Stochastic Empirical Loading and Dilution Model (SELDM) Version 1.0.0—Appendix 2. Definitions of Basin Characteristics

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Abbreviations

BDA	basin drainage area (the USGS Streamstats variable name is DRNAREA)
BDF	basin development factor
BLF	basin lag factor
BL	basin length (the USGS Streamstats variable name is LENGTH)
BMP	best management practice
DCIA	directly connected impervious area
EIA	effective impervious area
GIS	geographic information system
MCS	main channel slope (the USGS Streamstats variable name is CSL10_85)
MS4	municipal separate storm-sewer system
NHD	National Hydrography Dataset
NPDES	National Pollutant Discharge Elimination System
PDA	percent developed area
R_v	volumetric runoff coefficient
SELDM	Stochastic Empirical Loading and Dilution Model
TIA	total impervious area (the USGS Streamstats variable name is IMPERV)
USGS	U.S. Geological Survey

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Introduction

Six basin characteristics were selected for calculating the volume and timing of runoff from a selected highway site and its upstream basin by the Stochastic Empirical Loading and Dilution Model (SELDM). Three primary physiographic variables—basin drainage area (BDA), basin length (BL), and main channel slope (MCS)—must be measured (or estimated) for the highway site and the upstream basin to calculate the volume and timing of runoff. SELDM calculates one secondary physiographic variable, the basin lag factor (BLF), from the basin length and main channel slope to estimate the basin lagtime. SELDM also uses two anthropogenic basin characteristics—the total impervious area (TIA) and the basin development factor (BDF)—to calculate the volume and timing of runoff. These basin characteristics were considered sufficient for use with SELDM because they have been shown to be important hydrologic variables for describing the rainfall-runoff characteristics of many different drainage basins (Benson, 1962; Linsley and others, 1975; Sauer and others, 1983; Masch, 1984; Chow and others, 1988; Wanielista, 1990; Wanielista and Yousef, 1993; McCuen and others, 2002; Fang and others, 2005; Granato, 2010; Granato, 2012). Another commonly used basin characteristic is the percent storage, which is commonly defined as the total percentage of contributing area occupied by the surfaces of lakes, ponds, swamps, and wetlands (Langbein and others, 1947; Benson, 1962; U.S. Geological Survey, 1977; Sauer and others, 1983; Federal Emergency Management Agency, 2001b). The percent storage is not used in SELDM because this characteristic is more difficult to characterize consistently, and it usually has a lesser effect on the magnitude and timing of runoff in developed drainage areas than do the six selected basin characteristics (Granato, 2012).

In SELDM, the volumes of runoff from the highway site and from the upstream basin for each storm are used to calculate the stormflows, loads, and dilution factors. The volume of runoff is the product of the precipitation volume, the drainage area, and the volumetric runoff coefficient (R_v). In SELDM, the R_v is a function of the TIA of the drainage area (Granato, 2010).

In SELDM, the timing of runoff determines the proportion of the upstream stormflow hydrograph that is available for dilution with highway runoff or with the discharge from a best management practice (BMP) used to treat runoff from the highway. The timing of runoff is calculated by using the basin lagtime and a hydrograph-recession ratio (Granato, 2012). The basin lagtime is defined as the time between the centroid of the precipitation event and the centroid of the runoff hydrograph. The centroid of the precipitation event is the midpoint of the storm-event duration because synoptic storm events commonly are modeled as having a uniform distribution within the duration of the storm event (Granato, 2010). Estimating the centroid of the precipitation event as defining half the duration of the storm has been shown to be a good planning-level approximation even for more complex hyetographs (Yen and Chow, 1980; 1983; Granato, 2010).The hydrograph-recession ratio is the ratio of the time between the peak of the hydrograph and the end of the hydrograph to the total duration of the hydrograph (Granato, 2012). The time between the beginning of the storm and the peak can be estimated by using the basin lagtime and the hydrograph-recession ratio. Hydrologic studies show that both of these quantities are correlated to the basin physiographic and anthropogenic characteristics selected for use with SELDM (Granato, 2012).

The purpose of this appendix is to document standard definitions for each characteristic and describe commonly used methods for estimating the values of each characteristic. References are provided to help the reader pursue other sources of information if the information in this appendix is not sufficient.

Physiographic Basin Characteristics

Physiographic basin characteristics are defined herein as the largely natural characteristics that result from the interactions between water and the land surface. These characteristics result from geological processes that build landforms and from erosional processes that form drainage networks. Although these characteristics are largely natural, anthropogenic modifications to drainage networks can alter these variables. For example, sewering an area can change drainage area, basin length, and main channel slope.

Basin Drainage Area (BDA)

The BDA is defined as the river-basin area projected onto a horizontal plane and enclosed by a topographic divide, so that direct surface runoff from precipitation normally would drain by gravity into the river basin (U.S. Geological Survey, 1977). The BDA can be determined manually in three steps: mark the point of interest, mark the high points on the topographic map around the stream and its tributaries, and draw lines that follow the ridges to connect the high points all around the basin. The curvilinear segments of the polygon that delineates the basin should cross contour lines perpendicularly at the point where the bulge follows the ridge between the high points. Runoff flows are perpendicular to the contours, and so the curvilinear segments between high points should split bulges in the contours that point downhill. Any arrow drawn perpendicular to the basin-delineation segments into the resulting polygon should represent a flow path toward the stream or its tributaries. Amman and Stone (1991) provide a step-by-step example with illustrations. Once the watershed divide has been delineated, the area of the polygon can be determined by using a grid, a planimeter, a digitizer, or geographic information system (GIS) software. The contributing drainage area is calculated by subtracting areas within the basin that do not drain to the main stem or to a tributary. Noncontributing areas may include topographic depressions and areas where runoff is diverted across a topographic divide. The USGS Streamstats Web application can be used in the States where it is available to quickly and easily delineate basins and determine the drainage area at any point on a stream defined in the National Hydrography Dataset (Ries, 2007; Ries and others, 2008; U.S. Geological Survey, 2011).

Drainage areas in urban areas and in very small, highly impervious sites can be difficult to determine because microtopography and drainage diversions can substantially affect the amount of runoff that may flow to one outlet or another (Strecker and others, 2001; Church and others, 2003; Lee and Heaney, 2003; Richards and Brenner, 2004; Smith and Granato, 2010; Liu and others, 2011). Strecker and others (2001) noted that it is difficult to accurately delineate a small low-slope catchment because small surface features have an inordinate effect on drainage patterns. In such catchments, the drainage area may change from storm to storm. For example, Smith and Granato (2010) noted that periodic bypass flows from neighboring drainage areas occurred during some storm events with high-intensity rainfall at one site in Massachusetts. This portion of the runoff from the neighboring drainage areas flowed along ruts in the roadway and along the road edge around neighboring catch basins. Lee and Heaney (2003) noted that the use of topographic contours of about 2 feet and manual inspection of drainage basins were necessary to delineate basins on the scale of a city block (about 0.02 square miles (mi^2), equal to about 14 acres) in a suburban area with storm sewers. Differences between natural topographic divides and anthropogenic divides can be substantial even in relatively large urban basins. For example, Richards and Brenner (2004) noted that sewer-drainage delineation for Mallets Creek in Michigan more than doubled the drainage area from about 3.9 to 8 mi^2. Liu and others (2011) used GIS coverages to delineate small urban catchments, and they discovered substantial differences in drainage areas (greater than 20 percent) in 17 of 18 basins on the basis of differences between expected and measured median runoff coefficients. In this study, differences as large as several orders of magnitude were confirmed by obtaining detailed drainage plans and by doing site inspections.

Basin Length (BL)

The BL (also known as the main channel length; fig. 2–1) is the total distance in miles from the point of interest to the highest point on the basin boundary along the main channel route (Benson, 1962; U.S. Geological Survey, 1977; Sauer and others, 1983; Federal Emergency Management Agency, 2001a). The BL may be much longer than the straight-line length between the point of interest and the selected point on the basin divide if the channel is sinuous. The primary method for identifying the main channel at each bifurcation is by following the fork that has the largest drainage area (Benson, 1962; U.S. Geological Survey, 1977). A secondary but nonetheless acceptable method is to follow the forks that have the longest watercourses (Langbein and others, 1947; U.S. Geological Survey, 1977). The upstream end of the system is determined by extending the main channel from the end of the mapped representation of the stream to the basin divide. The channel is extended to the basin divide by drawing a line that crosses crenulations in topographic contours that point uphill perpendicularly. If the length is measured manually, then a minimum chord length of 0.1 mile (mi) is recommended for maps with scales greater than or equal to 1:24,000; a chord length of 0.25 mi is recommended for maps with scales less than or equal to 1:250,000 (U.S. Geological Survey, 1977). The

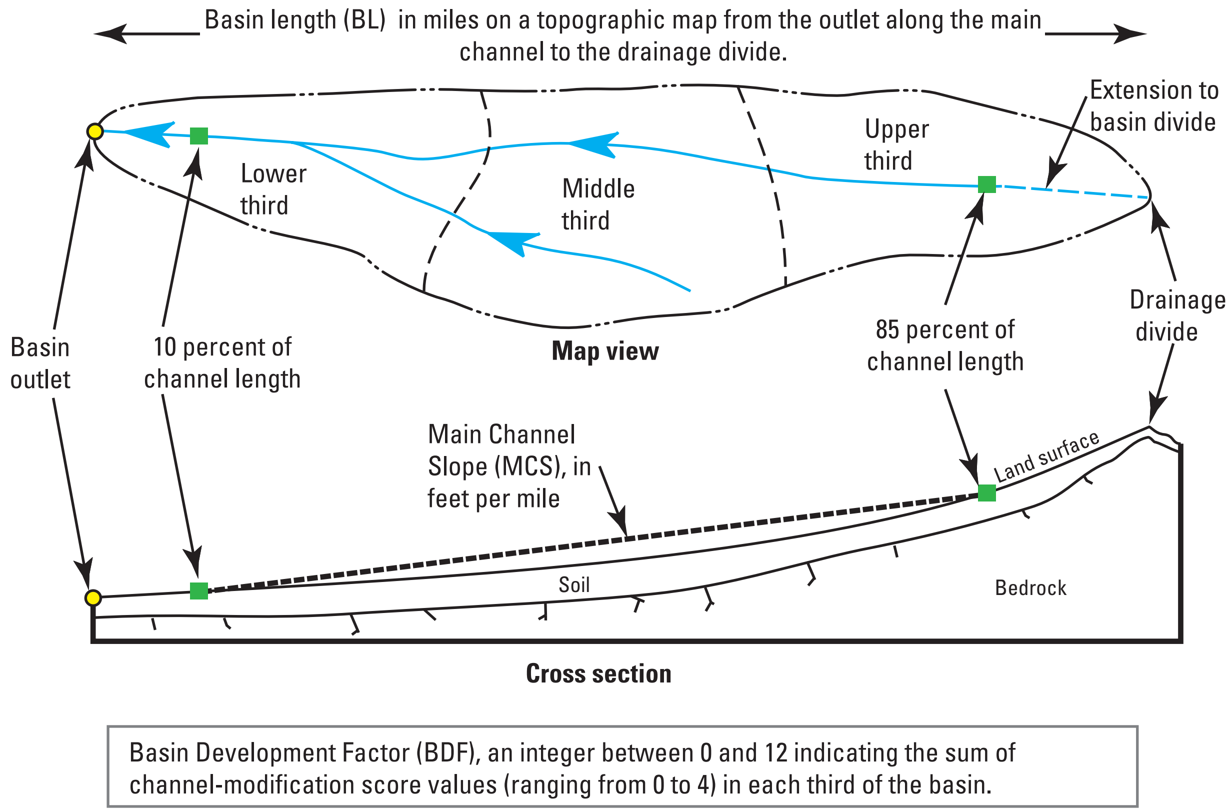

Figure 2–1. The physiographic basin characteristics used by Sauer and others (1983) to estimate basin lagtime.

USGS Streamstats Web site has several tools that can be used to determine the natural basin length (the Streamstats variable LENGTH); the tools will also output a table of distance and elevations along the path of interest (Ries and others, 2008; U.S. Geological Survey, 2011). In sewered areas, the designated main channel may follow the storm-sewer outfall if the upstream drainage area of the storm drain system is larger than the drainage area obtained by following the natural channel upstream.

Main Channel Slope (MCS)

The MCS is the average slope of the main channel of the stream upstream from the point of interest (Benson, 1962; U.S. Geological Survey, 1977; Sauer and others, 1983; Federal Emergency Management Agency, 2001a). Several different measures of basin slope and channel slope are used (U.S. Geological Survey, 1977), and it is not always clear which method was used in a given report because the terms for each method are commonly used interchangeably. The main channel slope selected for SELDM analyses is known as the “10–85” slope because it is calculated by determining the locations and elevations of points at 10 and 85 percent of the distance along the main channel from the point of interest to the basin divide, then dividing the difference in elevations by the distance in miles between these points (fig. 2–1). Historically, hydrologists did this by delineating the main channel as described above and then selecting the topographic contours that were closest to the selected points or by visually interpolating between contours in areas of very low slope. The MCS commonly is reported in units of feet per mile. Benson (1962) selected the 10–85 MCS for several reasons. He postulated that the steep headwaters near and above the uppermost part of the stream probably affect the slope out of proportion to the volume of water furnished by the headwater areas. He also postulated that flows from the low-slope areas commonly found at the downstream end of monitored drainage basins may not represent flows from the areas with steeper slopes, which represent most of the area of the monitored basins. Benson (1962) did exhaustive tests to determine the best measure of slope by using data from 164 streamgages with drainage areas ranging from 1.64 to 9,661 mi^2. He determined that the 10–85 MCS yielded the minimum standard error and the maximum accuracy for regression models for different flood sizes among different measures of slope. USGS flood studies commonly use the 10–85 MCS based on Benson’s findings. The USGS Streamstats Web application will calculate the 10–85 slope of the natural channel (the Streamstats variable CSL10_85) if this slope was used to develop local regression relations; if it was not used, this slope can be calculated by using the output of the Streamstats stream-network and basin-profiling tools (U.S. Geological Survey, 2011).

Basin Lag Factor (BLF)

The BLF is used in many hydrologic studies to calculate a number of hydrograph timing variables, including the basin lagtime, the time to peak, and the time of concentration (Benson, 1962; Linsley and others, 1975; Sauer and others, 1983; Masch, 1984; Chow and others, 1988; McCuen and others, 2002; Fang and others, 2005; Granato, 2012). The BLF is a secondary physiographic variable because it is calculated from primary variables as the main channel length divided by the square root of the channel slope. In SELDM, the user enters data for the main channel length and the channel slope, and SELDM calculates the BLF, which it uses to calculate the hydrograph timing variables.

Anthropogenic Basin Characteristics

The anthropogenic basin characteristics are the total impervious area and the basin development factor. Increases in the total impervious area and the basin development factor tend to increase the volume of runoff and to decrease the duration of runoff from developed areas. The total impervious area and the basin development factor are correlated, but because the basin development factor is strongly influenced by engineered modifications to receiving-water channels, the total impervious area does not determine the basin development factor (Granato, 2012).

Total Impervious Area (TIA)

The TIA is defined as the percentage of contributing area occupied by anthropogenic impervious surfaces, which primarily consists of pavement and roofs. TIA can be expressed as the fraction (0–1) or the percentage (0–100) of the total drainage area. TIA is an important explanatory variable for characterizing rainfall–runoff transformations, because impervious areas can rapidly convey precipitation towards the drainage-channel network. Impervious areas that drain directly to streams or to a storm-sewer outfall are known as effective impervious areas (EIA) or directly connected impervious areas (DCIA). Some parts of the TIA, however, may convey runoff to adjacent pervious (or semi-pervious) areas that may retain or retard this portion of runoff.

Granato (2010, appendix 6) provides an overview of methods used to estimate imperviousness (both TIA and DCIA) in a drainage basin. He tabulated TIA values by land-cover category in 30 studies from the literature and compiled 11 equations from the literature that were formulated to predict TIA on the basis of land-cover characteristics. Granato (2010) also developed a regression equation to calculate TIA from the percent developed area (PDA) within a basin by using data from 262 stream basins in 10 metropolitan areas of the conterminous United States with drainage areas ranging from 0.35 to 216 mi^2 and PDA values ranging from 0.16 to 99.06 percent. The total PDA is commonly defined as the sum of individual areas within a basin that are covered by at least 30 percent of constructed materials; some of these individual areas are shown as shaded built-up areas on USGS topographic maps if they cover at least 40 acres with a 660 foot minimum width. Granato (2010) developed a multisegment regression equation for estimating TIA from population density with data from 6,255 stream basins in the United States that have drainage areas ranging from 0.62 to 19,229 mi^2. He also developed two multisegment regression equations to correct bias in TIA estimates in the 2001 National Land Cover Dataset. If TIA is to be determined manually from maps or aerial photographs (for example, in Google Earth), then calculating TIA from the percent developed area is most feasible. However, GIS coverages are commonly used to estimate TIA from data on land use or land cover. The USGS Streamstats application can be used to calculate the PDA or the TIA (the Streamstats variable IMPERV) of a delineated basin in states which use these values in streamflow regression equations. The USGS Streamstats application also can produce a GIS coverage of the delineated basin that may be used with other GIS coverages to estimate TIA in the basin of interest.

Basin Development Factor (BDF)

The BDF is defined as an index of the prevalence of engineered drainage features (Sauer and others, 1983; Masch, 1984; Federal Emergency Management Agency, 2001c; McCuen and others, 2002; Granato, 2012). The BDF is an important explanatory variable for characterizing transformations of rainfall to runoff because it is an index that quantifies directly connected impervious areas and the characteristics of the conveyance network. The BDF is estimated by first dividing the area of the basin into equal-area thirds that drain the upper, middle, and lower parts of the drainage system (fig. 2–1), and then applying binary criteria to four components in each third of the basin. The basin should be split into thirds so that the travel distances among tributaries within each third of the basin are approximately equal. Each third of the basin may cut across one or more different tributary subbasins. Precise definition of the basin thirds is not considered necessary because such precision has little effect on the final value of the BDF. Therefore, the boundaries between basin thirds can be drawn by eye without the need for precise measurements. Once the basin is divided, the analyst must assign a score of 1 or 0 to characterize each of four drainage-system components in each third of the basin. If more than 50 percent of the area in each third of the basin can be characterized as having one of the four drainage-system components, a score of 1 is given for that component in that third of the basin area. The four drainage-system components defined by Sauer and others (1983) are:

1. Channel Improvements—Channel improvements are defined as straightening, enlarging, deepening, and clearing the channel to reduce flow resistance. If at least 50 percent of the length of the main drainage channels and principal tributaries (those that drain directly into the main channel) has been straightened, enlarged, deepened, or cleared, then a code of 1 is assigned. If such channel improvements have not been made, then a code of 0 is assigned. The 50-percent criterion should be applied to the total length of the main channel and principal tributaries in each third of the basin.

2. Channel Linings—Channel linings are defined as smooth impervious surfaces such as concrete. If more than 50 percent of the length of the main channels and principal tributaries has been lined with an impervious surface, then a code of 1 is assigned for this criterion; otherwise, a code of 0 is assigned. This criterion also is applied to the total length of the main channel and principal tributaries in each third of the basin. If a section of the basin can be classified as meeting the channel-lining criterion, then by default this third of the basin must meet the channel-improvement criterion. If the main stem or principle tributaries are routed through pipe or box culverts, then these segments should also be considered as lined channels.

3. Storm Drains or Storm Sewers—Storm drains and storm sewers are defined as enclosed drainage structures (usually pipes) that convey runoff directly from streets, parking lots, or roofs to the main channels or tributaries. This criterion is applied to the length of secondary tributaries in each third of the basin. If more than 50 percent of the secondary tributaries are storm sewers, then a code of 1 is assigned for this criterion; otherwise, a code of 0 is assigned.

4. Curb-and-Gutter Streets—Curb-and-gutter streets are defined as paved areas that are constructed to collect sheet flow and route runoff along their edges to a drainage area. Drainage from curb-and-gutter streets commonly empties into storm drains, but this criterion also may apply to areas that route runoff directly to streams or to disconnected pervious areas. If more than 50 percent of each third is urbanized (covered with residential, commercial, and (or) industrial development), and if more than 50 percent of the streets and highways in the subarea are constructed with curbs and gutters, then a code of 1 is assigned to this criterion; otherwise, a code of 0 is assigned.

Under these definitions, the BDF will be calculated as an integer in the range from 0 to 12. It is clear that a basin with a BDF of 12 is highly developed. A BDF score of 0, however, does not necessarily indicate that a basin is undeveloped. A basin with a BDF of zero may have a substantial amount of development and a relatively high value of TIA. For example, Granato (2012) compiled a dataset of 493 sites and found that 7 of these sites had BDF values of zero and TIA values between 20 and 30 percent. The BDF is considered to be a fairly easy index to estimate manually for a given basin because each criterion is assigned a 1 or a 0 (Sauer and others, 1983; Masch, 1984; Federal Emergency Management Agency, 2001c; McCuen and others, 2002; Granato, 2010). Sauer and others (1983) indicate that this binary four-category ranking system seems to produce consistent scores among similar basins when different analysts rank them.

The BDF, however, is not currently (2012) in common use. Use of the BDF has declined with increases in the use of GIS for stream-basin analysis, because the BDF ranking system has been more difficult to automate than methods to estimate TIA. Use of the BDF is not readily characterized through use of a single GIS coverage. The binary BDF classification system produces an integer scale for the BDF, and one particular score does not define a unique set of conditions for the basins. For example, a rural basin channelized for agricultural drainage may have a BDF of 3, which would exceed a BDF score of 2 for a basin with two-thirds that are relatively undeveloped and a lower third that is fully urbanized with curb-and-gutter streets and storm sewers that drain to a natural channel. The feasibility of automating the BDF scoring system is expected to increase as information about the degree of imperviousness (from land-use or land-cover data); flood-control features; and private, municipal, and transportation drainage systems becomes widely available in GIS formats. First, the stream reaches would have to be coded to identify areas with channel improvements, channel linings, and storm sewers. This may be possible with continuing improvements to the National Hydrography Dataset (NHD; http://nhd.usgs.gov). In some areas, such data may be available because National Pollutant Discharge Elimination System (NPDES) Phase II rules require sewer-system mapping for many municipal separate storm-sewer systems (MS4s), which includes the collection of information about the location of intakes, major pipes, and outfalls to waters of the United States (U.S. Environmental Protection Agency, 2000). Second, algorithms would need to be developed to divide a basin into three equal sections that may cut across subbasin boundaries.

Although the BDF was initially designed and implemented for basin studies (Sauer and others, 1983), development of the basin lag equations for very small drainage areas by Granato (2012) indicates that the BDF is useful for estimating hydrograph timing variables for sites with very small drainage areas (including highway sites). Highway drainage plans can be used to estimate the BDF for highway sites. If the drainage from more than 50 percent of each third of a highway site is routed through a storm-sewer system or a paved channel, then the BDF score for each third of the basin would receive a channel-improvement code. If check dams or other obstacles to flow are used, however, these codes would not be added to the BDF score. If the drainage from a site is routed through a storm-sewer system or through a paved channel, then the BDF score for each third of the basin would receive a channel-linings code. These codes may not be added to the BDF if more than 50 percent of the flow path to the sewer or to the lined swale was routed over pervious shoulders in each third of the highway site. If drop inlets on the pavement or at the end of paved channels from the edge of the pavement drain more than 50 percent of each third of the drainage area, then the storm-drain codes should be added to the BDF for each third of the drainage area. These points would be used in addition to the scores for channel improvements and channel linings. If, however, a trunk-line storm drainage system is employed such that stormwater flows over pervious surfaces to be collected at the foot of a swale, then the storm-drain code should not be added to the BDF. In this case, the effect of the sewer is taken into account by using the channel-improvement and channel-linings codes as appropriate. As with the storm-sewer code, the curb-and-gutter-streets code would be assigned if more than 50 percent of the highway area is drained by drop inlets that route water to a storm-sewer system or a swale in the median or a swale at the foot of the slope of the shoulders.

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