watersheds
— McCuen

3.1.1 Analysis versus Synthesis

In hydrologic analysis, the watershed characteristics are used in defining the nature of the transfer function (Figure 1–3). In hydrologic synthesis or design, the characteristics are measured at the design site in order to define the transfer function that is necessary to compute the output function. When using a hydrologic model for design, the watershed characteristics that are required as input to the design method should be similar in magnitude to the values that were used in development of the design method (i.e., the analysis phase). When the values of the characteristics used for design are much different from those used in developing the design method, the design represents an extrapolation of the design method and may not be accurate because of the extrapolation. Therefore, it is important for the design engineer to be knowledgeable about the development of the design method and not just be able to make the measurements of the input characteristics of the design method.

As an example, consider the problem of estimating the maximum flood flow, which is the peak discharge q_p of Chapter 7. Many investigators have developed simple prediction equations that relate the peak discharge to the drainage area A. If, for example, the parameter C in the equation $q_p = CiA$ is based on watersheds for drainage areas from 1 to 200 acres, the equation may not provide accurate design estimates of q_p for drainage areas outside this range. In this case, the use of the equation for synthesis or design should be based on knowledge of the values of the watershed characteristics used in the analysis phase.

3.2 WATERSHED: DEFINITION AND DELINEATION

The concept of a watershed is basic to all hydrologic designs. Since large watersheds are made up of many smaller watersheds, it is necessary to define the watershed in terms of a point; this point is usually the location at which the design is being made and is referred to as the watershed "outlet." With respect to the outlet, the watershed consists of all land area that sheds water to the outlet during a rainstorm. Using the concept that "water runs downhill," a watershed is defined by all points enclosed within an area from which rain falling at these points will contribute water to the outlet. This is best shown pictorially, as in Figure 3–1. The shaded area of Figure 3–1 represents the watershed for the outlet at point A. Water is contributed to the outlet from many smaller areas, which are also watersheds. For example, if a design were being made at point B rather than point A, the watershed would be the small area enclosed within the dashed lines. The watershed for point B is made up of smaller watersheds, with the two stream tributaries reflecting the collecting areas for water resulting from rain on the watershed. The concept of smaller watersheds making bigger watersheds can be carried to the extreme. The watershed of the Mississippi River drains almost fourteen million square miles, and the continental divide, which runs from northern Montana to southern New Mexico, divides the continuous part of the United States into two watersheds, with one watershed directing runoff to the Pacific Ocean and the other watershed to the Atlantic Ocean.

Given this definition of a watershed and assuming that the delineation of a watershed is important to hydrologic design, it is necessary to show how the boundary of a watershed is delineated. Keeping in mind that the boundary of a watershed is defined by all points that will shed water to the outlet, it is only necessary to decide which points in a region will con-

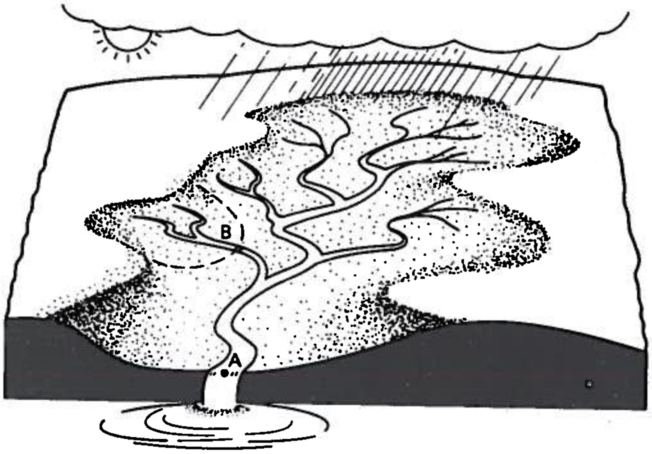

FIGURE 3–1 Delineation of watershed boundary.

tribute water to the outlet; the most extreme of these points represents the watershed boundary.

Consider the hypothetical schematic of a topographic map that is shown in Figure 3–2. If the point of design is at *A*, which is the outlet of the watershed and the downstream end of reach *AB*, then all points bounded by the elevation contours *CDEF* would contribute runoff to point *A*. Water will travel perpendicular to the elevation contours, which is the direction that maximizes the slope. Rain falling at points *C* and *F* would travel overland directly to point *A*. Rain falling at points *D* and *E* would travel toward the upper end of the channel (i.e., point B), and from there the water would travel in the channel to point *A*. Rain falling at points *G*, *H*, and *K* would not flow toward point *A* because the elevations of these points are less than that of the watershed divide, which has an elevation of 70; thus the rain falling at these three points would travel to the outlet of other watersheds.

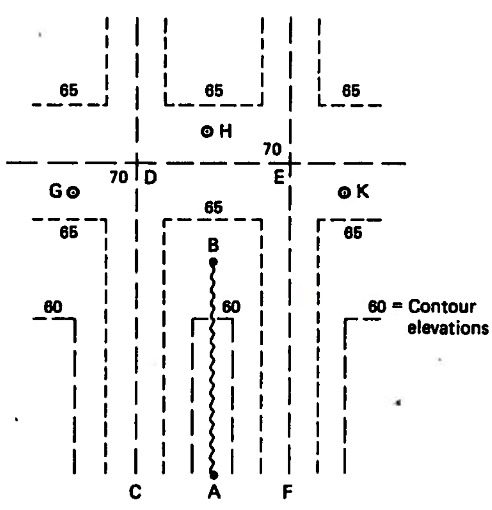

FIGURE 3–2 Delineation of hypothetical watershed.

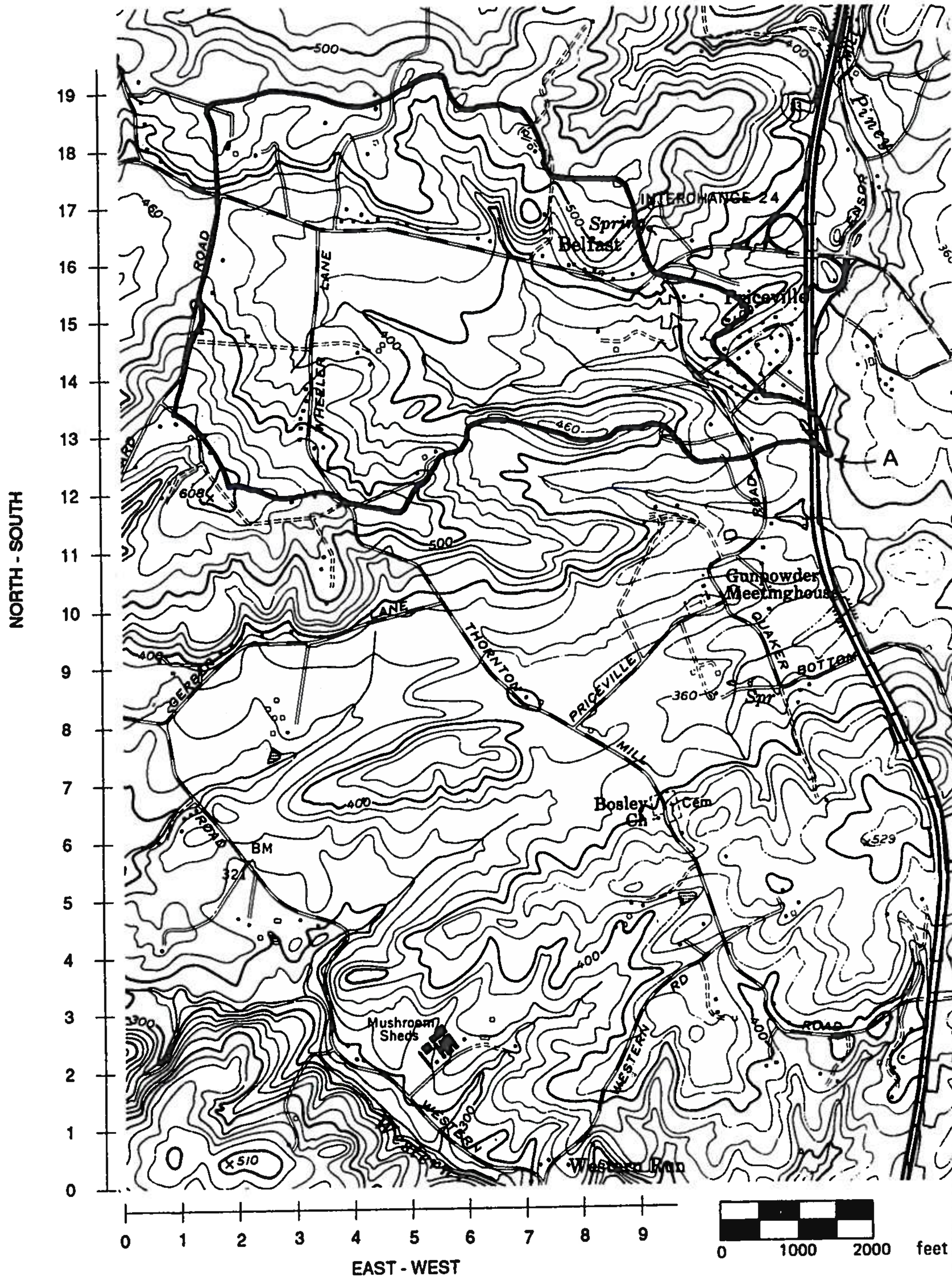

FIGURE 3–3(a) Topographic map.

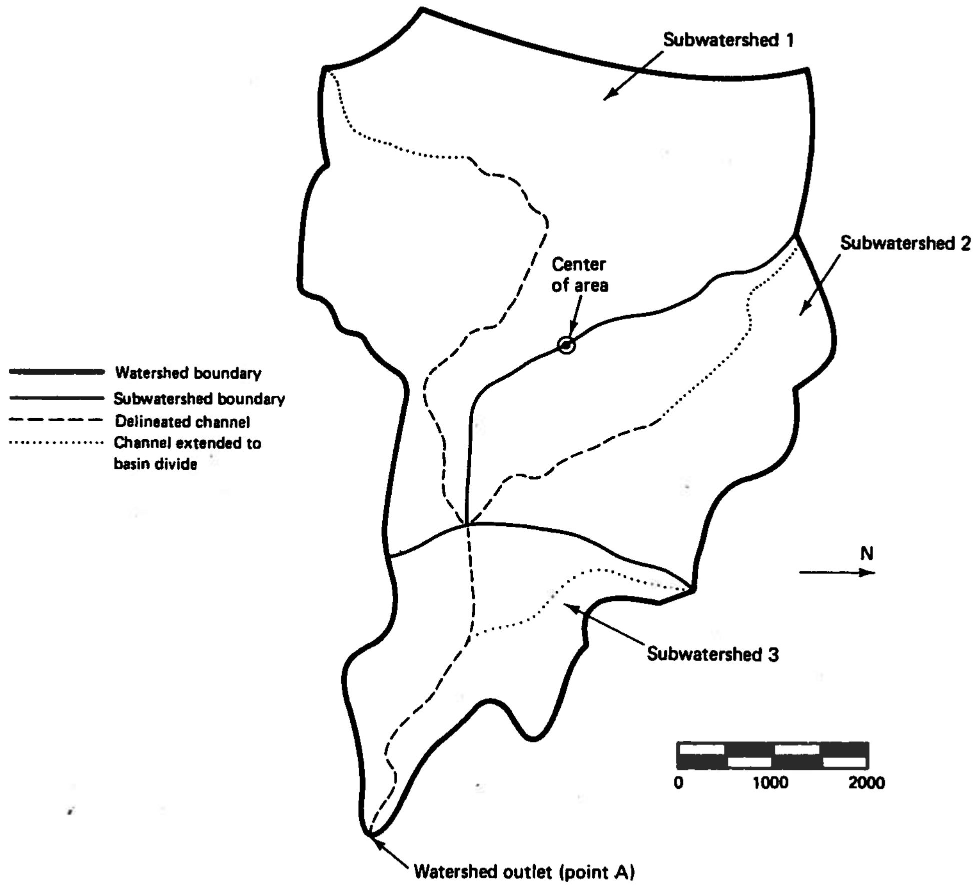

FIGURE 3–3(b) Delineation of watershed boundary.

As indicated previously, the watershed boundary is defined by identifying all points within an area from which rain will contribute water to the outlet. The hypothetical watershed of Figure 3–2 suggests that watersheds have regular geometric shapes such as rectangles. This is not generally the case. Figure 3–3a shows a topographic map of an area. If one were interested in making a design at point *A*, the watershed boundary would be delineated by drawing lines perpendicular to the elevation contour lines for land that drains to point *A*. The resulting watershed boundary is shown in Figure 3–3b. Approximately 3600 feet upstream of point *A* the channel divides, with one stream channel coming from the northwest and the other from a direction slightly south of west. Using the confluence of the two tributaries as a point, the subwatersheds that drain the tributaries can be delineated, as shown in Figure 3–3b. Thus the watershed can be viewed as consisting of three subwatersheds. Subdividing a watershed is often necessary for modeling, such as when only a portion of the watershed is being developed and stormwater management is necessary.

3.3 WATERSHED GEOMORPHOLOGY

3.3.1 Drainage Area

The drainage area (A) is probably the single most important watershed characteristic for hydrologic design. It reflects the volume of water that can be generated from rainfall. It is common in hydrologic design to assume a constant depth of rainfall occurring uniformly over the watershed. Under this assumption, the volume of water available for runoff would be the product of the rainfall depth and the drainage area. Thus the drainage area is required as input to models ranging from simple linear prediction equations to complex computer models.

The drainage area of a watershed requires the delineation of the watershed boundary. Geographic information systems are commonly used to delineate watershed boundaries. Once this is done, the area is automatically computed. The area can be computed manually with an instrument called a planimeter. Where this is not available, the "stone-age" method of counting squares can be used. A transparency showing a grid, usually square, is laid over the map showing the drainage boundaries, and the number of grid blocks within the boundary is counted. The drainage area equals the product of the number of grid blocks and the area of each grid block. The area of each grid block is computed using the scale of the topographic map from which the watershed boundary was delineated. The accuracy of the estimated value of the drainage area will depend on the care taken in counting the grid blocks, especially the partial grid blocks along the watershed boundary. Given the importance of the drainage area in hydrologic design, special care should be made to ensure that the estimated value of the drainage area is accurate.

As computers become more prevalent in hydrologic design, they are being used to compute drainage areas. The watershed boundary can be delineated by indicating the latitude and longitude of points along the boundary; the boundary is assumed to be linear between each pair of points and the drainage area is the area enclosed by the series of linear segments. The drainage area is computed internally by the computer using basic trigonometry. Some software packages do not even require the user to specify points; from the user-specified watershed outlet, the watershed boundary is constructed from an analysis of computed slopes, with the slopes evaluated numerically from the topographic map that is stored within the computer.

Example 3–1

To illustrate the calculation of the drainage area, Figure 3–4 shows the watershed of Figure 3–3 with a square-grid overlay. The scale of the topo map is 1 in. = 2000 ft. Since each side of the grid square is 0.1 in., then each square of the grid represents an area of 40,000 ft^2, or slightly less than 1 acre. The watershed boundary encloses 733 squares. Thus the total drainage area is 673 acres. The areas of the three subwatersheds can be determined at the same time. They have areas of 375, 179, and 119 acres.

3.3.2 Watershed Length

The length (L) of a watershed is the second watershed characteristic of interest. While the length increases as the drainage area increases, the length of a watershed is important in hydrologic computations; for example, it is used in time-of-concentration calculations. The wa-

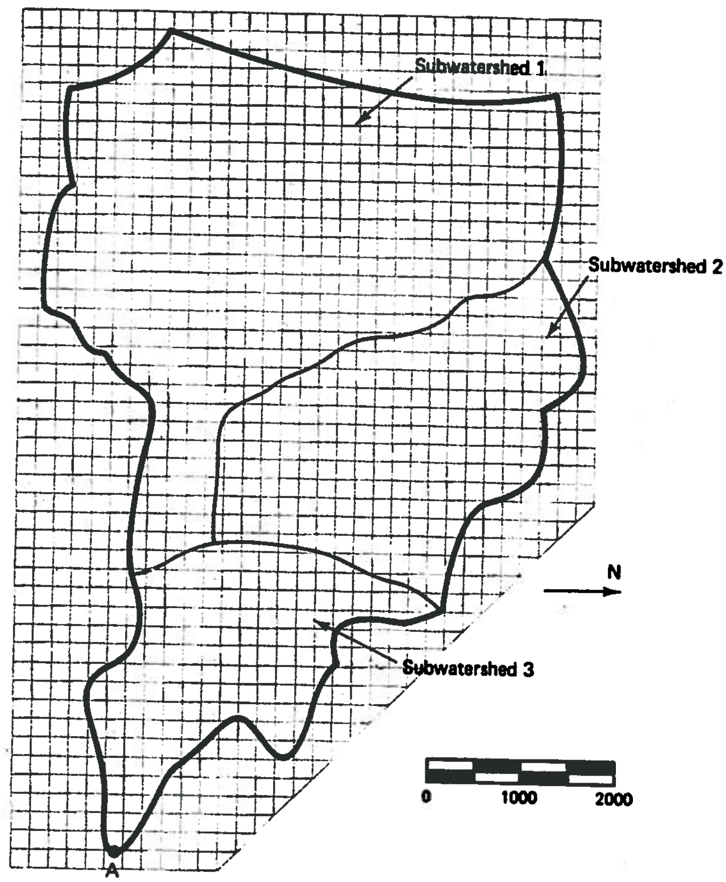

FIGURE 3–4 Delineation of watershed boundary.

tershed length is also highly correlated with channel length, which is discussed in Section 3.5.1.

Watershed length is usually defined as the distance measured along the main channel from the watershed outlet to the basin divide. Since the channel does not extend to the basin divide, it is necessary to extend a line from the end of the channel to the basin divide following a path where the greatest volume of water would travel. The straight-line distance from the outlet to the farthest point on the watershed divide is not usually used to compute L because the travel distance of flood waters is conceptually the length of interest. Thus, the length is measured along the principal flow path. Since it will be used for hydrologic calculations, this length is more appropriately labeled the hydrologic length.

While the drainage area and length are both measures of watershed size, they may reflect different aspects of size. The drainage area is used to indicate the potential for rainfall to provide a volume of water. The length is usually used in computing a time parameter, which is a measure of the travel time of water through the watershed. Specific time parameters will be discussed in Section 3.6.

Example 3–2

The lengths of the channel and total watershed for the basins of Figure 3–4 are delineated in Figure 3–3b. Based on a map scale of 1 in. equals 2000 ft, the lengths were computed using a map wheel (see Table 3–1). The channel lengths as a proportion of the total length of the subarea or watershed range from 50% for subarea 2, 73% for subareas 1 and 3, and 82% for the total watershed.

3.3.3 Watershed Slope

Flood magnitudes reflect the momentum of the runoff. Slope is an important factor in the momentum. Both watershed and channel slope may be of interest. Watershed slope reflects the rate of change of elevation with respect to distance along the principal flow path. Typically, the principal flow path is delineated, and the watershed slope (S) is computed as the difference in elevation (ΔE) between the end points of the principal flow path divided by the hydrologic length of the flow path (L):

$$S = \frac{\Delta E}{L} \tag{3–1}$$

The elevation difference ΔE may not necessarily be the maximum elevation difference within the watershed since the point of highest elevation may occur along a side boundary of the watershed rather than at the end of the principal flow path.

Where the design work requires the watershed to be subdivided, it will be necessary to compute the slopes of each subarea. It may also be necessary to compute the channel slopes for the individual sections of the streams that flow through the subareas. When computing the slope of a subarea, the principal flow path for that subarea must be delineated. It should reflect flow only for that subarea rather than flow that enters the subarea in a channel. The stream-reach slope may also be necessary for computing reach travel times.

Example 3–3

The upper and lower elevations for the watersheds of Figure 3–3b are given in Table 3–1. They are used with the watershed lengths to compute watershed slopes. The watershed slopes range from 3% for the entire watershed to 5% for subarea 3.

TABLE 3–1 Lengths and Slopes of Watersheds of Figure 3–4

	Length (ft)		Channel Elevation (ft)			Watershed Elevation (ft)			Slope (ft/ft)	
Area	Channel	Watershed	Upper	Lower	Difference	Upper	Lower	Difference	Channel	Watershed
Sub 1	4940	6810	450	340	110	608	340	268	0.022	0.039
Sub 2	2440	4875	400	340	60	545	340	205	0.025	0.042
Sub 3	3670	5000	340	295	45	545	295	250	0.012	0.050
Total	8610	10480	450	295	155	608	295	313	0.018	0.030