable network is that which makes the geometric mean bifurcation ratio close to 4." The distributions of the bifurcation ratios for 1st to 2nd, 2nd to 3rd and 3rd to 4th order in 13 basins ranged from 2.8 to 7.0. The average bifurcation ratios were almost constant and equal to about 4.5. This shows that Indiana stream networks have a slightly higher bifurcation ratio than those of topologically random networks which might indicate that minor geological controls occur in this area. The general trend indicates that the mean bifurcation ratio decreases as the stream order increases and that the standard deviations increase as the stream order increases.

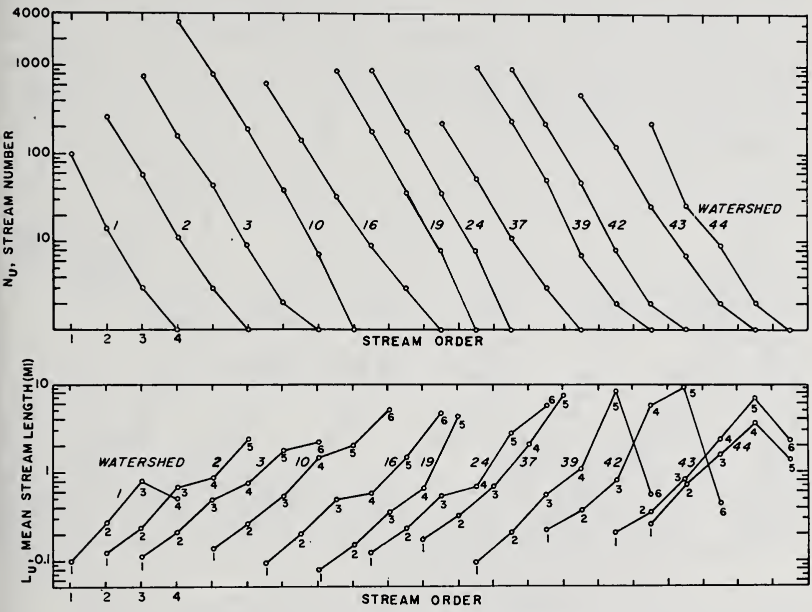

FIGURE 2. *Laws of stream numbers and stream lengths.*

Shreve (5), in his study of the "Law of Stream Lengths", stated that the average length of streams increases with order as a geometric series with ratio 2. Thus the stream length ratio should be approximately equal to 2. This was found to be indeed true for the lower order streams but both the bifurcation ratio and the stream length ratio of the highest order (*i.e.*, 5-6 order) do not follow the trend, because they contain "incomplete segments". The mean stream length tends to increase slowly as the stream order increases. At the same time, the standard deviation increases as the stream order increases.

Shreve (6) reported that the discrete probability density function V(M) of randomly drawing a link of magnitude M in an infinite topologically random channel network is:

$$V(M) = \frac{2^{-(2M-1)}}{2M-1} \binom{2M-1}{M} \qquad [1]$$

and that the differences between the probabilities for infinite and finite topologically random networks are very small when M_B is larger than 200. The basin magnitudes of the Indiana watersheds studied ranged from 97 to 3,066 with an average of 900 and with only two basins having magnitudes less than 200. Figure 3 shows the function V(M) and the observed frequency distribution for six basins. The link number probability density distribution function is a discrete function but for easier visualization link magnitudes were connected by lines. The streams with magnitudes greater than 10 were neglected because they represent a very small portion of the total population. The departures from the topologically random network magnitude frequency were not too large for most of the networks. The differences show the lower magnitudes have lower frequencies than those of random networks. This property causes the bifurcation ratio to increase at low Strahler stream order. This conclusion coincides with the results from bifurcation ratios.

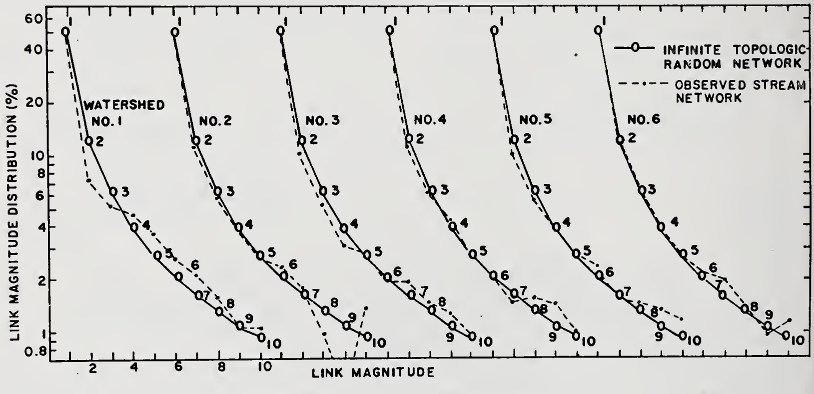

FIGURE 3. *Link number distribution.*

Means and standard deviations of link lengths are shown in Figure 4 for some of the watersheds. The mean link length varies with the link magnitude. For most of the basins the exterior links have larger mean link lengths than the interior links. The means of interior links show a general trend to decrease as the link magnitudes increase in most basins. The standard deviations vary little with the link magnitudes. This information illustrates the conclusion that the mean exterior links are larger than the mean interior links.

Summary Table of Watershed Characteristics

The summary of watershed characteristics of these 14 basins is given in Table 2. From this table, a few relationships between watershed characteristics may be obtained.

1) Relationship between drainage areas and mean stream lengths. The data were plotted in log-log scales, a least square fit gave the regression equation:

$$L_o = 1.64\ A_o^{0.55} \qquad [2]$$

Where L_o = main stream length, in miles, and A_o = drainage area, in square miles.

2) Smaller watersheds tend to have steeper slopes.
3) Watersheds with steeper slopes have higher drainage densities.
4) The drainage density tends to increase as the texture ratio increases.
5) There is no consistent relationship between the elongation ratio and the drainage area.

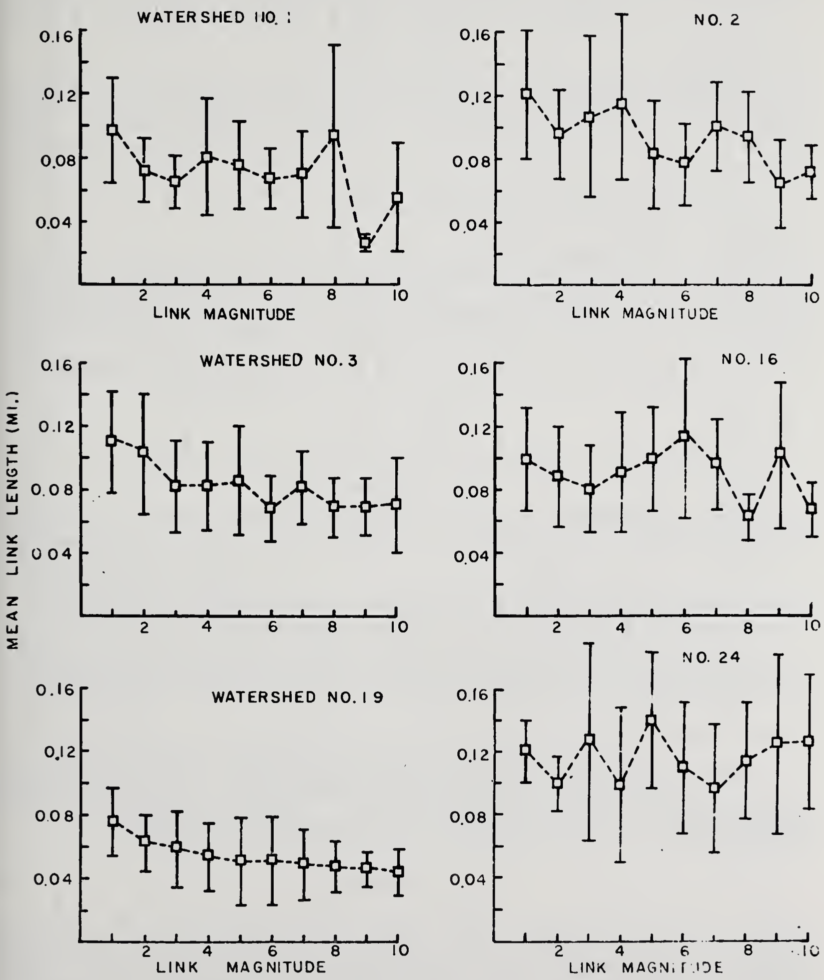

FIGURE 4. *Means and standard deviations of link lengths.*

TABLE 2. *Geomorphologic characteristics of 14 Indiana watersheds.*

Item	Symbol	Unit	WS 1	WS 2	WS 3	WS 10	WS 16	WS 19	WS 22	WS 24	WS 35	WS 37	WS 39	WS 42	WS 43	WS 44
1 area	A_O	sq.miles	2.64	5.80	13.4	169.72	18.2	10.31	205.738	33.84	80.55	22.03	42.06	138.2	78.85	33.43
2 Basin perimeter	P	miles	7.42	11.39	18.7	71.94	19.4	18.27	68.12	33.32	40.27	25.31	36.07	68.45	50.42	26.31
3 Basin length	L_B	miles	2.170	3.66	5.22	26.39	4.83	6.63	18.40	9.72	12.03	7.38	9.68	16.68	11.52	8.82
4 Relative relief	H	feet	120.9	310.0	373.6	240.67	110.0	207.8	200.	45.3	182.4	81.7	110.0	80.0	95.3	77.3
5 Basin order	U_B	No	4	5	6	6	6	5	6	6	7	5	6	6	5	6
6 Total No. of seg.	T_{NS}	No	115	332	990	4113	815	1119	3928	1091	2820	294	1304	1216	647	167
7 Basin magn.	M_B	No	97	259	785	3066	624	894	3066	817	2159	226	1003	933	490	129
8 Total No. of link	T_{NM}	No	193	517	1569	6138	1247	1787	631	1633	4282	451	2005	1865	979	257
9 Total stream length	L_T	miles	16.15	57.03	149.9	809.66	120.6	116.7	885.722	192.6	469.00	75.40	195.4	386.0	196.6	72.53
10 Main st. length	L_O	miles	2.30	4.17	7.2	29.75	9.8	7.5	42.0	12.5	17.0	11.17	15.75	23.0	15.5	10.45
11 Azimuth of basin length		degree	28.34	205.72	212.9	225.23	86.9	231.48	156.04	280.2	291.0	3.34	76.51	58.41	273.08	263.94
12 Texture ratio	T_R	1/mile	15.49	29.14	52.9	42.62	41.9	61.23	12.771	32.73	70.03	11.61	36.07	17.76	12.83	6.35
13 Link Texture ratio	T_T	1/mile	25.99	45.38	83.8	85.32	64.2	97.77	19.304	49.00	106.33	17.82	55.57	27.24	19.41	9.77
14 Drainage dens.	D_D	mi/sq.mi.	6.10	9.8	11.8	4.88	6.62	11.31	4.305	5.69	5.82	3.42	4.64	2.79	2.49	2.17
15 Const. channel maintenance	C	sq.ft/ft	865.14	537.8	472.12	1219.47	797.3	466.5	1226.5	927.9	906.57	1542.4	1136.6	1890.5	2116.9	2433.6
16 Channel freq.	F_C	1/sq.mi.	43.47	57.15	73.86	21.99	44.7	108.5	19.092	32.23	35.01	13.34	30.9	8.79	8.20	4.99
17 Link freq.	F_L	1/sq.mi.	72.95	88.99	117.06	32.82	68.4	173.3	29.800	48.24	53.16	20.47	47.6	13.49	12.41	7.68
18 Area with basin perimeter	$\frac{P^2}{4\pi}$	sq. mi.	4.38	10.33	27.8	411.92	30.02	26.6	369.286	88.37	129.04	50.97	103.6	372.9	202.34	55.06
19 Dia. of circle	$\sqrt{4A_O/\pi}$	mile	1.84	2.72	4.13	14.70	4.81	3.62	16.185	6.56	10.12	5.29	7.32	13.2	10.02	6.52
20 Basin circularity	B_C	No	0.603	0.562	0.48	0.412	0.61	0.38	.557	0.382	0.624	0.432	0.406	0.371	0.389	0.607
21 Elongation ratio	B_E	No	0.846	0.742	0.79	0.557	0.99	0.54	.879	0.675	0.839	0.717	0.755	0.795	0.870	0.739
22 Watershed shape factor	B_W	No	1.25	1.53	1.74	2.024	2.04	2.07	2.593	1.01	1.68	2.11	2.15	1.74	1.55	1.60
23 Unity shape factor	B_U	No	1.334	1.52	1.43	2.026	1.13	2.06	1.283	1.67	1.343	1.57	1.493	1.42	1.29	1.52
24 Basin Mean link length	ℓ	miles	0.0836	0.1103	0.0955	0.1319	0.0967	0.0653	0.140	0.1179	0.1095	0.1671	0.0976	0.2069	0.2008	0.2822
25 Basin slope	B_S	ft/mi	52.1	44.7	22.1	8.07	8.01	26.4	4.762	7.39	10.73	7.31	6.98	3.47	6.10	7.39
26 Link drainage width fact*	K	No	1.95	0.925	0.887	1.748	1.561	1.353	1.608	1.490	1.581	1.748	2.211	1.732	1.999	1.632
27 Link drainage width fact**	K	No	1.96	0.926	0.841	1.751	1.561	1.354	1.608	1.489	1.569	1.750	2.210	1.733	2.001	1.631
28 Channel drainage width fact	K_S	No	1.168	0.595	0.530	1.172	1.019	0.848	1.030	0.995	1.033	1.14	1.43	1.12	1.32	1.05

* $1/(\ell D_D)$ ** F_L/D_D^2

Shreve (6) reported two important parameters relating the linear and area dimensions: the basin mean link length, *l*, and the drainage width factor, K. The area A_O of the basin may be written:

$$A_O = Kl^2(2M_B-1) \qquad [3]$$

where K*l* is the average width which the stream link can cover and M_B is the magnitude of the basin and K is the ratio of the average width to basin average link length. The *l* values ranged from 0.084 to

0.28 miles and the K values ranged from 0.887 to 1.99. The drainage density D_D may be expressed as $D_D = 1/Kl$.

The identification of l and K values can be done as follows: l can be expressed as $l = L_T/T_{MN}$ where L_T and T_{MN} are the total stream length and the total number of links, respectively. The K value can be obtained in two ways. First, it can be obtained from the relationship between the basin mean link length, l, and the drainage density D_D. A plot of $1/l$ versus D_D showed, for drainage density below 8 miles per square mile, a K value of approximately 5/3. The other way to identify the K value is based on the link frequency, F_L. The link drainage factor width can be expressed as $K = F_L/D_D^2$. The plot of F_L versus D_D^2 yielded an estimated value of about 5/3. Similarly, for Strahler's ordering system, the channel drainage width factor can be expressed as $K_s = F_c/D_D^2$, where F_c is the channel frequency.

One of the most important applications of the geomorphologic parameters is in the regionalization of hydrologic models for runoff prediction. In this type of analysis correlation equations are developed between hydrologic and geomorphologic parameters.

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