GEL 446: Applied Environmental Geology

Watershed Delineation and Geomorphology

Watershed Geomorphology

Watersheds are fundamental geospatial units that provide a physical and conceptual framework widely used by scientists, natural resource managers and policy makers. The geomorphological attributes of watersheds often provide valuable insight into their hydrological behavior and can be used to develop design hydrologic models. The purpose of this exercise is to demonstrate how some of the most important and most often used geomorphological variables are measured and used by hydrogeologists. The upper Little Chazy River watershed in the northwestern Champlain Valley will be used as an example.

1. Length Measurements

Watershed Length (L_w):

Watershed length is measured along the course of the principal stream from the basin outlet to the divide (Figure 1).   Gray (1961) (Table 1) demonstrated that for small basins watershed length correlates with basin area.

$$L_w = 1.4A^{0.568}$$
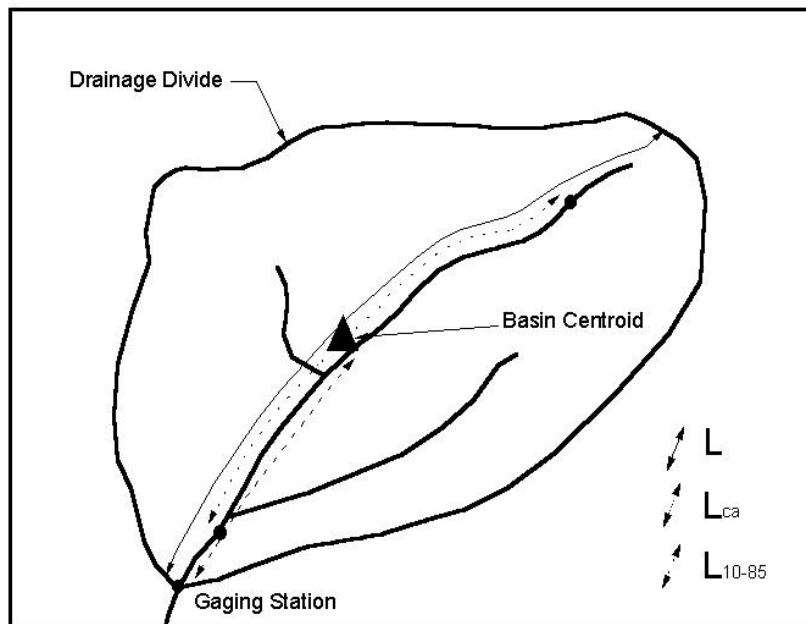
for L_w in kilometers and and A in km^2

Figure 1. Watershed map showing common watershed length measurements.

Several other authors have developed similar relationships (Table 1).

Table 1. Empirical relationships between basin area (mi^2) and channel length (mi) (from Singh, 1989).

$L_w = 1.4A^{0.6}$	Hack (1957): Virginia and Maryland
$L_w = 1.7A^{0.58}$	Brown (1973): Australia
$L_w = 1.64A^{0.55}$	Lee, et al. (1972): Indiana

Empirical relationships of this type should be used cautiously. Gray's (1961) relationship can be rewritten as;

$$\frac{A}{L_w^2} = 0.5A^{-0.136}$$

Note that as A increases the ratio $\left(\frac{A}{L_w^2}\right)$ decreases which indicates that basins tend to become more elongate as their size increases (Singh, 1989).

Channel Length (L_c):

Channel length is measured along the mainstream from the basin outlet to its source (Figure 1).

Channel length to centroid of basin (L_{ca}):

The channel length to the centroid of the basin is used in several models for predicting peak flows. The distance L_{ca} is the distance measured along the mainstream to a point opposite the centroid (or center of area). The basin centroid may be found by cutting a scale image of the watershed on paper by drawing vertical lines from 2 or 3 points located along the watershed divide. The intersection of these points should identify the centroid. For best results the points should be spaced 90° apart (if 2 points are used) or 60° apart (if 3 points are used). The distance to the centroid of the basin may also be estimated from a graph of cumulative area versus distance. Gray (1961, 1962) found that L_{ca} is approximately half the watershed length;

$$L_{ca} = 0.54L_w^{0.96}$$

Channel length between 10% and 85% points ($L_{10\text{-}85}$)

2. Watershed Relief

Watershed (or basin) relief (H_w):

Watershed Relief refers to the difference in elevation between the basin outlet and the highest point on the drainage divide. Relief, however, can be defined between any two points in the watershed so careful definition of the relief parameter being used is important. Two common relief parameters are the relief ratio and relative relief. The relief ratio is defined as;

$$R_h = \frac{H}{L_b}$$

where H is the basin relief and L_b is the basin length. Relative relief is given by;

$$R_p = \frac{H}{p}$$

where p is the watershed perimeter.

3. Slope Parameters

Watershed Slope:

$$S = \frac{\Delta E}{L}$$

where ΔE is the difference in elevation measured along the watershed length divided by the watershed length. Note that this elevation difference is usually not equal to the maximum relief.

Channel Slope:

$$S_c = \frac{\Delta E_c}{L_c}$$

where E_c is the difference in elevation measured along the main channel between the outlet and the upper end of the main channel divided by the channel length (L_c).

Channel Slope Index (weighted average channel slope):

$$S_i = \left(\frac{n}{k}\right)^2$$

where n is the number of stream segments into which the stream is divided and K is given by;

$$k = \sum_{i=1}^{n} \frac{1}{\sqrt{\Delta e_i / l_i}}$$

where Δe_i and l_i are the elevation difference and length of each segment.

4. Hypsometric Curve

The hypsometric curve is a measure of the relationship between elevation and area within a basin (Figure 2) . Single-value indices of the hypsometric curve are;

Hypsometric Integral: the area under the hypsometric curve. It is a measure of the basin's stage in the erosion cycle.

Profile Factor: the ratio of the maximum deviation of the hypsometric curve from a straight line between the points (0,1) and (1,0) to the length of that line.
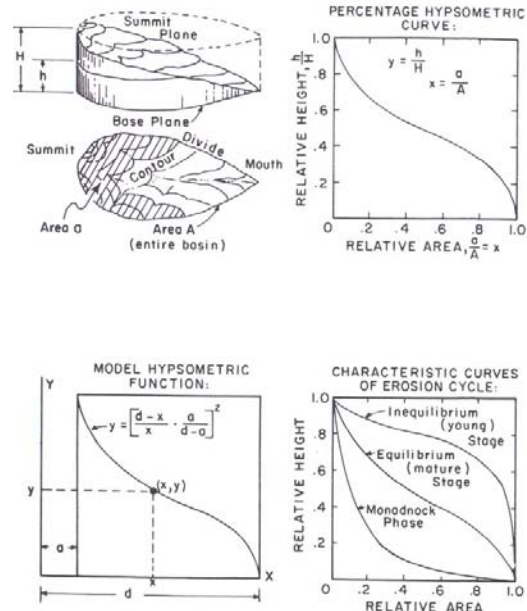
5. Watershed Shape

Shape Factor:

$$L_l = \left(LL_{ca}\right)^{0.3}$$

where L and L_{ca} (mi) are the watershed length and length to centroid, respectively.

Figure 2. Method of hypsographic analysis (after Strahler, 1964 and Singh, 1989).

Circularity Ratio:

$$F_c = \frac{P}{\left(4\pi A\right)^{0.5}}$$

where P and A are the basin perimeter (ft) and area (ft^2), respectively. Another measure of circularity is given by;

$$R_c = \frac{A}{A_o}$$

where A_0 is the area of a circle with the same perimeter as the basin.

NOTE: $R_c = \dfrac{1}{F_c^2}$

Elongation Ratio: The ratio of the diameter of a circle (Dc) with the same area as the watershed to the watershed length. The ratio equals 1.0 for a circular watershed.

$$R_e = \frac{2}{L_m}\left(\frac{A}{\pi}\right)^{0.5}$$

if Gray's (1961) relationship between watershed length and area, $L = 1.4A^{0.568}$ (Gray, 1961), is substituted into the above equation, then Re is inversely related to basin area;

$$R_e = 0.805A^{-0.068}$$

Form Factor:

The form factor is defined as the ratio of watershed area to the square of the basin length:

$$R_f = \frac{A_w}{L_b^2}$$

6. Drainage Networks

Drainage Density

$$D = \frac{\sum L_c}{A}$$

where $\sum L_c$ is the total length of stream channels in the basin.

Constant of Channel Maintenance (CCM)

$$CCM = \frac{1}{D}$$

7. Stream Orders and Stream Magnitude

Stream order is a stream network classification based upon the relative size and position of stream channel segments within the drainage network. The method currently used was originally devised by Horton (1945) and later modified by Strahler (1957). In this scheme, first-order streams are defined as headwater (source) streams or streams without tributaries. Second-order streams are formed by the junction of two first-order streams, third-order streams by the junction of two second- order stream, and so on. The junction of a stream of lower order does not affect the order of the larger-order stream. The Horton-Strahler method of stream ordering is depicted in Figure 3 for a 4th order basin.
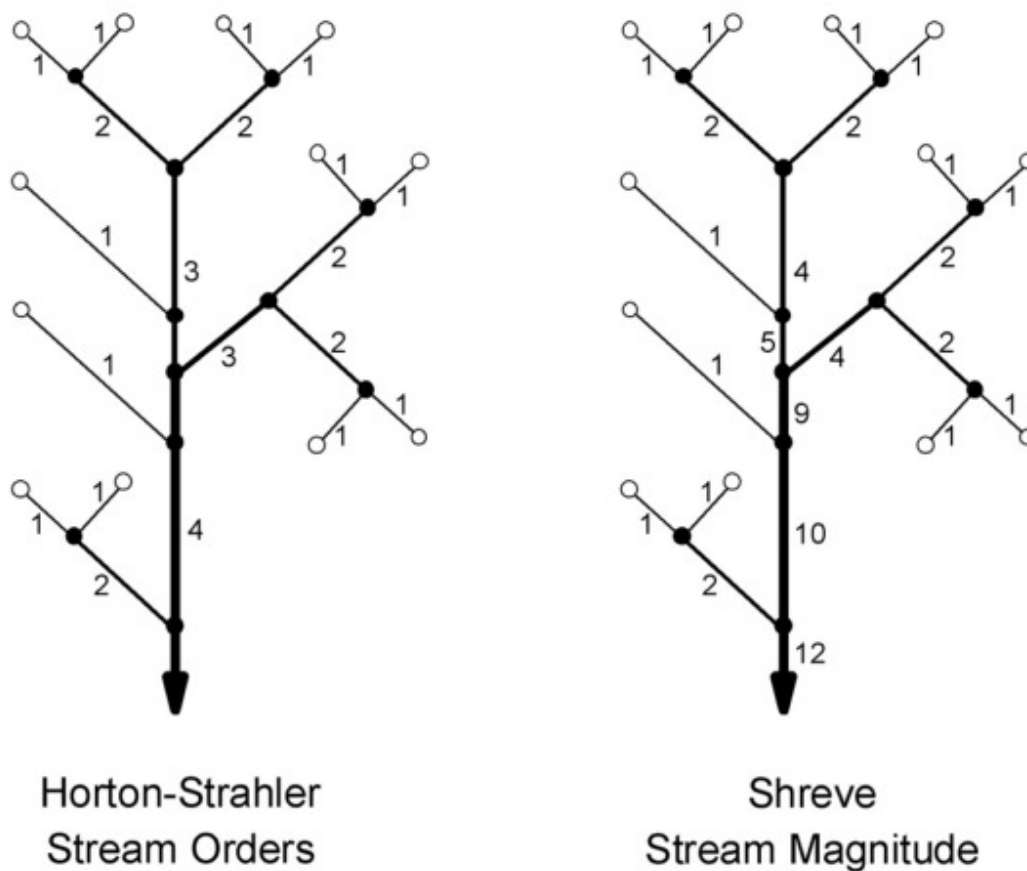
Horton-Strahler
Stream Orders

Shreve
Stream Magnitude

Figure 3. Comparison of Horton-Strahler stream order and Shreve stream magnitude.

8. Horton's Laws of Drainage Composition

Law of Stream Numbers

The Law of Stream Numbers relates the number of streams of any order (i) to the bifurcation ration (R_b) and the principal order (k) in the basin.

$$N_i = R_b^{k-i}$$

where k is the highest order stream, i is the ith order stream and R_b is the bifurcation ratio. The bifurcation ratio is the average ratio of the number of stream streams of a given order to the number of streams of the next highest order The ratio can be determined by rearranging the equation above and solving for R_b;

$$\ln R_b = \frac{\sum [(\ln N_i)(k-i)]}{\sum (k-i)^2}$$

or by averaging the stream number ratios for each set of stream orders;

$$R_b = \frac{\left(\dfrac{N_1}{N_2} + \dfrac{N_2}{N_3} + ... \dfrac{N_{k-1}}{N_k} \right)}{(k-1)}$$

Law of Stream Lengths

The Law of Stream Lengths relates the average length of stream of a given order to the Stream Length Ratio and the average length of the first order streams.

$$L_i = \bar{L}_1 \, r_L^{i-1}$$

where L_i is the average length of the ith order stream, L_1 is the average length of the first order streams and r_L is the length ratio. Like the bifurcation ratio, the Length Ratio is average length of streams of any order to the average length of the next lower order. The Length Ratio can be determined by;

$$\ln r_L = \frac{\sum [(\ln \bar{L}_i - \ln \bar{L}_1)(i-1)]}{\sum [(i-1)^2]}$$

or by averaging the average stream length ratios for each set of stream orders;

$$r_L = \frac{\left(\dfrac{\bar{L}_1}{\bar{L}_2} + \dfrac{\bar{L}_2}{\bar{L}_3} + ... \dfrac{\bar{L}_{k-1}}{\bar{L}_k}\right)}{(k-1)}$$

c. Law of Stream Areas:

The Law of Stream Averages relates the mean tributary area of streams of order i to the average area of first order basins and the stream area ratio:

$$A_i = \bar{A}_1\, r_L^{i-1}$$

where A_i is the average area of the ith order basin, $\bar{A}_1$ is the average area of the first-order basins and r_a is the area ratio (average area of basins of any order to the average area of the next lower order).

$$\ln r_a = \frac{\sum[(\ln \bar{A}_i - \ln \bar{A}_1)(i-1)]}{\sum[(i-1)^2]}$$

or by averaging the average stream area ratios for each set of stream orders;

$$r_a = \frac{\left(\dfrac{\bar{A}_1}{\bar{A}_2} + \dfrac{\bar{A}_2}{\bar{A}_3} + ... \dfrac{\bar{A}_{k-1}}{\bar{A}_k}\right)}{(k-1)}$$

EXERCISE

1. Delineate the watershed for one of the following upper Little Chazy River watersheds;

> Cold Brook at Chasm Lake
> Robinson Brook at Chasm Lake
> Farrell Brook at the City of Plattsburgh Flume
> Tracy Brook at Slosson Road.

Figure 4 illustrates the relationship between topographic contours and the location of the surface-water drainage divide. Determine the basin and sub-basin areas (in km^2) using a polar planimeter. Instructions for the proper use of the planimeter will be provided in class.
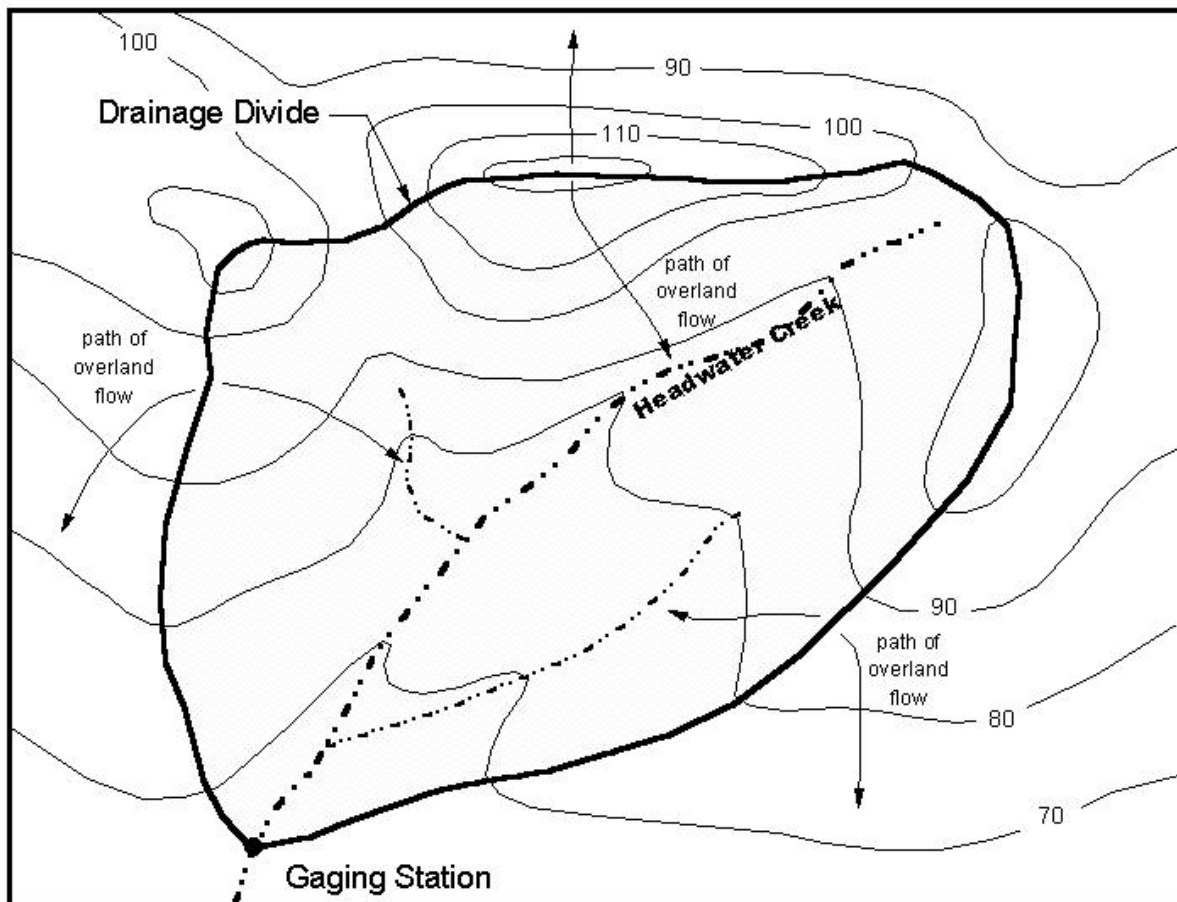

Figure 4. Relationship between topographic contours and drainage divide

2. Using ArcView software and the Little Chazy River GIS database provided to you determine and tabulate the following geomorphological parameters for the basin;

Watershed Length	Watershed Area
Watershed Perimeter	Shape Factor
Channel Length to Basin Centroid	Circularity Ratio (F_c and R_c)
Relief Ratio	Elongation Ratio
Relative Relief	Form Factor
Watershed Slope	Drainage Density
Channel Slope	Bifurcation Ratio

3. Determine the proportion of bedrock, land cover, and surficial deposits using ArcView tools demonstrated in class and the watershed shape files provided.

4. (Optional) Construct a hypsometric profile for the basin and determine the hypsometric integral.

Discussion Questions

1. Briefly describe the composition and morphology of your watershed with respect to the rock and sediment types pand morphological variables that were calculated.

2. Comment upon the advantages and disadvantages of using morphological variables as indices of the hydrologic character of the basins. What are possible sources of error for these analyses?