ABSTRACT

Title of Thesis: SENSITIVITY OF PEAK DISCHARGE CALCULATION TO GIS-DERIVED HYDROLOGIC ROUTING PARAMETERS IN THE TR-20 RAINFALL-RUNOFF MODEL

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Hydrologic routing of runoff from upstream locations is a central element in rainfall-runoff modeling. Channel cross-section geometry is used to develop routing parameters for this process. The sensitivity of the routed peak discharge to cross-section location along the routing reach is examined using two methods in this thesis. First, an enumeration method was used to analyze the sensitivity of overall peak discharge to the channel routing process by executing the TR-20 model for all possible cross-section locations evaluated within the GIS. Second, a regression equation as a function of the modified att-kin method routing coefficient, reach length, and channel slope shows promise as a planning and decision making tool when implementing the rainfall-runoff model. Finally, case study analyses support the usefulness that a possible future expert system would provide for guidance on developing routing reach cross-section characteristics to engineers and other professionals that use GIS to perform hydrologic rainfall-runoff modeling.

SENSITIVITY OF PEAK DISCHARGE CALCULATION TO GIS-DERIVED HYDROLOGIC ROUTING PARAMETERS IN THE TR-20 RAINFALL-RUNOFF MODEL

by

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Dedication

To Ellie.

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1 Introduction

The stream channel cross-section geometry provides key information used in the reach routing process within hydrologic runoff modeling. The physical characteristics of the flow path derived from the cross-section geometry are used to determine flow within the channel and surrounding floodplain. The stream channel (routing reach) may only be represented by a single cross-section geometry. Each possible cross-section will produce unique routing parameters and hence different peak discharge results from the hydrologic model. The importance of the cross-section geometry to the reach routing process leads to the question of peak discharge sensitivity to the cross-section location where the channel geometry is measured and how to quantify this sensitivity. This study will quantify the effects from the cross-section location along a routing reach, and provide a methodology to assist the engineer with assessing a watershed as to the sensitivity of its overall peak discharge based on the cross-section location along the routing reach during the hydrologic modeling process.

The cross-section geometry may be obtained from many methods including a true survey at the stream location, or from spatial data within a Geographic Information System (GIS). A GIS is a technology that allows for the storage, display, and analysis of spatial data in digital format. This technology combined with hydrologic modeling provides the engineer powerful analytical tools to utilize in planning and decision making processes.

1.1 Modeling

Hydrology is defined as “The science that relates to the distribution and circulation of naturally occurring water on and under the earth’s surface.” (ASCE, 1996).

Over time there have developed various methods to better understand and help predict how each of the different elements of the hydrologic processes behave. The hydrograph is the relationship of a watershed's discharge to time. An important aspect of hydrology is the ability to infer watershed characteristics from the discharge hydrograph (Leopold, 1994). There are several types of models that attempt to predict hydrographs based on known watershed characteristics. These models include, but are not limited to, rainfall excess, rainfall-runoff, flood routing, and stream flow (ASCE, 1996). Rainfall-runoff models are used to develop a representation of the watershed response to a storm event based on both watershed and stream channel characteristics.

The inputs for rainfall-runoff models vary depending on the exact model being executed. Some common inputs needed for rainfall-runoff models include rainfall amount, watershed area, stream channel network and geometry, land use, and soils information (ASCE, 1996).

1.2 Reach Routing

Reach routing is the process by which the effects of channel storage are modeled quantitatively as the hydrograph moves through the stream reach (ASCE, 1996). This enables a model to move the flood wave associated with a storm event through the stream reach network within the watershed. The reach routing process generally attenuates hydrograph peaks and adds a time lag to the hydrograph as it translates down the channel. There are several different routing methods available for use within most common rainfall-runoff models. These methods include: Time Lag, Impulse Response, Muskingum, Muskingum-Cunge, Kinematic Wave, and Storage Routing (ASCE, 1996).

The underlying concept behind all the methods of reach routing is the successive solution to the storage equation (Leopold, 1994):

$$I - O = \frac{dS}{dt} \quad (1\text{-}1)$$

where I is the inflow (cfs), O is the outflow (cfs), dS is change in storage (ft^3), and dt is change in time (s). In reach routing, the inflow is the hydrograph at the upstream end of the reach and the outflow is the hydrograph at the downstream end of the reach (ASCE, 1996). The rate of change of storage is simply the change in storage over a specific time span. In order to determine the storage capacity of a stream and compute the upstream and downstream hydrographs it is necessary to know the channel geometry. The channel geometry is described through the use of the channel cross-section.

1.3 Cross-Section

The cross-section geometry of a stream provides the necessary information for determining how much water can move through that stream at a specific location. The information provided by the cross-section geometry plays an important role in determining the cross-sectional area of a channel leading to the development of the stage-area – discharge relationship also referred to as a rating table. The stage-area-discharge relationship is the relationship between the cross-sectional area of a stream and the discharge at various depths. It is used to calculate certain coefficients and exponents required during the routing process as described later in this paper.

In a natural channel, the cross-section varies continuously along the reach. Many reach routing model implementations represent each routing reach within a channel network with a single cross-section. When this is the case, it may be difficult to determine where to best obtain the cross-section information along the reach. Theoretically, any stream reach may be described by some best representation that captures the behavior of that routing reach. This may not be the result of a cross-section from a single location, but a composite of cross-sections from several locations. This is true regardless of the method to be used to calculate the cross-section geometry. When using geospatial data within a GIS it is possible to systematically examine numerous cross- sections along a reach. This may not be possible using traditional surveying methods due to a variety of reasons including location, cost, and time limitations.

1.4 Geographic Information Systems

A GIS may be combined with a rainfall-runoff hydrologic model for performing hydrologic analysis and study. The power of a GIS provides support in all facets of hydrologic rainfall-runoff modeling including the following areas (Maidment, 2002):

- Manage data – basic data management tasks such as storage and extraction, and spatial data processing such as buffering and overlays
- Extract parameters – necessary characteristics of stream reaches and watersheds
- Provide visualization – display data both before and after a model is run to analyze the results
- Model surfaces – surface model processing such as DEMs to delineate watersheds and surface water networks
- Develop interfaces – map based interfaces to link GIS to hydrologic models

One of the main inputs into the TR-20 rainfall-runoff model (USDA, 1992a) is the rating table containing the elevation or stage relationship between cross-sectional area and discharge. The rating table can be developed within a GIS based on input from the user and the hydrologic characteristics obtained from the geospatial data. Cross-section geometry values may be generated for each routing reach within a watershed utilizing various watershed relationships (e.g. Leopold and Maddock, 1953; Dunne and Leopold, 1978; Leopold, 1994; McCandless and Everett, 2002; McCandless, 2003a; and McCandless, 2003b). For example, McCandless, 2003b relates bankfull width, bankfull depth, and cross-sectional area to watershed drainage area by Maryland hydrologic regions Allegheny Plateau and the Valley and Ridge, Piedmont, and Coastal Plain. The cross-sectional area, bankfull width, and bankfull depth can be calculated by obtaining only the drainage area. The drainage area is calculated from the geospatial data based on where the cross-section is measured along the routing reach. The power of the GIS allows for a systematic investigation of the results based on varying the location used to obtain the routing reach geometry information.

1.5 Motivation / Case Study

The primary motivation for this study is to provide guidance on developing routing reach cross-section characteristics to engineers, planners, and other professionals who use GIS to perform hydrologic rainfall-runoff modeling. The watershed shown in Figure 1-1 contains a single routing reach, but many possible locations for measuring a channel cross-section.

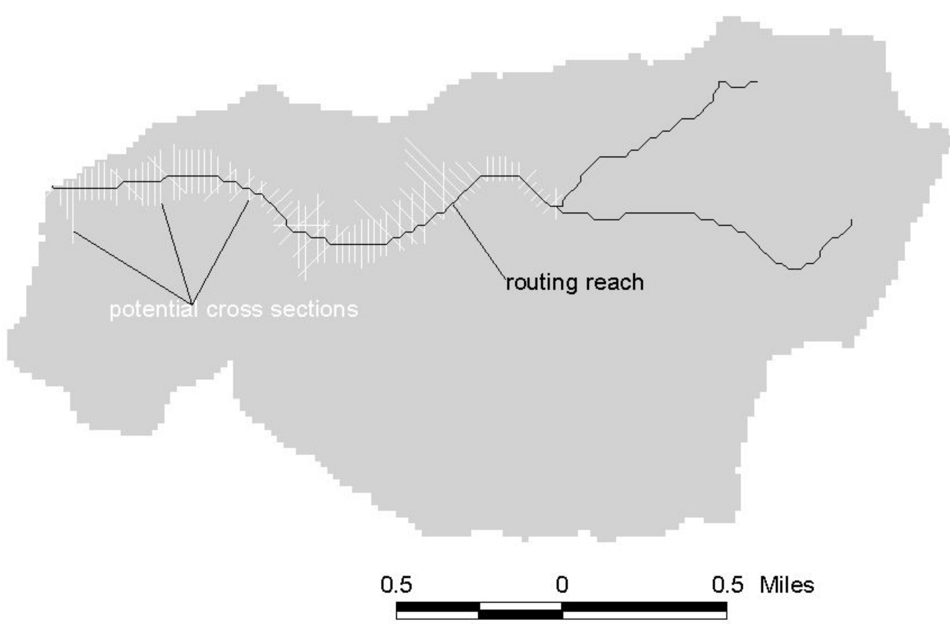


Figure 1-1: Test case watershed with routing reach and cross-sections

The number of cross-section possibilities can be decreased by measuring cross-sections perpendicular to the direction of flow and by approximating a continuous physical reality by discrete grid cells that make up the routing reach. The cross-sections are demonstrated in Figure 1-1 as the white lines perpendicular to the flow direction within the routing reach.

The systematic method for measuring cross-sections within a GIS creates a limited number of possible solutions to a hydrologic rainfall-runoff model equal to the number of cells that make up the routing reach. Each cross-section measured produces its own unique rating table which, in turn, returns a unique peak discharge for the watershed when used in the execution of a hydrologic rainfall-runoff model such as TR-20. The variability of the resulting peak discharge values is shown in Figure 1-2 for a storm depth of magnitude 7 inches in 24 hrs.

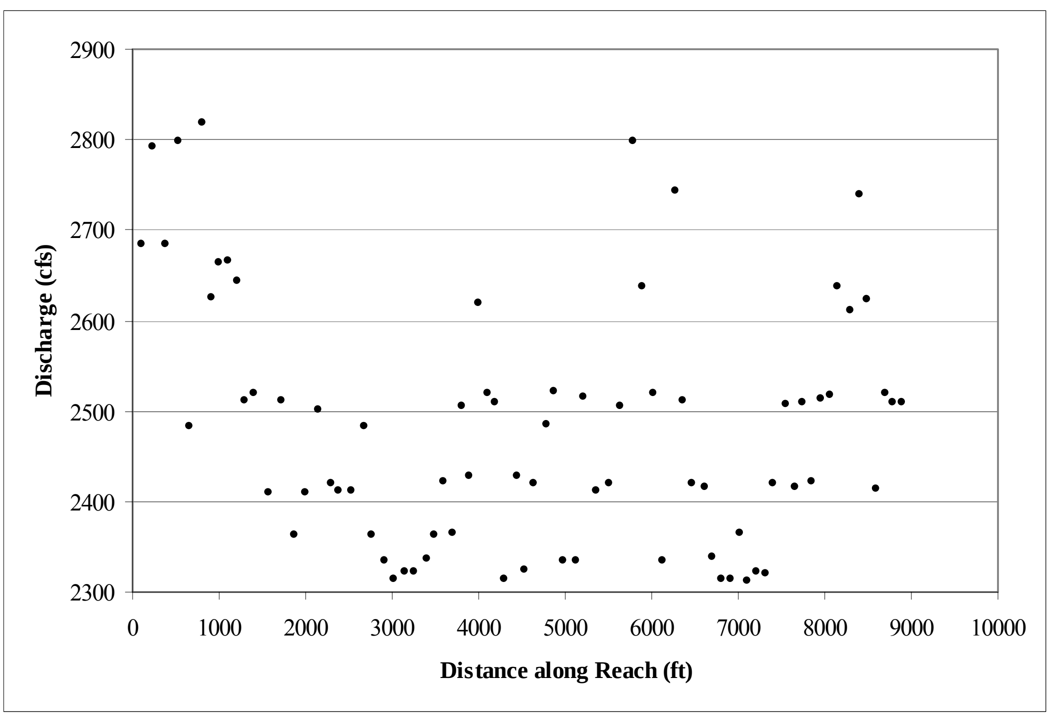


Figure 1-2: Peak discharges resulting from a 7 inch, 24-hour storm based on cross-sections along routing reach shown in Figure 1-1

The x-axis indicates where along the routing reach from upstream to downstream the cross-section is measured. The larger the x-axis value, the further downstream the cross-section location. This distance is an estimate based on grid cell center to grid cell center for grid cells that are located on the routing reach. The y-axis is the resultant peak discharges calculated at the watershed outfall based on stream channel geometries for each measured cross-section.

The maximum peak discharge for this stream reach is 2,819 ft^3/s derived from channel characteristics at a location 807 feet downstream from the start of the reach. The minimum peak discharge for this stream reach is 2,313 ft^3/s derived from channel characteristics at a location 7112.4 feet downstream from the start of the reach. This is a difference of 506 ft^3/s or 22 percent. An examination of Figure 1-2 shows several additional points slightly below the maximum peak discharge and slightly above the minimum peak discharge. These additional points are spread across the entire length of the routing reach with no clear trend between peak discharge and distance along the reach. The variation identified in this case study drives the following objectives for this study.

1.6 Objectives

The objectives of this study are:

1. To develop a methodology to systematically quantify all the potential rating tables along routing reaches for input into a hydrologic rainfall-runoff model.
2. To quantify the sensitivity of peak discharge to the cross-section location along the routing reach within a watershed based on the methodology developed in objective 1.
3. To quantify the sensitivity of peak discharge to the cross-section location along the routing reach with changes in watershed characteristics (topography,

precipitation magnitude, and routing reach length) using the methodology developed in objective 1.

4. To provide recommendations based on this study's findings that should inform the use of GIS in performing reach routing.

1.7 Value of Work

Hydrologic engineers use rainfall-runoff modeling as a standard analysis tool in decision making processes that may affect dimensions of bridges, culverts, and stream restoration plans. The engineer needs to have an understanding of how discharge estimates may vary based on the uncertainty in the development of the rating table. The value of this study is to provide knowledge to the engineer regarding the discharge sensitivity combined with the power of a GIS to guide the engineer as the inputs to the rainfall-runoff models are developed.

The primary value of the rating table analysis is to provide information regarding the sensitivity of the hydrologic analysis to the channel geometry. Channel geometry plays an important role in providing input into a hydrologic model, and therefore an understanding of how this may affect the results of the hydrologic model is vital to producing trustworthy data. In some cases the model may not be sensitive to which cross-section is used to determine channel geometry and little or no additional analysis is needed before proceeding. The opposite may also be true. The model may be sensitive to which cross-section is used and care may then be needed when selecting a cross-section location.

Hydrologic engineers use rainfall-runoff modeling as a standard part of many different design decisions and analysis. The engineer needs to understand how much the estimates of design discharges may vary based on the cross-section location. This study will examine the sensitivity of peak flow estimates to cross-section location and should provide tools that an engineer can use to quickly discriminate between situations where sensitivity is a concern and where it is not a concern.

2 Literature Review

The integration of GIS with raster data processing and hydrologic modeling has provided an efficient, easy to automate framework that is reproducible when performing rainfall-runoff modeling (Olivera, 2001). Olivera et al. (1998) presented a paper discussing the scope of a software product designed to process geospatial data in a GIS for input into the Hydrologic Modeling System (HMS) (HEC, 1990) developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (USACE HEC). These algorithms can be adapted within the GIS to produce the required inputs to other models such as the rainfall-runoff model TR-20 developed by the United States Department of Agriculture Soil Conservation Service or SCS (USDA, 1992a).

2.1 The TR-20 Rainfall-Runoff Model

The purpose of TR-20 is to provide the engineer with a means of analyzing flood events based on either actual or synthetic storm events. TR-20 is a physically based modeling program able to simulate flood hydrographs based on unit hydrograph concepts and hydrologic reach routing. For this study the component of interest from the TR-20 system is the reach routing. The information obtained through the cross-section analysis is a primary ingredient in producing the reach routing inputs. Reach routing within TR-20 is performed using the Modified Att-Kin (attenuation-kinematic) methodology (USDA, 1992a).

The Modified Att-Kin model addresses the two components that describe the movement of a flood wave through a stream reach: translation and reservoir storage effects. Translation is the process of routing a hydrograph through a reach while keeping the hydrograph shape intact. This is accomplished with a kinematic wave model. The reservoir effects involve diminishing or attenuating the flood hydrograph peak. This is accomplished with a storage model. The cross-section geometry can be used to provide necessary inputs for both the translation and storage components of the Modified Att-Kin routing method (USDA, 1992a).

The data derived from the cross-section geometry is stored in a rating table that contains the stage-area-discharge relationships. These relationships can be used to compute the values of the routing parameters for the Modified Att-Kin method: C, x, and m, where C is the routing coefficient, x is a proportionality coefficient, and m is the rating curve exponent. The routing coefficient, C, is a function of the reach length, velocity, and the rating curve exponent and governs the routing process within the Modified Att-Kin model. The rating curve exponent, m, is a function of the discharge and slope of the discharge-area curve and is used to relate the average and wave velocities. This relationship governs the travel time of the peak discharge through the reach. TR-20 has set limits on what the m values can be in order to control the stability of the math and numeric models (USDA, 1992a). The proportionality constant, x, relates area and velocity and governs the attenuation of the peak discharge through the reach (USDA, 1992a). These computations are described in further detail in Chapter 3.

The importance of the rating table and hence the cross-section geometry can be demonstrated from the relationships outlined above between the Modified Att-Kin routing method and the parameters calculated based on data derived from the cross-section geometry. Each cross-section of a routing reach has the potential to create a unique rating table and set of parameters that drive the routing process. The guidance provided by the TR-20 user manual states "…cross section data should represent the hydraulic conditions for the reach through which reach routing is to be performed." (USDA, 1992b). There is no guidance on how to determine where along the reach the most representative cross-section location is. Although this study does not attempt to quantitatively address the most representative location, it will show that the choice of cross-section location may greatly affect the TR-20 model results.

2.2 GIS and the Integration of Hydrologic Modeling

The combination of GIS and hydrologic modeling is useful to study the effects of varying cross-section geometry along a routing reach. As mentioned earlier the key is automation and ease of data processing. The Center for Research in Water Resources (CRWR) of the University of Texas at Austin is at the forefront for developing software systems to be used in combination with hydrologic modeling. The CRWR, under the leadership of Dr. David Maidment, originally developed a package called HEC-PrePro (Hellweger and Maidment, 1999). HEC-PrePro provided the topologic analysis component necessary for hydrologic modeling (Oliver and Maidment, 1999). HEC-PrePro has since been replaced by CRWR-PrePro which combines components that are necessary for hydrologic modeling within a GIS. These components were extracted from various other data processing algorithms including the Watershed Delineator ArcView extension developed by ESRI for terrain analysis, the Flood Flow Calculator developed at the CRWR for hydrologic parameter calculation, and HEC-PrePro for the topologic analysis (Oliver and Maidment, 1999). The use of some of these components is further described in Chapter 3. Although these tools alone don't determine all the inputs necessary for executing TR-20, a means for estimating the channel cross-section geometry is needed, they do provide the backbone of an automated process that with some additional development can be utilized to analyze the sensitivity of the hydrologic routing algorithm in TR-20 to varying cross-section geometry.

2.3 Guidelines for Cross-Section Selection

The impacts on modeled discharge from varying cross-section geometry along the routing reach may be difficult to quantify. These impacts may depend on how the results will be used. For some analyses the impacts may be negligible based on how the results will be used, or based on the characteristics of the watershed and routing reach. In other cases the impacts may be large. Regardless, it is important for the engineer to understand that those impacts may exist. A case study performed during a project for the Maryland State Highway Administration makes the observation that the automation of the hydrologic modeling processes with a GIS has a negative side such that the engineer is more removed from the process and may begin to treat the modeling process as a black box. This type of treatment may produce erroneous results that could have an impact on the final results of the project or analysis (Brown and Dee, 2000). This black box treatment is not limited to the location of the cross-section, but the location of the cross-section is certainly included as a subjective parameter within the overall analysis.

Guidelines or guidance regarding the development of cross-section information are often provided with modeling tools or by groups that perform hydrologic modeling with a GIS. For instance, the Department of Natural Resources (DNR) for the state of Indiana states that cross-sections should be selected that represent the average conditions for the reach (Indiana DNR, 2002). The IN DNR guidelines primarily relate to performing true surveying to measure the cross-sections. Depicting an average condition within a GIS with DEM data may be rather difficult. The Maryland State Highway Administration (MD SHA) documents the use of a representative cross-section to be used for determining the input data for TR-20 (Maryland Hydrology Panel, 2005). The hydraulic radius is an important parameter for estimating the channel velocity. The MD SHA observes that the larger the hydraulic radius the greater the velocity and shorter the time of concentration. This is directly related to the cross-section geometry from which the hydraulic radius determined. The variation in cross-sections from point to point along a reach makes it difficult to determine the most “representative” location to measure the cross-section (Maryland Hydrology Panel, 2005). The following study provides two methods that provide guidance as to when the cross-section location greatly affects the results from TR-20.

3 Methods and Procedures

Reach routing is a primary component of the rainfall-runoff modeling process. Each of the reach routing methodologies rely on some set of parameters to attenuate the discharge moving through a stream channel (routing reach). Although the procedures described in this study focus on the Modified Att-Kin routing method, they may be applied to other methods such as the Muskingum Cunge method (ASCE, 1996) by analyzing the different parameters specifically associated with those particular methods.

3.1 Data Preparation and Processing

The primary building block to performing raster-based terrain analysis is elevation data. Digital Elevation Model (DEM) data is available from the United States Geological Survey (USGS) and quantifies how terrain elevation varies throughout the U.S.

Delineating a watershed and extracting the stream network requires an understanding of how water flows over the land surface. From this understanding a method is needed to relate this to the available DEM data. The first component to delineating a watershed is defining the flow direction from grid cell to grid cell. The most common method used to identify flow direction is the D8 method (Marks et al, 1984). The D8 method describes the flow of water by the steepest slope in 8 possible directions. The 8 directions are east, southeast, south, southwest, west, northwest, north, and northeast. This method is implemented within a GIS by assigning a unique number to each grid cell based on its flow direction. These numbers are arbitrary and may be assigned differently depending on preferences of the designer. Figure 3-1 (a) describes the possible physical flow assignments for the center grid cell X, and Figure 3-1 (b) describes the GIS-stored representations of those flow assignments (ESRI, 2000).

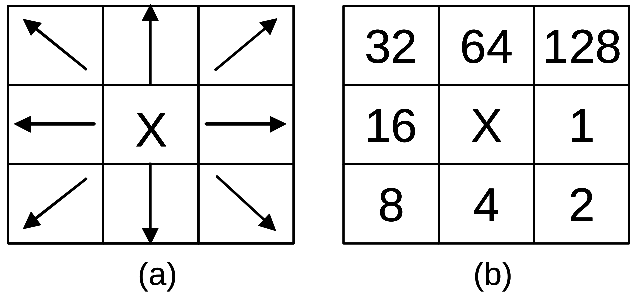


Figure 3-1: (a) Visual flow direction, (b) GIS-stored flow direction (ESRI, 2000)

For example, if the steepest slope from grid X is to the southeast the flow direction value for grid cell X would be 2. Once the flow direction is determined for each grid the flow accumulation grid can be computed.

The flow accumulation grid identifies the number of grid cells that flow into a given grid cell. The flow accumulation grids developed in this study used a slightly modified ESRI implementation based on Jenson (1988). There are three possible scenarios for each flow direction grid cell: 1) A grid cell of unknown flow, 2) a grid cell that receives flow and flows to another grid cell, and 3) a grid cell that does not receive flow and flows to another grid cell. Flow accumulation for a grid cell is calculated based on the sum of flow accumulation units that flow to it plus 1 unit for itself. Cells with no contributing grid cells have a flow accumulation value of 1.

Figure 3-2 illustrates the process for calculating the flow accumulation grid and extracting the stream network.

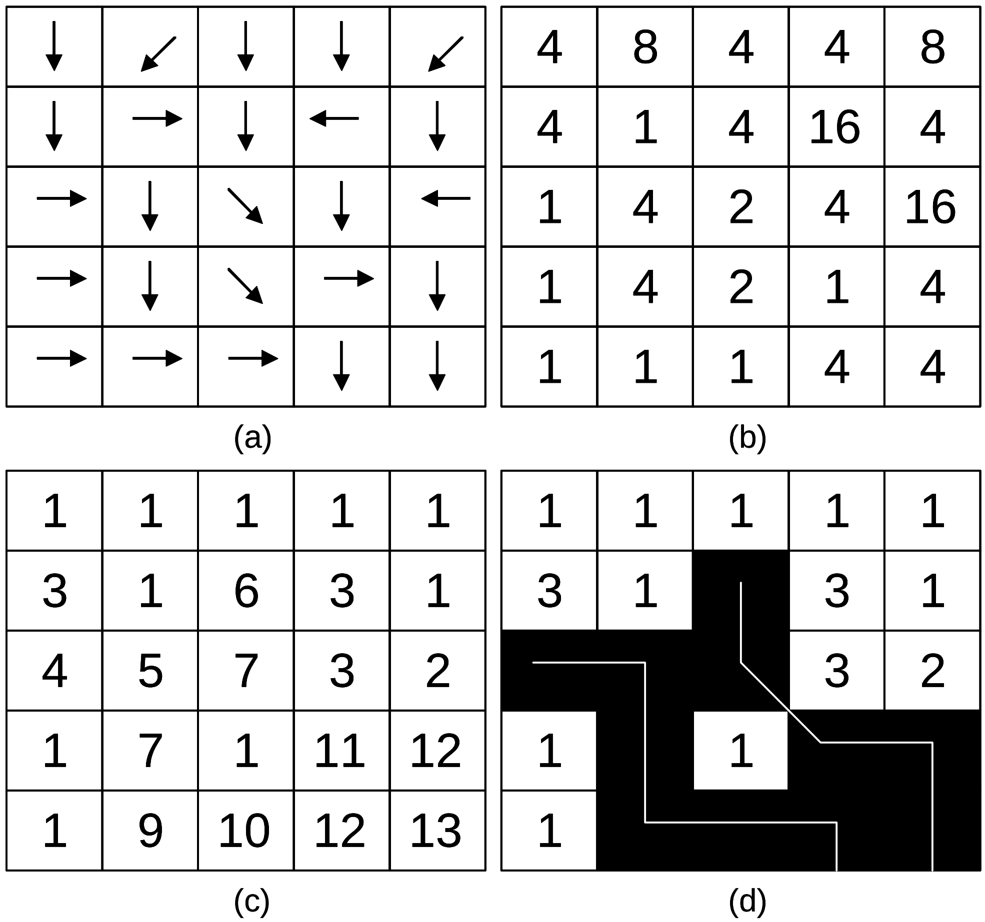


Figure 3-2: Physically interpreted grid cell based flow directions (a), GIS-based grid cell flow directions (b), flow accumulation (c), and threshold based channel network (d)

Figure 3-2(a) demonstrates the flow directions based on the D8 method. These flow directions are represented as numbers when implemented in a GIS and seen in Figure 3-2(b). Figure 3-2(c) shows the flow accumulation grid based on the flow direction grid. All the flow accumulation grid cells with a value of 1 have no other grid cells flowing into them.

Channel initiation is based on a subjective drainage area threshold defined by the engineer. Drainage area can be calculated from the flow accumulation grid based on the resolution of the grid dataset. Figure 3-2(d) demonstrates what the stream network would look like if the flow accumulation threshold was 3600 m^2. Assuming these grid cells were 30m grids then the channel initiation threshold would be 3600 / 30^2 (drainage area threshold / grid cell area) which equals 4 flow accumulation units.

An additional process that can be performed using the flow direction grid is the delineation of watersheds. ESRI provides functionality within a GIS to delineate watersheds based on the flow direction grid (ESRI, 2000). Figure 3-3 shows the watersheds delineated based on the two outfall points at the bottom right of the 5 x 5 grid in Figure 3-2(a).

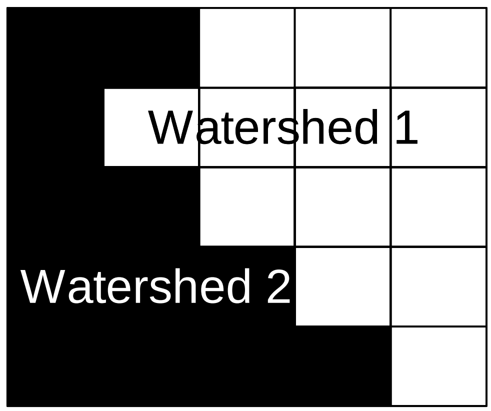


Figure 3-3: Watershed delineation based on Figure 3-2(a)

The techniques described above to extract the stream network and delineate watersheds based on flow direction are the building blocks for creating the necessary inputs for hydrologic modeling utilizing a GIS. The first step in the process is subdividing the watershed. Determining where to subdivide a watershed is a subjective process and is used to account for hydrologic differences that may stem from such things as confluences of tributaries, watershed shape, changes in curve number, and changes in slope. The resulting areas created from the watershed subdivision process are referred to as sub-areas. Each sub-area should be hydrologically homogeneous and no larger than 25 square miles in area (USDA, 1992b). The sub-areas should also be of roughly equal areas. Sub-areas with large variations in area will provide a combination hydrograph that is only as accurate as the hydrograph from the largest sub-area. This accuracy is due to the large time of concentration and area in comparison to the other smaller sub-areas (USDA, 1992b).

For the purposes of this study, the watersheds examined were divided into only three sub-areas. This created two upper sub-areas that combine and flow into a lower sub-area and, hence, a single routing reach for the overall watershed. The reasoning behind this decision was to control for the timing complexities associated with multiple routing reaches and the need to compare all combinations of cross-section locations if more than one routing reach exists. An examination of how the peak discharge varies based on watershed sub-division decisions was performed by Michael Casey in 1999 for his Master's thesis from the University of Maryland (Casey, 1999).

Following the appropriate subdivision of the watershed the necessary attributes to perform hydrologic analysis must be calculated. These attributes include area, time of concentration, and average curve number. Additional parameters are required in order to calculate the lag-time including slope and length of the longest flow path. The time of concentration for each sub-area can be computed from the SCS Lag Formula, Curve Number Method as seen in Equations (3-1) and (3-2) and (3-3) (USDA SCS, 1972) where t_c is the time of concentration (hrs.), t_L is the lag time (hrs.), ℓ is the hydraulic length of the watershed (ft.), S is the potential maximum retention (in.), CN is the hydrologic soil content complex number, and Y is the average land slope (percent).

$$t_c = 1.67 t_L \qquad (3\text{-}1)$$

$$t_L = \frac{\ell^{0.8}(S+1)^{0.7}}{1900 Y^{0.5}} \qquad (3\text{-}2)$$

$$S = \frac{1000}{CN} - 10 \qquad (3\text{-}3)$$

The additional parameters such as area, average curve number (required for SCS Lag Formula as well), slope, and length of the longest flow path can all be calculated from the available DEM and curve number raster data and basic GIS functionality.

Once the watershed has been subdivided and the attributes for each sub-area determined, the routing reach cross-section characteristics must be computed. In this study, the length of the routing reach determines how many cross-sections are analyzed based on the number of grid cells that make up the routing reach. Using the GIS a cross-section for each grid cell making up the routing reach is created and processed.

The GIS provides the capability to use an automated process to consistently define the extent of each transect (linear vector such that the end points define the length of the cross-section) used to measure a cross-section. This could be based on length, elevation differential, or other physical characteristics derived from the spatial data available. In this study we use elevation differential in order to insure enough flood plain width is captured to contain the flows examined in this study. Through trial and error, an elevation differential of more than 10 feet was determined to be satisfactory. The 30m DEM data was used to examine the elevation differential along the cross-section transect. This means that the extent of a cross-section transect extends from the center of the grid cell on the routing reach to the center of the first DEM grid cell such that greater than 10 feet of elevation is gained to both sides of the routing reach. The transect is taken perpendicular to the flow direction of the routing reach grid cell. In reality, the concept of a transect being perpendicular to flow would not be limited to a discrete number of transect orientations, but perpendicular to the eight flow directions was all that could be resolved in this study. Below is a list of the two exceptions that cause the 10 foot elevation differential to be over-ridden and a smaller differential to define the transect extents.

- Transect delineation ends at the first sub-watershed boundary that is encountered.
- Transect delineation ends if a routing reach grid cell is encountered.

Figure 3-4 shows the cross-sections for a typical watershed used in this analysis. The shaded areas outside the sub-divided watershed represent ranges of elevation based on the DEM data.

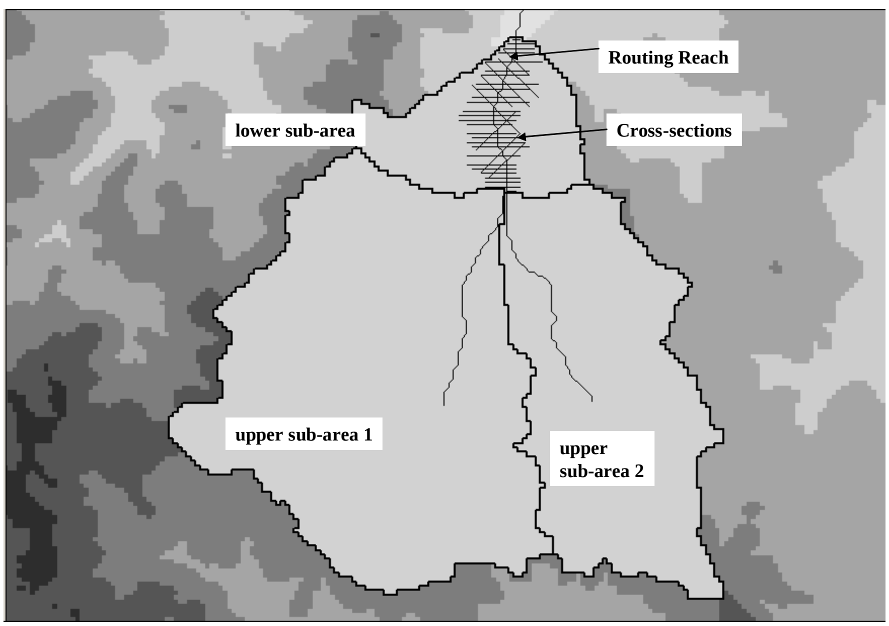


Figure 3-4: Sub-divided watershed with cross-sections along routing reach

Figure 3-5 shows an example of a cross-section transect and how the DEM is used to determine the end points. At the location where this transect is located the DEM value on the routing reach is 94 feet. The end values of 107 and 108 feet demonstrate the 10 foot change in elevation rule. It should be noted that the routing reach does not pass through the lowest point along the transect. This is due to a difference between the DEM data and the method used to digitize the stream network. In this study the stream network was forced to match the linework from the National Hydrography Dataset, NHD (USGS, 2006) as opposed to the DEM.

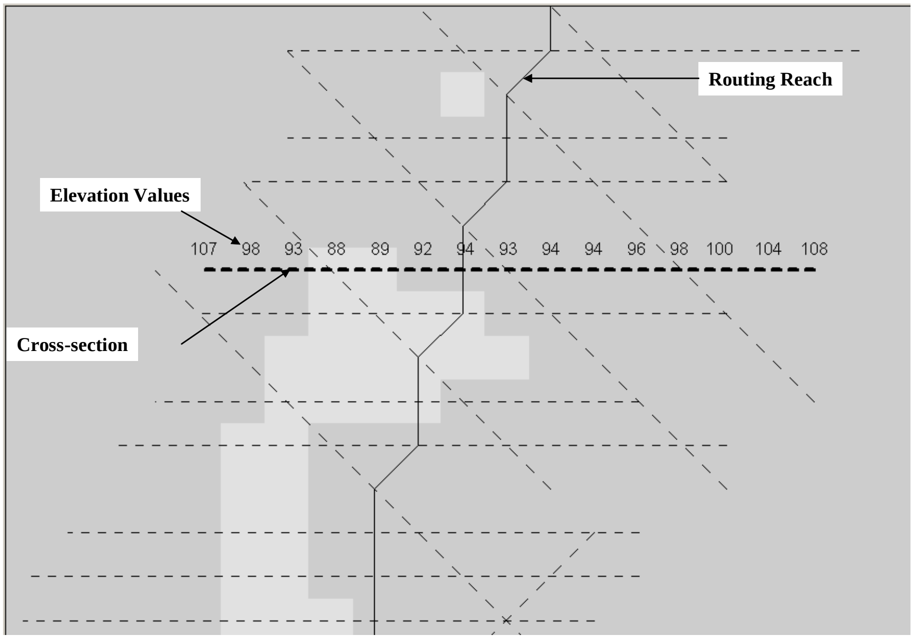


Figure 3-5: Elevation values to demonstrate determination of transect limits

The cross-section geometries are generated using a hybrid approach of in-channel and out-of-channel methodologies. This is necessary due to the 30 meter resolution of the DEM data. The DEM data at this resolution does not resolve the low flow channel but the more elevated flood plain surrounding the channel. The in-channel methodology is based on drainage area and utilizes the U.S. Fish and Wildlife Service (USFWS) regression equations to calculate bankfull width and depth values (McCandless, 2003b). The USFWS regression equations are based on three Maryland physiographic regions: Coastal Plain, Piedmont, and Allegheny Plateau/Valley and Ridge. The bankfull depth and width are treated as a power function of drainage area for which the coefficients and exponents are different for each physiographic region. Equations (3-4) and (3-5) can be used to calculate the bankfull width and bankfull depth respectively based on drainage area where W is the bankfull width (ft.), D is the bankfull depth (ft.), DA is the drainage area (mi^2). Table 3-1 displays the coefficients and exponents that can be substituted based on the Coastal Plain, Piedmont, and Allegheny Plateau/Valley and Ridge regions (McCandless, 2003b).

$$W = b(DA)^e \quad (3\text{-}4)$$

$$D = c(DA)^f \quad (3\text{-}5)$$

Table 3-1: USFWS regression equations for bankfull width and depth

	b	***e***	***c***	***f***
Coastal Plain	10.30	0.38	1.01	0.32
Piedmont	14.78	0.39	1.18	0.34
Allegheny Plateau/Valley and Ridge	13.87	0.44	0.95	0.31

Based on bankfull width, bankfull depth, and an assumed "U" channel shape, the in-channel cross-section geometry can be calculated. The "U" channel shape is based on width as a function of depth. Figure 3-6 illustrates a cut away view of the cross-section highlighted in Figure 3-5. There are two components that make up the actual cross-section in Figure 3-6. The in-channel portion is derived from the U.S. Fish and Wildlife Service regression equations, and the out-of-channel portion is derived from the elevation data obtained from the DEM. To the left of the thalweg is a short, steep bank and to the right of the thalweg is a longer more gradually rising bank. This can be identified in both the elevation data and the cut away cross-section. The 10 foot elevation threshold in Figure 3-6 demonstrates how the transect intersects the stream channel at an elevation of 94 feet and the end points of the transect extend to the next DEM grid cells greater than 104 feet.

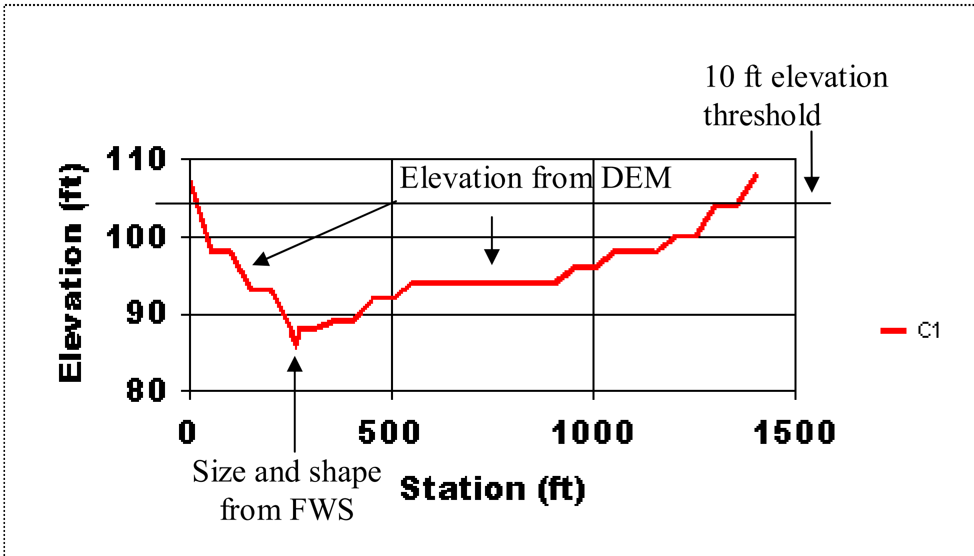


Figure 3-6: Cut away view of cross-section highlighted in Figure 3-5

The overall cross-section geometry information enables the calculation of the rating table.

The rating table describes the stage - area - discharge relationship of a stream, and is calculated using Manning's Equation (3-6) and the Continuity Equation (3-7) where

$$V = \frac{1.49 R_h^{2/3} S^{1/2}}{n} \qquad (3\text{-}6)$$

$$Q = AV \qquad (3\text{-}7)$$

R_h is the hydraulic radius (ft), S is the channel slope (ft/ft), n is the Manning's constant, A is the cross-sectional area (ft^2), V is the stream velocity (ft/s), and Q is the discharge (cfs). The hydraulic radius is the cross-sectional area divided by the wetted perimeter and is calculated based on the cross-section geometry at a discrete stage (or elevation) value. Once the velocity and area are calculated the discharge is calculated creating the stage – area – discharge relationship or rating table. The rating table used in TR-20 is created based on a maximum of 20 stage points, and in this study 5 stage points are from within the channel and 15 are from outside the channel.

On occasion the DEM data does not provide the necessary relief to create a valid rating table. A rating table must have both increasing discharge and cross-sectional area values with increasing stage. In very flat terrain or situations near a sub-area boundary the DEM data captured along a routing reach transect may not change. When this occurs the automated method used to process the out-of-channel portion DEM fails since there is no way to distinguish between the grid cells. These cross-sections were flagged and then dropped from the final datasets

The rating table is used by TR-20 in the hydrologic modeling process to determine the routing coefficient, *C*. The routing coefficient is used in the Modified Att-Kin routing process to drive the channel hydraulic modeling necessary to route the channel flow. The routing coefficient can be calculated with Equation (3-8).

$$C = \frac{2\Delta t \cdot 3600}{2K + \Delta t \cdot 3600} \qquad (3\text{-}8)$$

In Equation (3-8) Δt is the main time increment (hrs), *K* is the slope of the storage-discharge curve (s), and *C* is the routing coefficient (unit less). The main time increment (Δt) is controlled by the user, but the slope of the storage-discharge curve (*K*) must be calculated.

Equation (3-9) is used to calculate the slope of the storage-discharge curve, *K*.

$$K = \frac{L / m}{V_{ref}} \qquad (3\text{-}9)$$

In Equation (3-9) *L* is the reach length (ft), *m* is the rating curve exponent, and V_{ref} is the velocity of the reference discharge (ft/s). The reach length (*L*) is calculated based on the processed DEM data and the resultant stream network. The rating curve exponent, *m*, is a function of the rating table and the input peak discharge. When using a rating table to route the input hydrograph, *m* must be calculated for each discharge point in the hydrograph. Equation (3-10) can be used to calculate *m* at each point in the rating table.

$$m = S(2,3)\ for Q < Q(3)$$
$$m(I) = \frac{Q(3)S(2,3) + ...(Q(I) - Q(I-1))S(I-1,I)}{Q(I)}\ for Q(3) < Q < Q(I) \qquad (3\text{-}10)$$

In Equation (3-10) *m(I)* is *m* at flow number *I*, *Q* is the discharge (cfs), *Q()* is the discharge at the subscript point number (*Q*(1) = 0), *S(2,3)* is the log-log slope of the discharge-area curve between points 2 and 3, and *S(I-1,I)* is the log-log slope of the discharge-area curve between points *I*-1 and *I*. If *m* is required at a discharge between points in the rating table, it can be interpolated between discharge values, or *m* can be extrapolated from the last two points on the rating table. The cross-sectional area can also be interpolated or extrapolated from the rating table based on the input peak discharge.

The inflow peak discharge can be obtained based on the inflow hydrograph when available. For this study, because the inflow is from a hypothetical upper reach or set of sub-watersheds, the inflow hydrograph is not available when calculating the routing coefficient. The input peak discharge can be estimated using several methods. The method used here was to run a single cross-section through TR-20 and obtain the input peak discharge from the TR-20 output table. The input peak discharge to the routing reach is independent of cross-section and based on contributing hydrographs from the upper sub-areas. Another method could be to use USGS peak flow regression equations (e.g. Dillow, 1996).

When the inflow hydrograph is known, the inflow peak discharge can be obtained. An estimate of the outflow peak discharge (Q_{ref}) is required which is based on the calculation of the length factor (k^*) as seen in Equation (3-11).

$$k^* = \frac{Q_{pi}}{xVI^m} L^m \qquad (3\text{-}11)$$

VI is the volume of the input hydrograph (ft^3) and Q_{pi} is the peak inflow discharge (cfs). When the length factor is less than or equal to1, $Q_{ref} = Q_{pi}$, and when the length factor is greater than 1 $Q_{ref} = Q_{pi} / k^*$.

For this study the input hydrograph is not known therefore the assumption was made that $Q_{ref} = Q_{pi}$. This assumption eliminated the need to use Equation (3-11). Communications with William Merkel from the National Resources Conservation Service (NRCS) in summer of 2005 confirmed the difficulties in estimating the routing coefficient for floodplain hydrographs. TR-20 performs an iterative process for irregular rating curves that allow for a tolerance of 5 percent on the area calculation and a tolerance of 0.05 for the m calculation. In addition, TR-20 only reports the C value to two significant digits whereas at least 3 or 4 significant digits would be needed for comparison purposes. This makes it difficult to determine the error in calculating the routing coefficient based on the assumptions made for this study.

It follows that V_{ref} can be calculated from Equation (3-7) where $Q = Q_{ref}$, and A is interpolated or extrapolated from the rating table as described earlier. K is calculated from Equation (3-9), and finally C is calculated from Equation (3-8). This study uses the calculated routing coefficient in a regression equation, described later in this chapter, to calculate a sensitivity factor for gauging sensitivity of peak discharge to the cross-section location.

3.2 Methods to Predict Routing Sensitivity

In this study two methods were devised to provide information to the engineer regarding the sensitivity of the GIS based hydrologic model to the cross-section selection. The first method can be described as the enumeration method and involves running TR-20 for the series of all possible cross-sections along a reach created using a consistent and reproducible method as described earlier. The second method is based on a regression equation to estimate the percent change in routed hydrograph peak discharge due to routing along the stream reach. The enumeration method and regression method are described below.

The initial set of data used in this study was grouped into three categories or regions based on topography: flat sloped, moderate sloped, and steep sloped. The basis behind these groupings is to examine how the overall watershed relief affects the sensitivity of peak discharge to the cross-section / rating curve location. The analysis of the data based on these groupings will be presented in Chapter 4.

The enumeration method uses the peak discharges returned by TR-20 to analyze the sensitivity of peak discharge to cross-section location along the routing reach. A sensitivity factor, *%d*, is determined by examining the difference between the minimum and maximum peak discharges for the cross-sections measured along the routing reach. The *%d* sensitivity factor is calculated as follows:

$$\%d = \frac{Q_{\max} - Q_{\min}}{Q_{\max}} * 100 \qquad (3\text{-}12)$$

where Q_{max} is the maximum overall peak discharge returned for the routing reach (cfs) and Q_{min} is the minimum overall peak discharge returned for the routing reach (cfs).

Examination of the spread of the peak discharge data for larger values of *%d* can assist in determining whether or not the larger sensitivity values are caused by outlier data. Additional information acquired from the TR-20 output files, as described below, can be utilized in the second method to measure the sensitivity of a watershed to cross-section location.

In addition to the overall peak discharge returned by TR-20 at the watershed outlet, the TR-20 output files contain the input peak discharge at the upstream end and output peak discharge at the downstream end for the routing reach. These discharges do not include any local flow contribution from the lower sub-area. In this study the percent change in discharge due to routing through the stream reach will be referred to as *CR*. *CR* is defined in Equation (3-13):

$$CR = \Delta Q / Qin = \frac{Qin - Qout}{Qin} \qquad (3\text{-}13)$$

where Q_{in} is the peak discharge at the upstream end of the routing reach (cfs) and Q_{out} is the peak discharge at the downstream end of the routing reach (cfs) resulting from the reach routing process.

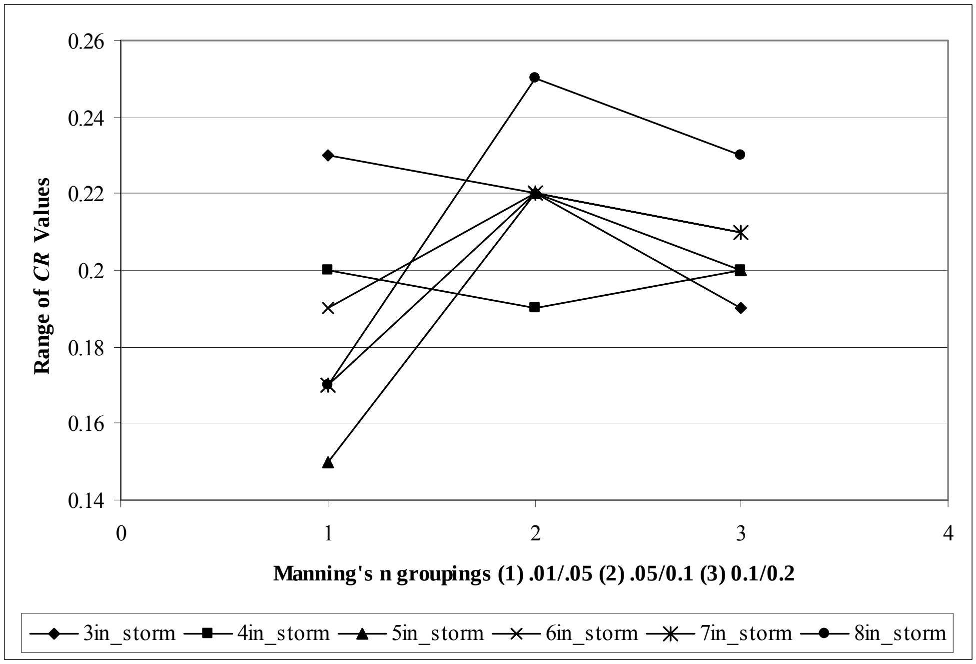
CR is of interest because of the relationship between the routing coefficient and the physical characteristics of the watershed and the cross-section geometry. ΔQ is the difference between the input peak discharge at the inflow to the routing reach and the resulting routed peak discharge at the outflow from the routing reach. As discussed earlier, the routing coefficient is the parameter that drives the reach routing process. The division by *Qin* is a normalizing factor in order to be able to compare the results across watersheds. A second sensitivity factor, ΔCR, is determined based on the difference between the minimum and maximum *CR* values for a routing reach computed using different cross-sections. The results and analysis of sensitivity factors *%d* and *ΔCR* will be discussed in much greater detail in Chapter 4.

3.3 Sensitivity of CR to Manning's Roughness Coefficient

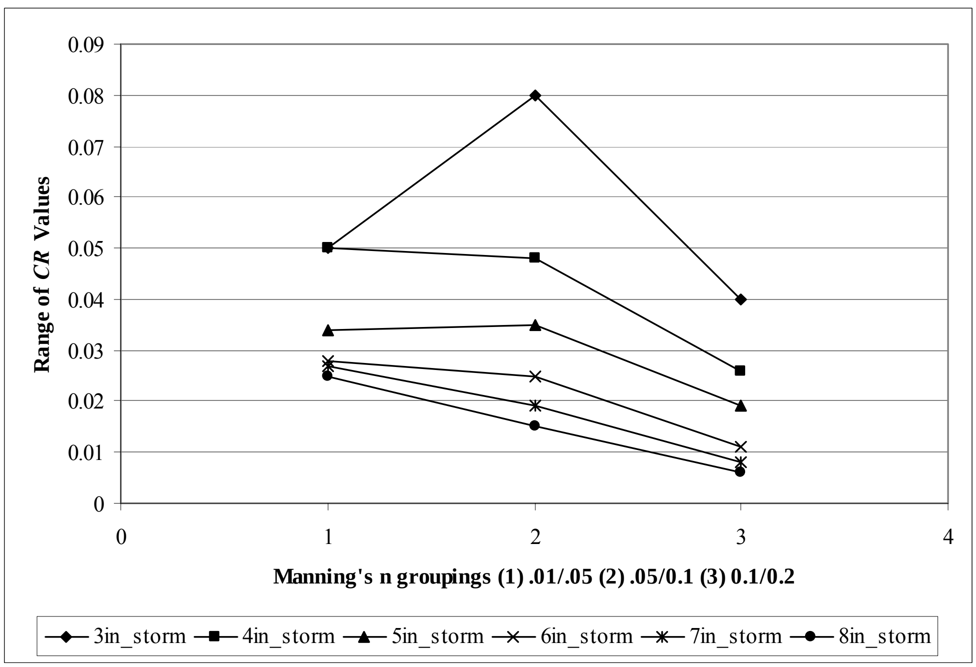
As discussed earlier, Manning's equation is a component in the creation of the rating table used in the TR-20 routing implementation. When examining Manning's equation, the roughness coefficient (Manning's n) is the only parameter that is not calculated from the channel cross-section geometry. Manning's roughness coefficient is subjective in nature and may be difficult to assess without any actual field-based information.

A change in the Manning's n may affect the routed discharge observed through the hydrologic modeling process as implemented in TR-20. The sensitivity of reach routing to Manning's n is not the subject of this study, but some value of Manning's n was needed. To examine the variation in peak discharge based on cross-section location only, this study chose to fix Manning's n to single values for in-channel and out-of-channel flow. A simple experiment based on upper/lower/typical Manning's n values was performed to determine what fixed values of Manning's n should be used.

The sensitivity of *CR* to different Manning's n values is presented in Figure 3-7.



(a)



(b)

Figure 3-7: *CR* sensitivity to Manning's n values; a) steep watershed, b) flat watershed. Three groups of n values - .01/.05, .05/.1, and .1/.2 based on in-channel flow/out-of-channel flow

This analysis determines what implications, if any, the selection of the fixed Manning's n values will have on the routing process and range of *CR* values along the routing reach. Two watersheds were used to perform the sensitivity analysis: one steep sloped and one flat sloped. The rationale behind using different categories of watersheds is the anticipated disparity of sensitivities for *CR* between them. Three groupings of Manning's n values were used in Figure 3-7. Group 1 consisted of an in-channel Manning's n value of 0.01 and out-of-channel Manning's n value of 0.05. Group 2 consisted of an in-channel Manning's n value of 0.05 and out-of-channel Manning's n value of 0.1. Group 3 consisted of an in-channel Manning's n value of 0.1 and out-of-channel Manning's n value of 0.2. Groups 1 and 3 represent the lower and upper bounds, respectively, of typically used Manning's n values, and group 2 contains the values consistent with average in-channel, and out-of-channel values (Chow, 1959). Each watershed was modeled with TR-20 for 6 storm depths: Figure 3-7(a) illustrates the results within a steep-sloped watershed, and Figure 3-7(b) illustrates the results within a flat-sloped watershed.

An analysis of the results in Figure 3-7(a) and Figure 3-7(b) do show some differences in the ranges of *CR* values between the Manning's n value groupings within a storm depth. The range of *CR* values describes the difference between minimum and maximum *CR* values for each Manning's n grouping. One method to measure the sensitivity of the routing process to cross-section definition is to compare the range of *CR* values. The differences between groups 1, 2, and 3 are relatively small for this study, with a maximum difference of 8 percent in Figure 3-7(a). In general though, grouping 2 exhibits the greatest sensitivity across the modeled storm depths. The Manning's n values from grouping 2, an in-channel value of 0.05 and out-of-channel value of 0.1, will be used throughout this study based on the results of the above experiment.

3.4 Preliminary Regression Analysis on CR

Figure 3-8 shows how *CR* varies with the routing coefficient for 11 watersheds and storm depths ranging from 3 to 8 inches. Each point on the graph represents the *CR* value for each cross-section for each storm depth. The 11 watersheds consist of 4 flat, 4 moderate, and 3 steep sloped. The data in Figure 3-8 show considerable scatter. Clearly *CR* and the routing coefficient are negatively correlated, but the figure indicates that for each *C* value ranging between 0.05 and 0.3 a wide range of *CR* values can be calculated. A routing coefficient of 0.20 can be used as an example of this. *CR* ranges from approximately 0.07 to 0.32 at a routing coefficient value of 0.20. The implication of this observation is that additional information is required to estimate *CR* accurately.

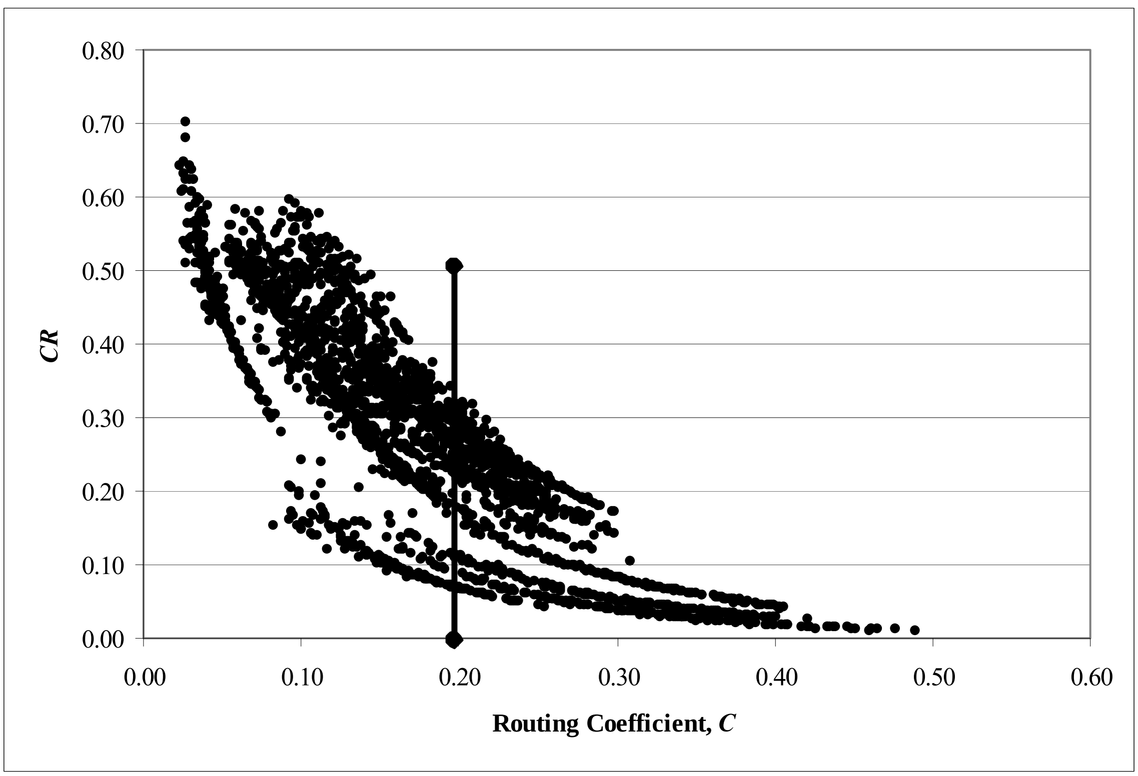


Figure 3-8: Relationship between *CR* and the TR-20 routing coefficient for initial 11 watersheds

Several parameters were considered to use in conjunction with the routing coefficient to better predict *CR*. These parameters included reach length, watershed slope, and 24-hr precipitation. The reach length, slope, precipitation parameters, and reach routing coefficient were identified as predictors for *CR*.

The reach length and channel slope parameters are characteristics of the watershed and can be easily obtained by processing the DEM data. Precipitation is a parameter controlled by the engineer. These three parameters are fixed for each watershed and independent of the cross-section location. The routing coefficient is additionally a function of the cross-section location and needs to be calculated, as described earlier, in order to be used as a predictor variable in the regression equation. There is a unique *C* value for each cross-section processed.

The power model used initially to predict *CR* is represented by Equation (3-14).

$$CR = \Delta Q / Qin = aP^{b} L^{c} C^{d} S^{e} \qquad (3\text{-}14)$$

P is the 24-hour precipitation event (in), *L* is the reach length (ft), *C* is the routing coefficient, and *S* is the routing reach slope (ft/ft).

NUMERICAL OPTIMIZATION (McCuen, 1991) was used to calibrate Equation (3-14). After 3 serial optimizations the change in the coefficient and exponents was minimal and the final values are shown in Table 3-2.

Table 3-2: Regression model coefficient and exponent results

Coefficient/Exponent	Value
a	0.00722
b	0.132
c	0.284
d	-0.869
e	0.166

The coefficient/exponents from Table 3-2 lead to Equation (3-15).

$$CR = \Delta Q / Qin = 0.00722 P^{0.132} L^{0.284} C^{-0.869} S^{0.166} \qquad (3\text{-}15)$$

Based on the exponents the parameters can be placed in order of influence or importance. As expected the routing coefficient has the most sensitivity in the regression since it has the largest exponent value. The length of the routing reach is next, followed by the slope and finally the precipitation. Both the slope and precipitation are similar in terms of sensitivity based on their exponents.

The goodness-of-fit statistics shown in Table 3-3 can be used to judge the quality of the regression model shown in Equation (3-15). Se/Sy is the standard error of the regression relative to the standard deviation of the quantity being modeled. In this case, Se/Sy is approximately 37 percent indicating that the regression model is an improvement over using the variation in the criterion variable itself. The explained variance, or R^2, statistic is a measure of how well the regression model explains the variance. It is valued between 0 and 1 with a 1 meaning the regression model accounts for 100 percent of the variance. The value of 0.8638 from Equation (3-15) means that approximately 86 percent of the variance is explained by the model. This R^2 value is acceptable for the goals of this study.

Table 3-3: Goodness-of-fit statistics from regression Equation (3-15)

0.0038	BIAS
0.0581	STANDARD ERROR OF ESTIMATE (Se)
0.1572	STANDARD DEVIATION OF Y (Sy)
0.3694	Se/Sy
0.9294	CORRELATION COEFFICIENT (R)
0.8638	EXPLAINED VARIANCE (R**2)

To analyze the quality of the regression model graphically Figure 3-9 shows the predicted values vs. observed values of *CR* for the 8-inch storm depth based on equation (3-15). Figure A-1 of Appendix A shows the graph of predicted *CR* vs. observed *CR* for all the data based on regression equation (3-15).

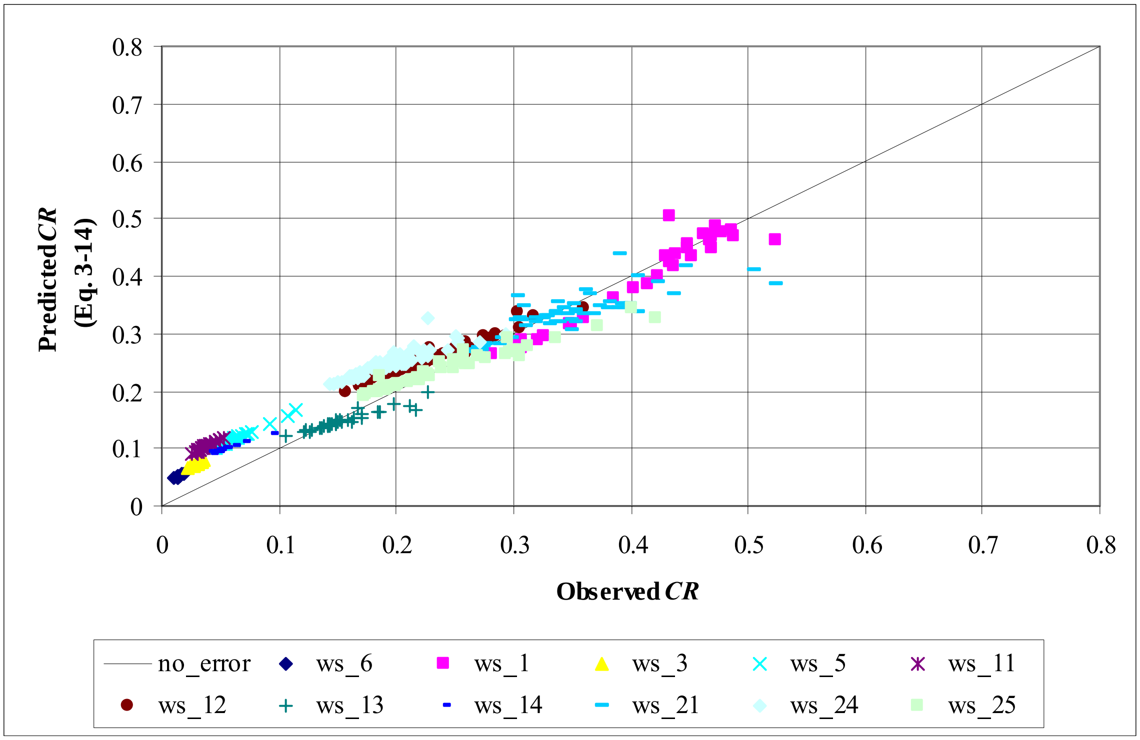


Figure 3-9: Predicted vs. Actual CR for 8-inch storm depth based on regression model Equation (3-15)

The examination of the predicted values vs. actual values to determine the quality of the regression model should include the distribution of points around the line designating a perfect match (no error), identifying positive or negative trends, and identifying any local biases. Figure 3-9 contains both inconsistencies in the distribution of points around the perfect match line and areas of local biases. As *CR* increases, the amount of spread in the data increases identifying a trend in the variability of residuals within the regression. Watershed 13 shows a degree of inconsistency (based on Figure A-1 in Appendix A). There are groupings of points both above and below the "perfect match" line. An examination of the data shows that the majority of over-predicted values are associated with the 7-inch storm depth. The remainder of data are either under-predicting or slightly over-predicting, but in a consistent pattern as *CR* increases. The data points at the smaller *CR* values can be identified as belonging to several watersheds and an area of local bias. These watersheds include 3, 5, 6, 11, and 14. Table 3-4 shows the watershed characteristics for the 11 watersheds used for the preliminary regression analysis and highlights the above 5 watersheds.

Table 3-4: Watershed characteristics for 11 watersheds used in preliminary analysis

Watershed	Area (mi^2)	Number of Cross-Sections	Reach Length (ft)	Channel Slope (ft/mile)	Land Slope (ft/ft)	Basin Relief (ft)	Percent Urban	Percent Impervious	Percent Forest Cover
1	3.5	33	7171	1.9	0.002	5.9	0.7	0.3	85.7
3	3.9	17	2626	6.3	0.008	23.5	1.8	0.5	63.4
5	3.8	24	3292	5.8	0.008	19.8	2.0	0.6	40.9
6	3.7	12	1391	9.4	0.010	28.2	0.5	0.2	50.2
11	3.6	29	3547	38.5	0.059	109.6	70.2	34.8	9.7
12	3.7	63	7303	40.1	0.048	95.3	31.2	8.4	39.0
13	3.5	32	3781	37.5	0.035	67.7	52.7	24.0	31.7
14	3.6	25	3078	44.1	0.055	100.3	76.9	34.6	12.1
21	3.7	63	9758	91.1	0.123	247.3	7.4	4.4	37.8
24	3.5	62	8824	217.1	0.178	529.2	4.9	1.4	81.3
25	3.8	55	6847	191.6	0.122	420.1	29.8	8.0	44.5

With the exception of reach length, there does not appear to be any obvious characteristic to account for the local biases. The reach length is the primary attribute that may imply a relationship because these are the five shortest reaches, but the next shortest reach (watershed 13) is of comparable length and exhibits different residual patterns.

Watersheds 1, 12, and 13 have similar slope values as the five highlighted watersheds but do not exhibit the same residual patterns. Watersheds 11 and 14 have larger percent urban and percent impervious values, and exhibit the same residual patterns as the five highlighted watersheds. This means that the percent urban and percent impervious characteristics were not factors contributing to these local biases.

In general, the overall results from the regression support the use of predicted *CR* to analyze the sensitivity of the reach routing process to the cross-section location. The regression equation developed shows promise for providing information to be used in the planning process. Chapter 4 will illustrate the use of the regression equation for planning purposes based on a larger dataset than used in this preliminary analysis.

The primary motivation for this study is to provide guidance on developing routing reach cross-section characteristics to engineers, planners, and other professionals that use GIS to perform hydrologic rainfall-runoff modeling. Both the enumeration method and regression method provide a means of doing this. The enumeration method provides a direct means of doing this through producing TR-20 results for each possible cross-section along the routing reach. The regression method can be used to provide an indication of how the reach routing within a watershed may be sensitive to the cross-section location. The results and discussions presented in Chapter 4 will examine the relationships between *CR*, peak discharge, and the *%d* and ΔCR sensitivity factors in greater detail.

The initial 11 watersheds used in the analysis above are a portion of the watersheds presented in Chapter 4. This preliminary analysis was used as a basis for further analysis presented below where 30 watersheds make up the study group. Chapter 4 will focus on defining the sensitivity of peak discharge for a watershed and exploring threshold values for determining if the sensitivity within a watershed should be considered when locating a cross-section. Watershed rankings based on the *%d* sensitivity factor will also be explored as well as a comparison of sensitivity factors across the two methods. Finally, a case study will be performed illustrating the synthesis of results from Chapter 3 and 4 into a useful predictive tool for estimating reach routing sensitivity.

4 Results and Discussions

Chapter 3 outlined the methods and procedures used to examine the sensitivity of peak discharge from the TR-20 model based on the selection of the cross-section location along the routing reach. In order to fully investigate this sensitivity and identify relationships that may exist between watershed characteristics and reach routing sensitivity, additional data are required beyond the 11 watersheds used in Chapter 3. Thirty watersheds were chosen throughout Maryland to be included in this study. These watersheds all have areas between 3 and 5 square miles.

4.1 Data Description

Figure 4-1 contains a map demonstrating the locations of the 30 watersheds used for the study.

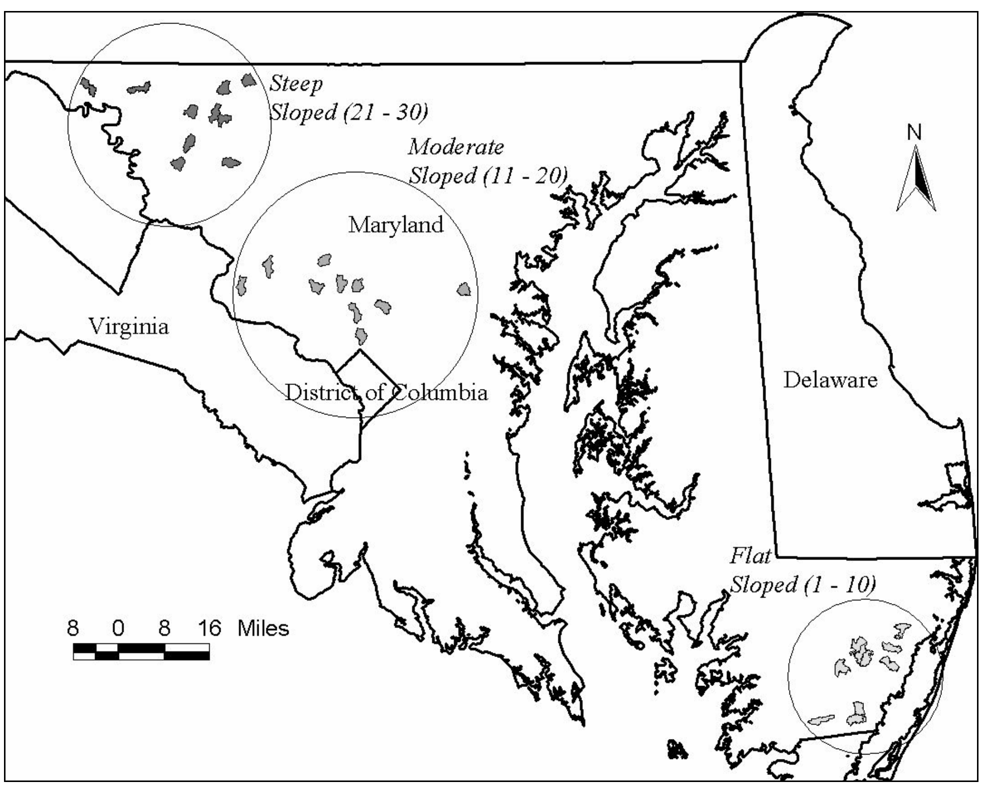


Figure 4-1: Locations of 30 watersheds grouped by topographic regions

Each watershed has been assigned a unique watershed identifier between 1 and 30. The watersheds are grouped by topographic region. The watersheds assigned to the "flat sloped" region are located on the Maryland's eastern shore and assigned watershed identifiers 1 - 10. These watersheds have the flattest topographic profiles with basin reliefs ranging from 5 to 30 feet. The watersheds assigned to the "moderate sloped" region are located in central Maryland between the District of Columbia and Baltimore and assigned watershed identifiers 11 - 20. These watersheds have basin reliefs ranging from 65 to 180 feet. The watersheds assigned to the "steep sloped" region are located in the north central portion of Maryland and assigned watershed identifiers 21 - 30. These watersheds have basin reliefs ranging from 140 to 660 feet. Watershed 22 is included in the "steep sloped" region based on geographic location. The basin relief of 140.5 is more appropriate for the "moderate" region and will be considered as such when identifying any patterns of interest.

Figure 4-2, Figure 4-3, and Figure 4-4 provide a more detailed view of each watershed grouping. The shaded areas represent the watersheds and are labeled according to their unique identifiers. The counties are labeled as well for reference.

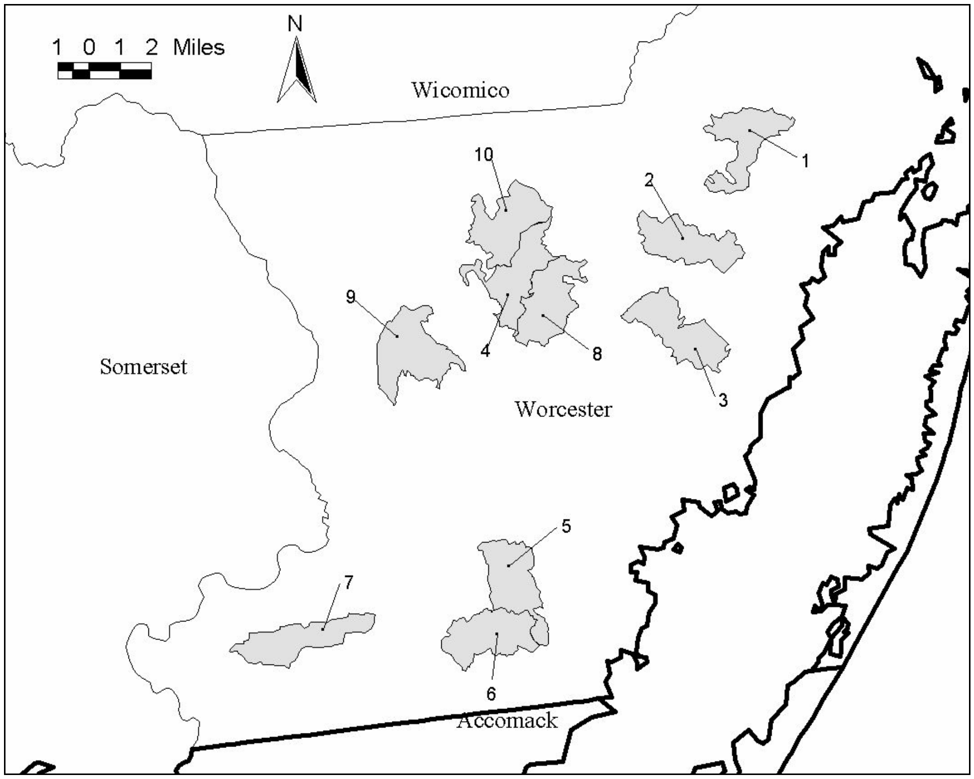


Figure 4-2: Watersheds 1 - 10 assigned to "flat" grouping

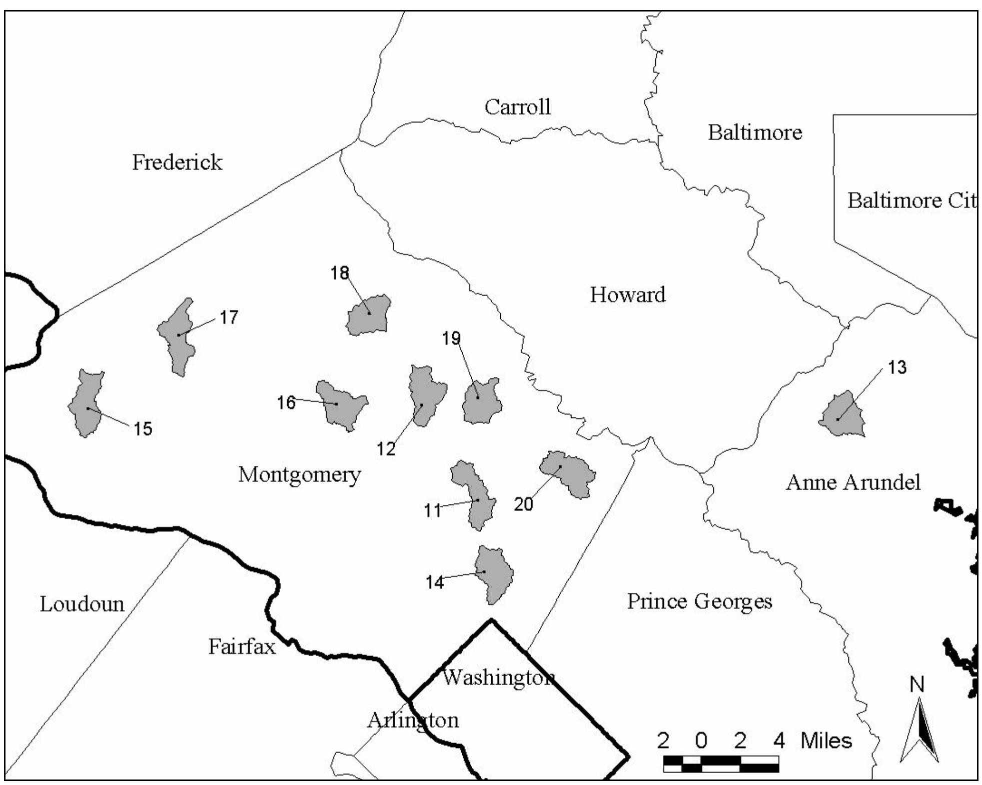


Figure 4-3: Watersheds 11 - 20 assigned to "moderate" grouping

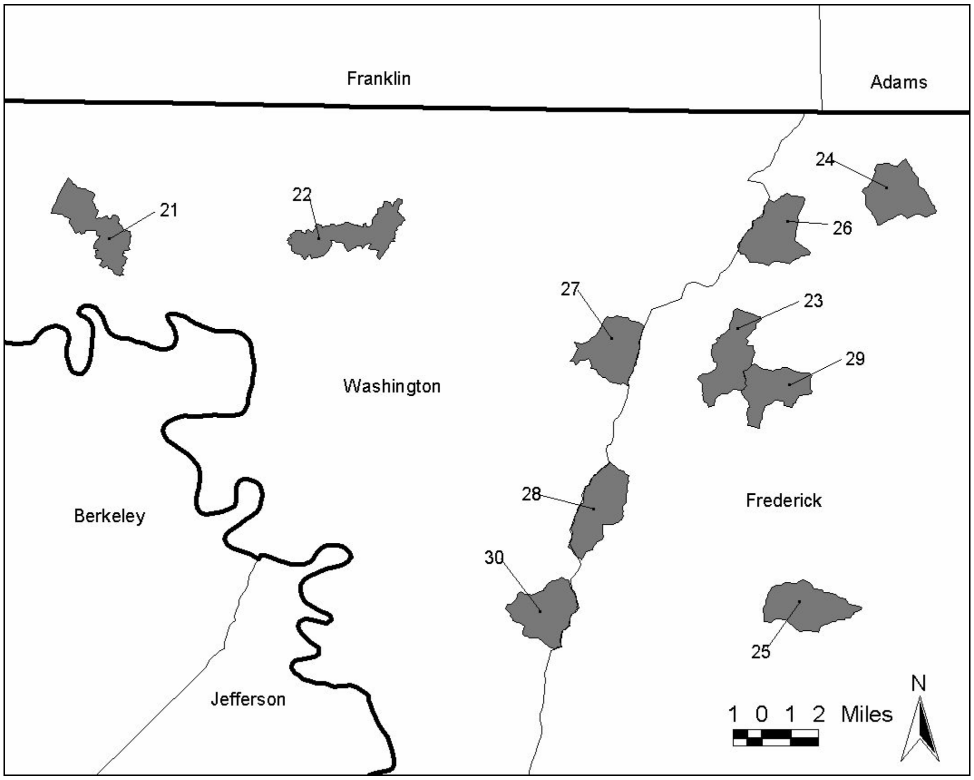


Figure 4-4: Watersheds 21 - 30 assigned to "steep" grouping

Table 4-1 presents the characteristics for the 30 watersheds used in this study. The watershed identifier is a sequential number assigned arbitrarily by grouping. The characteristics for each watershed are derived using a GIS and analyzing the DEM and land use/land cover datasets. Channel slope, land slope, and basin relief are related to the watershed groupings (flat sloped, moderate sloped, and steep sloped). Area, reach length, percent urban, percent impervious, and percent forest cover are all independent of the watershed groupings, although the watersheds that make up the moderate sloped grouping have generally less percent forest cover, greater percent urban, and greater percent impervious due to geographic location. The watershed characteristics can be used to identify possible patterns in the sensitivity of peak discharge to cross-section location.

Table 4-1: Watershed characteristics

Watershed	Area (mi2)	Number of Cross-Sections	Reach Length (ft)	Channel Slope (ft/mile)	Land Slope (ft/ft)	Basin Relief (ft)	Percent Urban	Percent Impervious	Percent Forest Cover
1	3.5	33	7171	1.9	0.002	5.9	0.7	0.3	85.7
2	3.5	28	4261	7.9	0.007	23.3	0.0	4.7	56.9
3	3.9	17	2626	6.3	0.008	23.5	1.8	0.5	63.4
4	3.7	24	5461	4.2	0.006	16.5	1.4	0.6	41.2
5	3.8	24	3292	5.8	0.008	19.8	2.0	0.6	40.9
6	3.7	12	1391	9.4	0.010	28.2	0.5	0.2	50.2
7	3.7	53	9238	4.6	0.004	9.2	3.0	3.1	51.7
8	3.7	28	6003	5.8	0.009	16.6	0.2	0.2	27.4
9	4.5	32	5857	1.4	0.003	6.1	0.0	0.0	86.1
10	3.9	14	2851	3.7	0.004	9.2	0.5	0.1	69.5
11	3.6	29	3547	38.5	0.059	109.6	70.2	34.8	9.7
12	3.7	63	7303	40.1	0.048	95.3	31.2	8.4	39.0
13	3.5	32	3781	37.5	0.035	67.7	52.7	24.0	31.7
14	3.6	25	3078	44.1	0.055	100.3	76.9	34.6	12.1
15	3.7	21	2581	55.4	0.037	93.0	8.3	3.3	21.2
16	3.5	58	7334	56.9	0.055	126.0	70.6	39.6	8.8
17	3.8	83	10369	61.0	0.074	178.0	4.1	1.2	42.0
18	3.3	12	1654	61.4	0.061	126.3	10.3	2.6	27.6
19	3.3	29	3751	58.0	0.059	144.6	40.0	18.8	26.6
20	3.8	9	1661	61.8	0.071	129.4	52.2	16.2	19.1
21	3.7	63	9758	91.1	0.123	247.3	7.4	4.4	37.8
22	3.7	7	1340	51.1	0.069	140.5	20.4	9.1	9.3
23	3.6	26	4047	165.9	0.135	522.4	3.8	0.9	83.9
24	3.5	62	8824	217.1	0.178	529.2	4.9	1.4	81.3
25	3.8	55	6847	191.6	0.122	420.1	29.8	8.0	44.5
26	3.8	66	9003	208.7	0.132	482.1	1.0	0.7	86.5
27	3.6	6	1840	227.3	0.157	502.6	10.1	3.9	80.9
28	3.8	8	974	221.1	0.136	354.6	10.0	2.7	64.2
29	3.0	24	3164	176.8	0.145	655.4	1.6	0.4	98.0
30	3.6	34	4723	184.0	0.139	394.8	4.8	1.2	45.7
31	3.5	31	6265	9.7	0.009	20.7	2.1	0.9	74.2
32	3.8	44	6389	47.9	0.056	123.4	79.8	34.8	6.8
33	3.7	31	3661	271.5	0.148	573.9	13.7	3.4	58.1

4.2 Analyses Methodologies

As discussed in Chapter 3, two methods are presented to measure the sensitivity of peak discharge from each watershed to the cross-section location. The first method defined as the enumeration method consists of processing all cross-sections for each watershed through the TR-20 model. The peak discharge results from these runs can be compiled and compared. The second method defined as the regression method consists of utilizing a power model regression based on certain watershed and cross-section characteristics to assess the change in routing results. For both the enumeration and regression methods, similar analyses are performed to identify the sensitivity within a watershed to the cross-section location and related patterns. A single factor for the watershed can be calculated and examined based on a sensitivity threshold for that factor. The sensitivity thresholds will be further addressed within the discussion of the sensitivity analyses methods. Various correlation analyses are performed to determine the relationships between the two methods and between each method and the watershed characteristics.

4.3 Enumeration Method Results and Discussion

The enumeration method provides actual output data from the TR-20 model. These results must be summarized in some way in order to quantify the sensitivity. The first step in quantifying these results is to graphically examine them. For comparison purposes it would be beneficial to examine results from all the watersheds on a single graph. In order to do this a single graph can be created for each storm depth. It would be difficult to interpret a graph containing all the data, but with the right set of statistics the graphs can be made meaningful. The minimum, average, and maximum peak discharges for each watershed can be graphed. To determine how the data may be grouped or spread around the average, one standard deviation from average is also shown. Figure 4-5 and Figure 4-6 show plots of the aforementioned statistics for each watershed for the 3-inch and 8-inch storm depths respectively. Appendix B contains the plots of the remaining 4 – 7-inch storm depths.

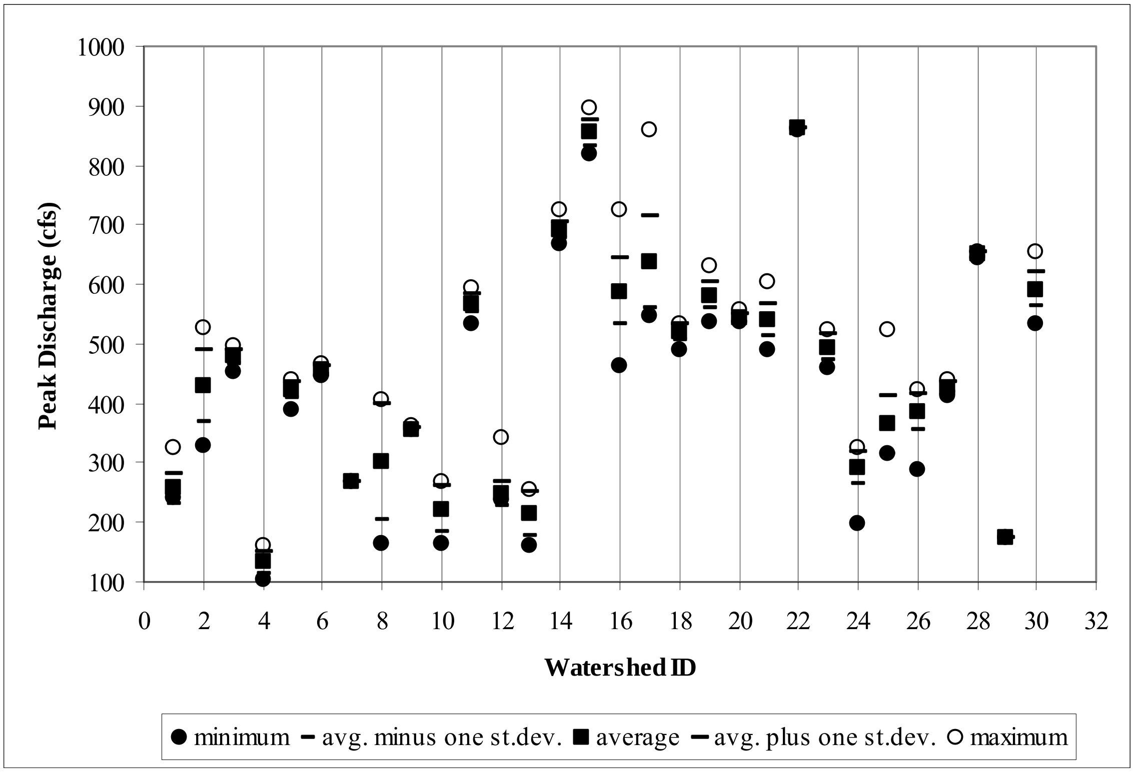


Figure 4-5: 3-inch storm depth peak discharge statistics

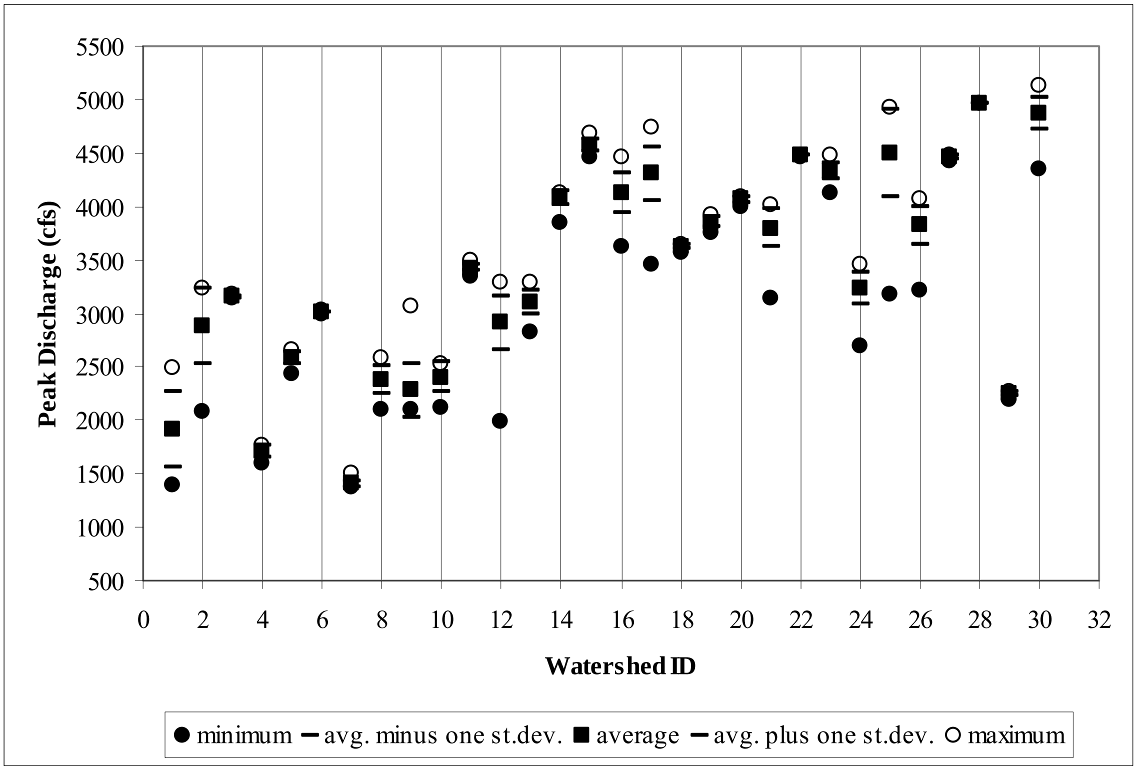


Figure 4-6: 8-inch storm depth peak discharge statistics

The difference between the average, plus or minus one standard deviation, and the maximum and minimum values respectively represent the variability in the data. The values of the average, plus or minus one standard deviation will be referred to as the above and below average data spread values respectively for the remainder of the document. The larger the difference the fewer the number of data points near the maximum or minimum values. This may indicate that the maximum or minimum value is anomalous or unlikely to occur. It should also be noted that the distribution of data for a watershed across storm depths may vary.

Watershed 17 is a good example of this. For the 3-inch storm depth (Figure 4-5) the minimum peak discharge is 548 cfs, the maximum peak discharge is 859 cfs, and the average peak discharge is 637 cfs. The above and below average data spread values are 715 cfs and 559 cfs respectively. The below average data spread value is 2 percent greater than the minimum peak discharge value. The above average data spread value is 17 percent less than the maximum peak discharge value. On the other hand, for the 8-inch storm depth (Figure 4-6) the minimum peak discharge is 3460 cfs, the maximum peak discharge is 4737 cfs, and the average peak discharge is 4307 cfs. The above and below average data spread values are 4556 cfs and 4057 cfs respectively. The below average data spread value is 15 percent greater than the minimum peak discharge. The above average data spread value is 4 percent less than the maximum peak discharge value. For the 3-inch storm depth (Figure 4-5) data there is a large gap between the above average data spread value and the maximum peak discharge. For the 8-inch storm depth (Figure 4-6) there is a large gap between the below average data spread value and minimum peak discharge. This was shown by the above percentages. This information is useful when examining the percent difference between the minimum and maximum peak discharges to determine the sensitivity of the watershed.

4.4 Enumeration Method Sensitivity Analysis

As a precursor to further examining the variability of data using Figure 4-5 and Figure 4-6, a method is needed to identify watersheds where the differences between the minimum and maximum peak discharges may be considered large and indicate a degree of sensitivity requiring additional exploration. One method to do this is to examine the percent difference between minimum and maximum peak discharges within the watershed. Equation (4-1) can be used to calculate the percent difference between the minimum and maximum peak discharges and is referred to as *%d*:

$$\%d = \frac{Q_{\max} - Q_{\min}}{Q_{\max}} * 100 \qquad (4\text{-}1)$$

Figure 4-7, shows *%d* plotted by watershed for the 8-inch storm depth. Appendix C contains the plots of *%d* by watershed for the remaining 3 – 7-inch storm depths. The value for *%d* means that there are at least two cross-sections along the routing reach that return peak discharges that differ by that percentage. The two horizontal lines on each figure represent a 20 percent and 30 percent difference between minimum and maximum peak discharges. Although decidedly arbitrary, this study used the 20 and 30 percent values as sensitivity thresholds because I felt that a difference in peak discharges greater than these percentages would be cause for concern, and hence additional examination. It should be noted that a 20 percent or 30 percent difference at the 8-inch storm depth would be a much larger cause for concern than at the 3-inch storm depth due to the scale of peak discharge values.

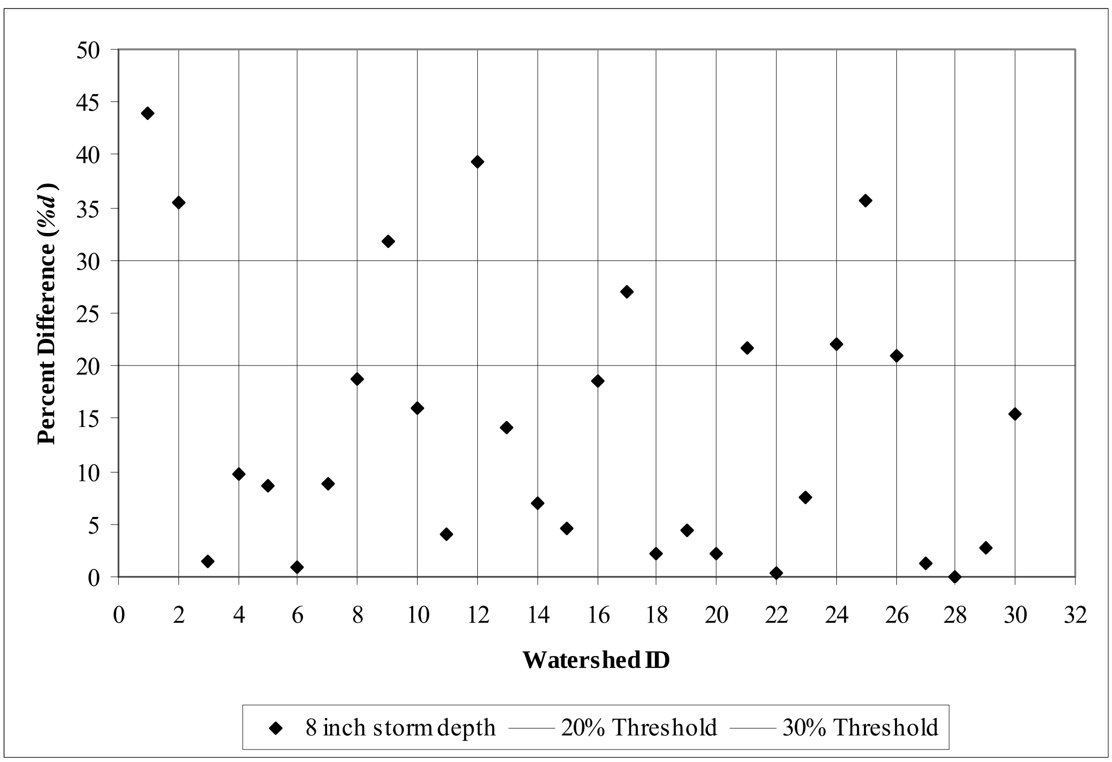


Figure 4-7: Sensitivity comparison using *%d* by watershed for 8-inch storm depth

Table 4-2 provides a list of watersheds by storm depth that exceed the 20 and 30 percent sensitivity threshold values.

Table 4-2: Watersheds exceeding sensitivity threshold values based on *%d* by storm depth

Storm Depth	Watersheds Exceeding 20% Threshold	Percent of all Watersheds	Watersheds Exceeding 30% Threshold	Percent of all Watersheds
3 in.	1, 12, 26, 16, 17, 4, 2, 13, 10, 24, 25, 8	40%	26, 16, 17, 4, 2, 13, 10, 24, 25, 8	33%
4 in.	21, 13, 26, 24, 12, 17, 16, 1, 4, 10, 2, 25, 8	43%	26, 24, 12, 17, 16, 1, 4, 10, 2, 25, 8	37%
5 in.	9, 30, 21, 4, 8, 10, 26, 17, 25, 2, 12, 1, 16, 24	47%	10, 26, 17, 25, 2, 12, 1, 16	30%
6 in.	21, 10, 16, 8, 24, 26, 30, 9, 17, 25, 2, 12, 1	43%	17, 25, 2, 12, 1	17%
7 in.	30, 8, 26, 21, 24, 9, 17, 25, 2, 12, 1	37%	17, 25, 2, 12, 1	17%
8 in.	26, 21, 24, 17, 9, 2, 25, 12, 1	30%	9, 2, 25, 12, 1	17%

The largest storm depth of 8 inches has the fewest watersheds identified with a large degree of sensitivity at the 20 percent threshold. This could be attributed to the scale of the discharges. The discharges must have a larger actual difference in value at the 8-inch storm depth to achieve a difference of 20 or 30 percent. Using the 8-inch storm depth as a baseline, those watersheds could be considered the most sensitive to the cross-section location. With the exception of watershed 21 not identified at the 3-inch storm depth and watershed 9 not identified at the 3- and 4-inch storm depths, all watersheds identified as sensitive at the 8-inch storm depth are identified as sensitive for all the storm depths.

These watersheds can be examined more thoroughly by looking at the above and below average data spread values in relation to the maximum and minimum peak discharge values, respectively, as discussed earlier. Table 4-3 can be used to examine the relationship between the above and below average data spread values and the maximum and minimum discharges respectively.

Table 4-3: Watersheds identified for additional examination based on percent differences between the average, plus or minus one standard deviation and maximum and minimum peak discharges respectively

	8-inch storm depth		
Watershed ID	***%d***	**Percent difference between avg. minus one st.dev. and Q_{min}**	**Percent difference between avg. plus one st.dev. and Q_{max}**
1	43.97	9.83	11.67
2	**35.56**	**-0.09**	**21.47**
3	1.54	0.62	0.07
4	9.83	0.17	3.80
5	8.70	0.61	4.22
6	0.96	0.26	0.18
7	8.75	5.61	0.18
8	18.69	2.54	7.23
9	**31.73**	**20.94**	**-3.00**
10	16.01	-0.80	6.82
11	3.98	0.87	1.20
12	**39.36**	**3.74**	**33.81**
13	14.17	2.55	5.51
14	6.90	-0.22	4.56
15	4.56	1.03	1.04
16	18.50	3.35	8.54
17	26.96	3.97	17.26
18	2.22	0.14	1.00
19	4.46	0.69	1.37
20	2.25	-0.17	1.07
21	21.69	1.13	15.29
22	0.31	0.00	0.10
23	7.61	1.66	2.79
24	21.98	2.56	13.83
25	**35.71**	**0.37**	**29.02**
26	21.04	1.81	13.03
27	1.27	0.02	0.20
28	0.00	0.00	0.00
29	2.74	0.03	1.47
30	15.44	2.36	8.52

The watersheds identified as having peak discharges with a high degree of sensitivity to cross-section location based on the 20 percent sensitivity threshold value are highlighted by a light gray. Of those, the watersheds in bold text have at least a 20 percent difference between the above or below average data spread values and the maximum or minimum peak discharges, respectively. A percent difference of greater than 20 percent may indicate the necessity to further examine the spread of data, and if the minimum or maximum value is anomalous.

The watersheds identified at the 8-inch storm depth that require further examination are 2, 9, 12, and 25. Figure 4-8 contains a graph of all the peak discharge data for these watersheds based on the 8-inch storm depth.

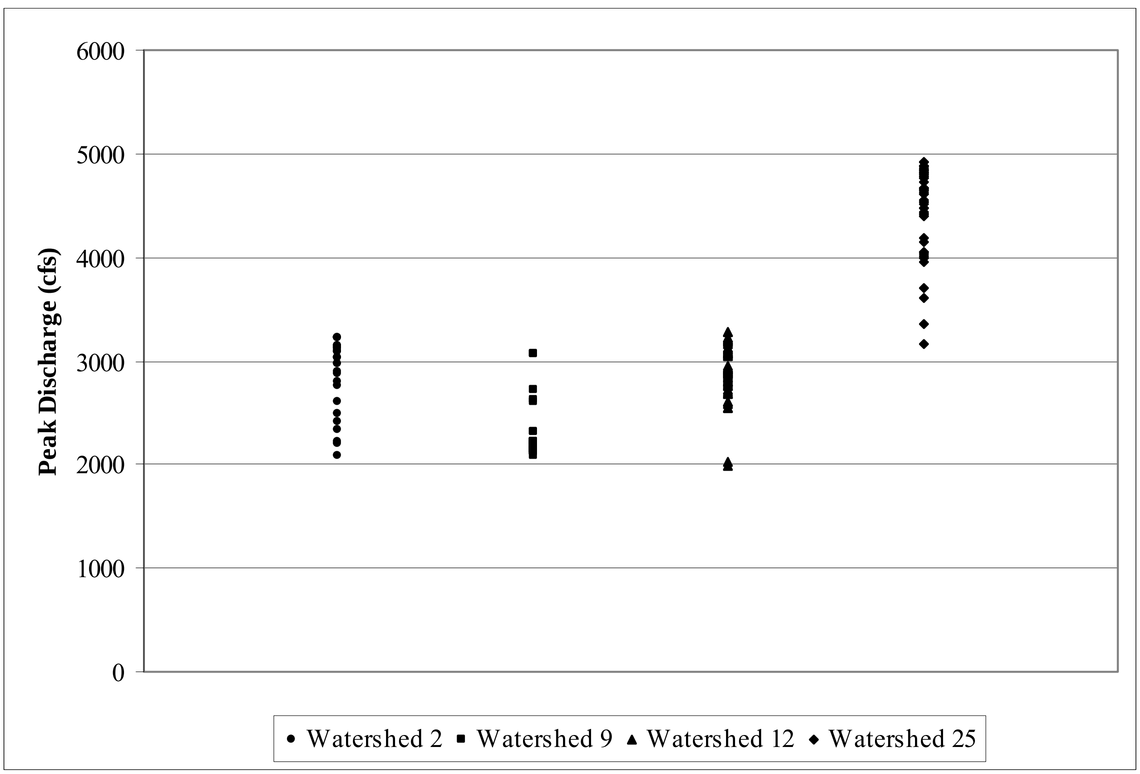


Figure 4-8: Distribution of overall peak discharge values by watershed (2, 9, 12, 25) for additional sensitivity research based on statistics analysis

The 4 watersheds (2, 9, 12, and 25) depicted in Figure 4-8 exhibit behaviors that may be expected based on the above and below average data spread values in comparison to the maximum and minimum peak discharges, respectively. The issue being that although the sensitivity value computed for a watershed is above the threshold for a moderate or high degree of sensitivity, the distribution of returned peak discharges is skewed. Watershed 12 has a two peak discharge values at approximately 2000 cfs and the remaining discharge values are between 2500 cfs and 3300 cfs. This difference (24%) would still identify the peak discharge for this watershed as being sensitive to cross-section location based on the 20% sensitivity threshold, but not the 30% sensitivity threshold. The difference in *%d* can be attributed to 2 out of 62 cross-sections.

4.5 Enumeration Method Watershed Rankings and Relationship to Watershed Characteristics

Table 4-4 includes watersheds ranked by *%d* for each storm depth. The ranking values are based on a scale of 1 to 30 where a 1 corresponds to the least sensitive watershed (smallest *%d* value) and a 30 corresponds to the most sensitive watershed (largest *%d* value). The column titled "Watershed ID" contains a list of the watershed identifiers in ascending order. The remaining six columns contain the ranked values based on *%d* and storm depth. For example, the first row of data is for watershed 1. The following are the rankings by *%d* of watershed 1 for the 3 – 8 inch storm depths respectively: 19, 25, 29, 30, 30, and 30. Based on these rankings watershed 1 is the 12th most sensitive watershed to cross-section location for the 3-inch storm depth (30 – 19 + 1). It follows that watershed 1 is the sixth most sensitive watershed for the 4-inch storm depth, second most sensitive for the 5-inch storm depth, and first most sensitive for the 6-, 7-, and 8-inch storm depths. Figure 4-9 contains a graph of the watershed rankings by

%d and storm depth. The larger the ranking by *%d* (30 being the largest) the more sensitive peak discharge is to cross-section location on the routing reach for the watershed being considered.

Table 4-4: Watershed rankings by *%d* by storm depth

Watershed ID	3-inch Storm Ranking	4-inch Storm Ranking	5-inch Storm Ranking	6-inch Storm Ranking	7-inch Storm Ranking	8-inch Storm Ranking
1	19	25	29	30	30	30
2	25	28	27	28	28	27
3	12	9	8	6	6	5
4	24	26	20	16	16	16
5	14	14	14	14	15	14
6	6	4	4	4	3	3
7	1	2	6	9	12	15
8	30	30	21	21	21	21
9	5	16	17	25	25	26
10	27	27	23	19	18	19
11	13	12	13	10	9	9
12	20	22	28	29	29	29
13	26	19	16	17	17	17
14	9	10	10	12	14	12
15	11	11	11	13	11	11
16	22	24	30	20	19	20
17	23	23	25	26	26	25
18	10	6	7	7	7	6
19	16	13	12	11	10	10
20	7	5	3	3	5	7
21	18	18	19	18	23	23
22	2	1	1	1	2	2
23	15	15	15	15	13	13
24	28	21	22	22	24	24
25	29	29	26	27	27	28
26	21	20	24	23	22	22
27	8	8	5	5	4	4
28	4	3	2	2	1	1
29	3	7	9	8	8	8
30	17	17	18	24	20	18

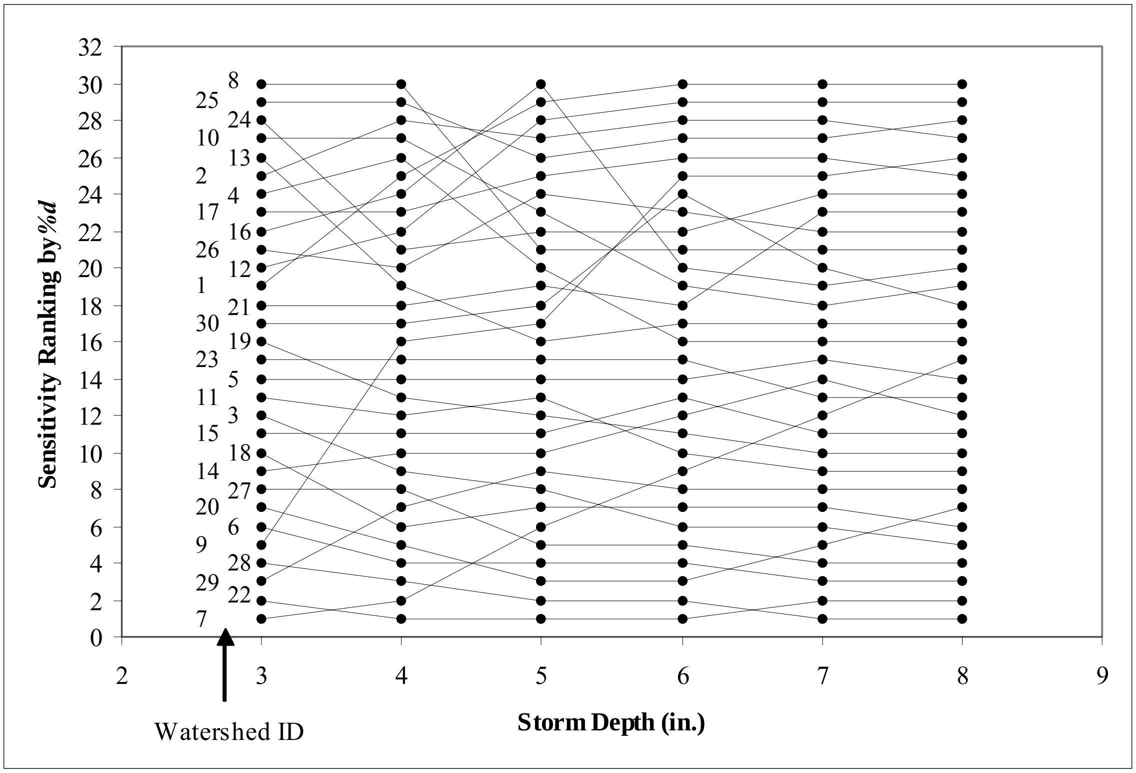


Figure 4-9: *%d* rankings for each watershed by storm depth

An observation that can be made from Figure 4-9 is the variability in sensitivity rankings by *%d* for the higher ranked watersheds between the 3- and 6-inch storm depths. This variability is identified by the crossing patterns between the lines representing individual watersheds in the figure. This type of variability is much less pronounced for the lower ranked watersheds.

Figure 4-9 is useful in determining which watersheds are consistent in *%d* rankings across storm depths and which watersheds are more variable (identified visually). Some examples of watersheds that are fairly consistent across storm depths are watersheds 22, 6, 5, and 23. Some examples of watersheds that are more variable are watersheds 7, 9, 19, 30, and 16. Finally, there are several examples of watersheds that are variable in the smaller storm depths (3 – 6-inch), but less variable (more consistent) at the larger storm depths (7 – 8-inch). These watersheds are 11, 1, 12, 4, 2, 13, and 8. These observations may be generalized by the following three watershed classes:

- Watersheds that have peak discharge sensitivity that varies at small storm depths, but not larger storm depths
- Watersheds that have peak discharge sensitivity that varies across all storm depths
- Watersheds that have peak discharge sensitivity that is consistent across all storm depths

The significance of these observations is that the assumption must not be made that because a watershed was found to be non-sensitive at one storm depth that it is precluded from being sensitive at other storm depths.

A correlation matrix can be used to examine the relationship between *%d* and the watershed characteristics. The correlation matrix is a quantitative analysis for how multiple data arrays relate to one another. The positive and negative signs indicate directionality. A positive correlation indicates that the directional changes of the data arrays are the same. A negative sign indicates that the directional changes of the data arrays are opposite. The magnitude of the correlation value indicates the strength of the correlation.

A correlation matrix between *%d* and the watershed characteristics assists in the assessment of the relationship between watershed characteristics and the sensitivity of peak discharge to cross-section location. The correlation matrix does not determine the sensitivity within a watershed, but rather helps determine which watershed characteristics show the strongest predictive relationships to the sensitivity of peak discharges to the cross-section location along the routing reach. The correlation data from this study are presented in Table 4-5.

Based on the correlation matrix in Table 4-5 it is evident that reach length has the strongest correlation with *%d*. The reach length has a positive correlation value across all storm depths signifying that as the reach length increases the sensitivity of peak discharge to cross-section location along the routing reach increases as well. The remaining parameters (channel slope, land slope, basin relief, percent urban, percent impervious, and percent forest cover) exhibit much weaker correlation values with *%d* than reach length. The reach length correlation values indicate that reach length is the primary watershed characteristic that is related to the sensitivity of peak discharge to the cross-section location along the routing reach.

Table 4-5: Correlation matrix between *%d* by storm depth and watershed characteristics

Correlation Matrix	*%d* 3-inch storm	*%d* 4-inch storm	*%d* 5-inch storm	*%d* 6-inch storm	*%d* 7-inch storm	*%d* 8-inch storm
Reach Length	0.51	0.56	0.69	0.66	0.70	0.68
Channel Slope	-0.06	-0.10	-0.04	-0.09	-0.09	-0.10
Land Slope	-0.09	-0.14	-0.06	-0.11	-0.10	-0.13
Basin Relief	-0.08	-0.10	-0.04	-0.09	-0.09	-0.11
Percent Urban	-0.03	-0.13	-0.07	-0.14	-0.15	-0.14
Percent Impervious	0.00	-0.09	-0.03	-0.13	-0.14	-0.14
Percent Forest Cover	-0.03	0.07	0.16	0.20	0.22	0.24

Scatter plots of these data provide another way to examine relationships between *%d* and the various watershed characteristics. Figure 4-10 - Figure 4-16 are scatter plots of *%d* vs. each of the watershed characteristics for the 8-inch storm depth. Scatter plots depicting *%d* vs. each of the watershed characteristics for all the storm depths can be found in Figure D-1 – Figure D-7 in Appendix D. These scatter plots support the findings contained in Table 4-5. Figure 4-10 demonstrates an overall pattern of increasing reach length values as *%d* increases. There is a degree of scatter within Figure 4-10 (*%d* by reach length), but the overall increasing pattern is evident and is consistent with the positive correlation values. The figures for the remaining watershed characteristics show considerable scatter with no discernable patterns evident. These figures are also consistent with the correlation matrix values and the findings that there is little or no actual relationship between the sensitivity of peak discharge to the cross-section location and channel slope, land slope, basin relief, percent urban, percent impervious, and percent forest cover. The implication here is that for a short reach it may not be as critical to the peak discharge estimate where the representative cross-section is measured, but it is for a longer reach.

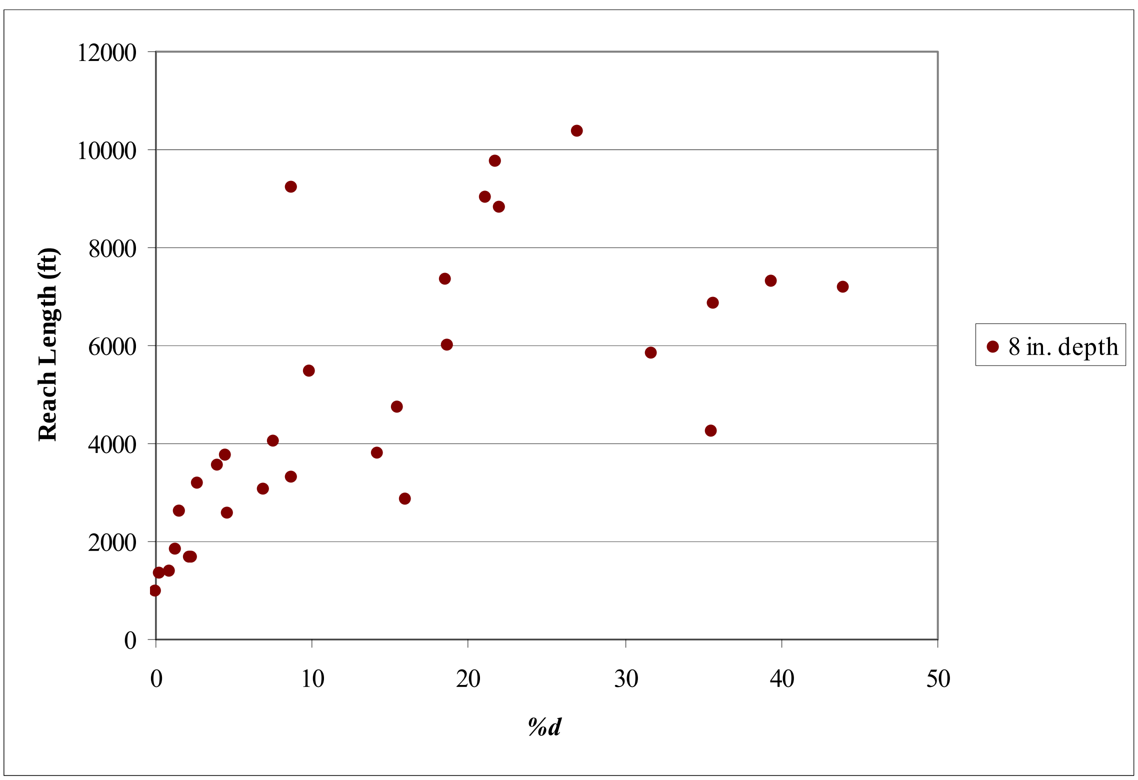


Figure 4-10: Relationship between *%d* and reach length for 8-inch storm depth

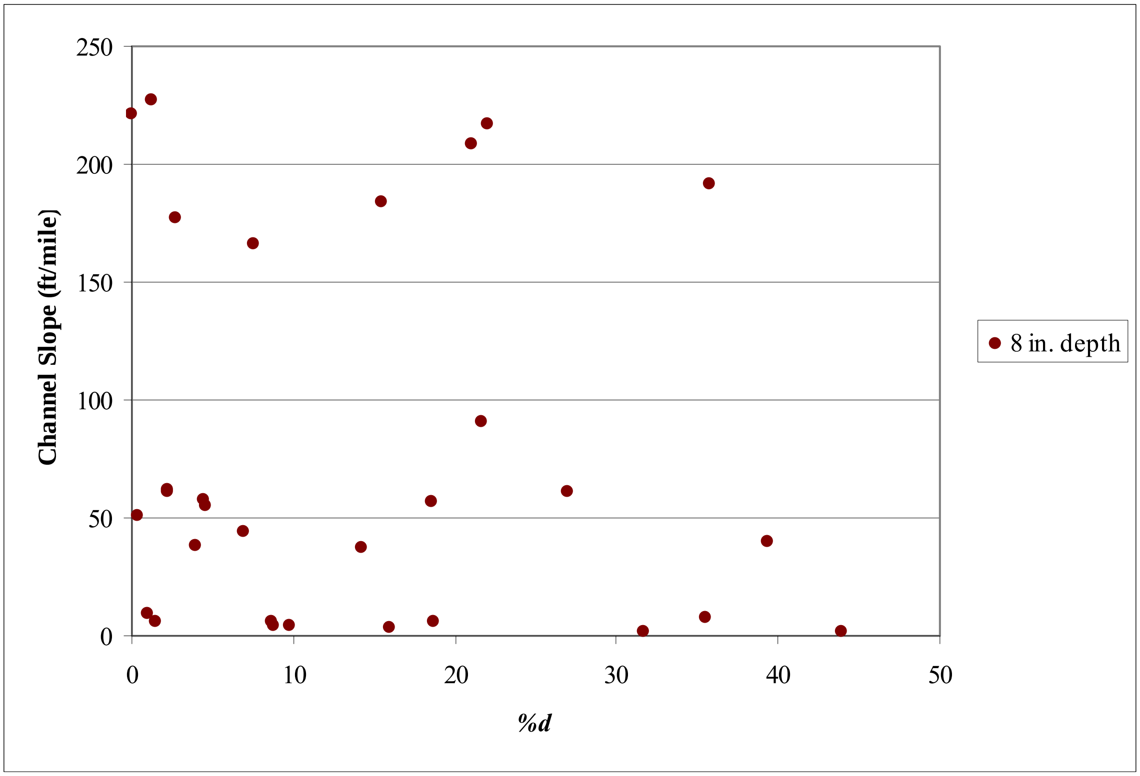


Figure 4-11: Relationship between *%d* and channel slope for 8-inch storm depth

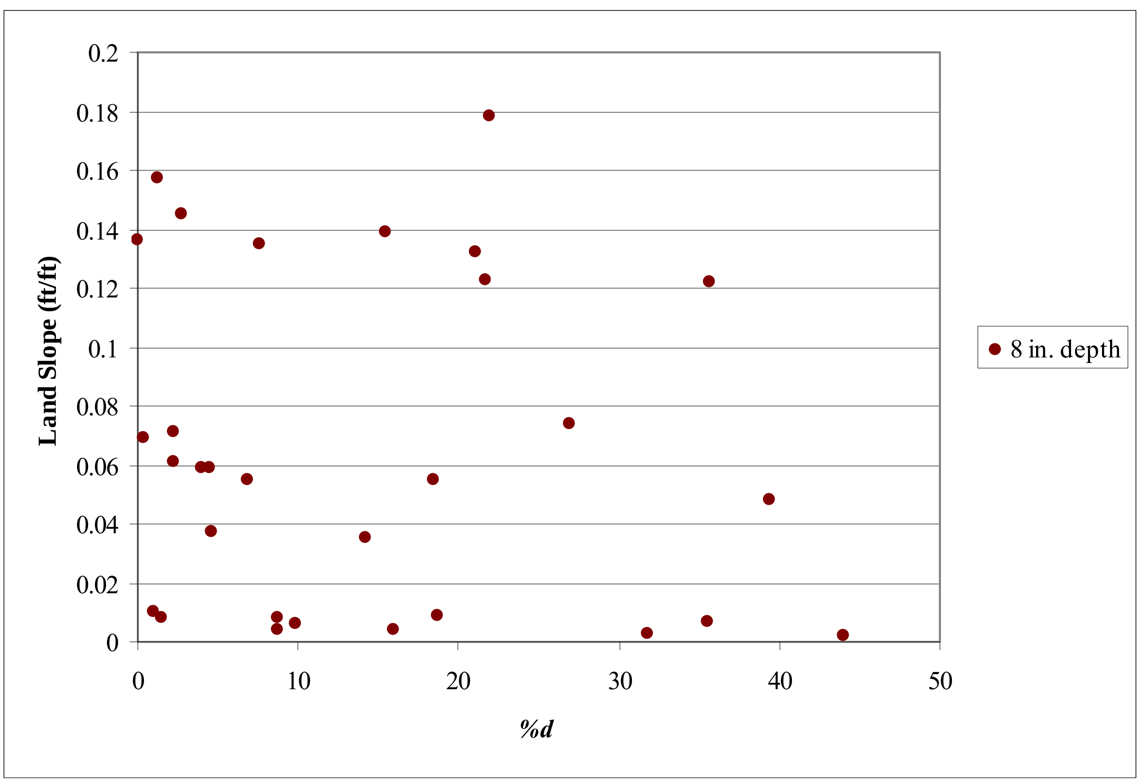


Figure 4-12: Relationship between *%d* and land slope for 8-inch storm depth

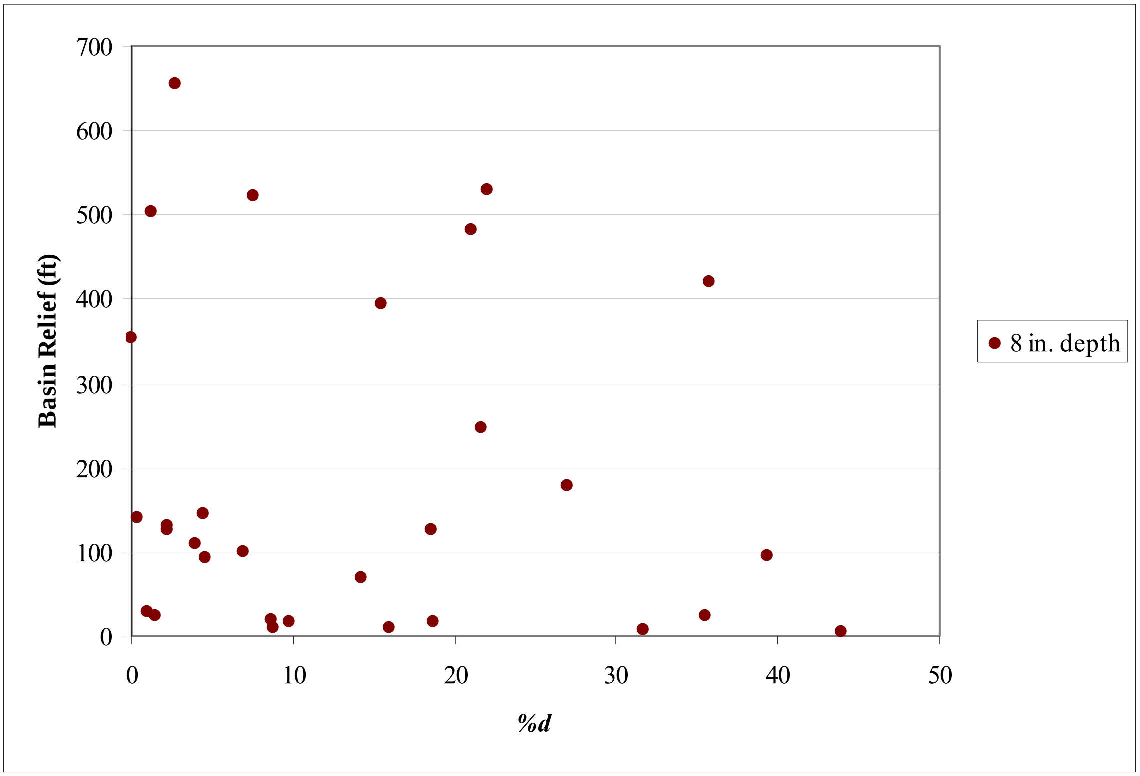


Figure 4-13: Relationship between *%d* and basin relief for 8-inch storm depth

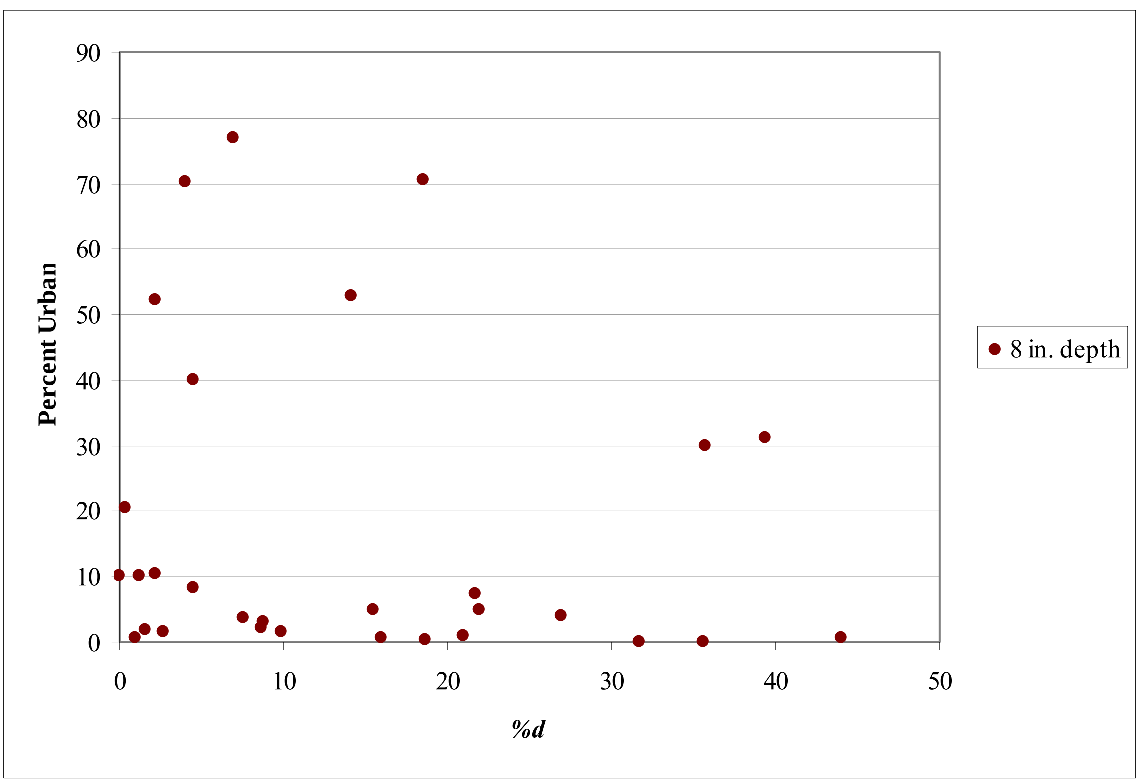


Figure 4-14: Relationship between *%d* and percent urban for 8-inch storm depth

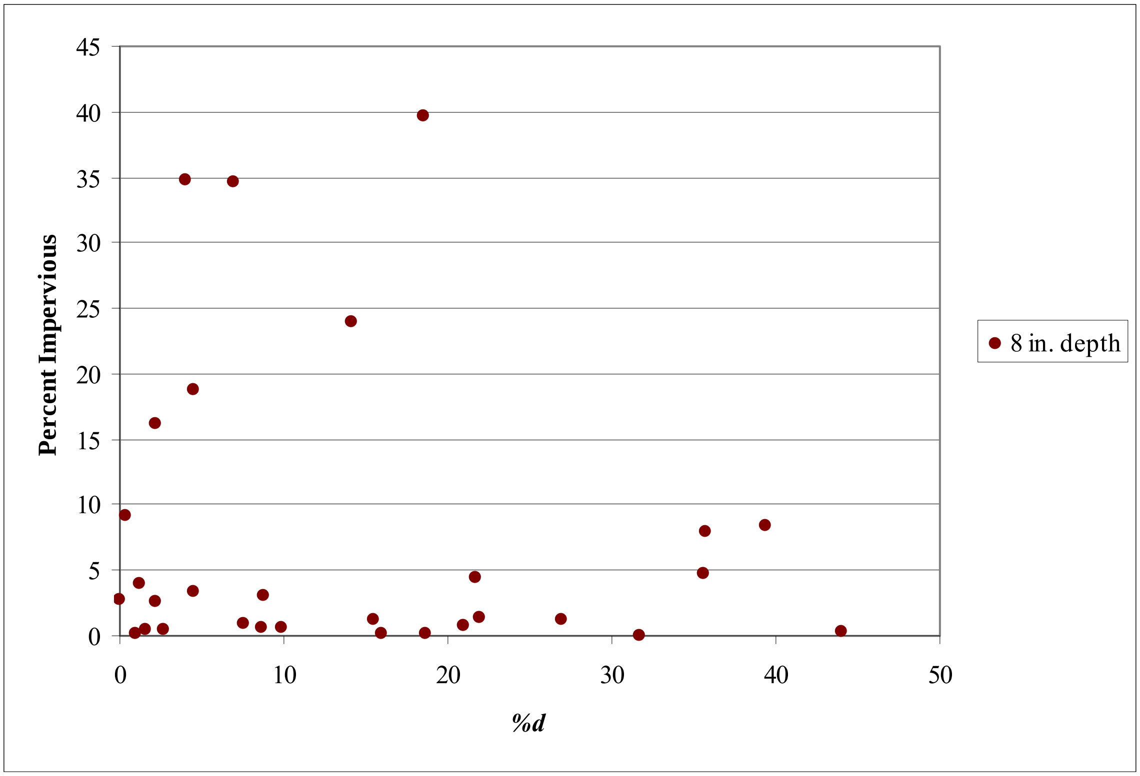


Figure 4-15: Relationship between *%d* and percent impervious for 8-inch storm depth

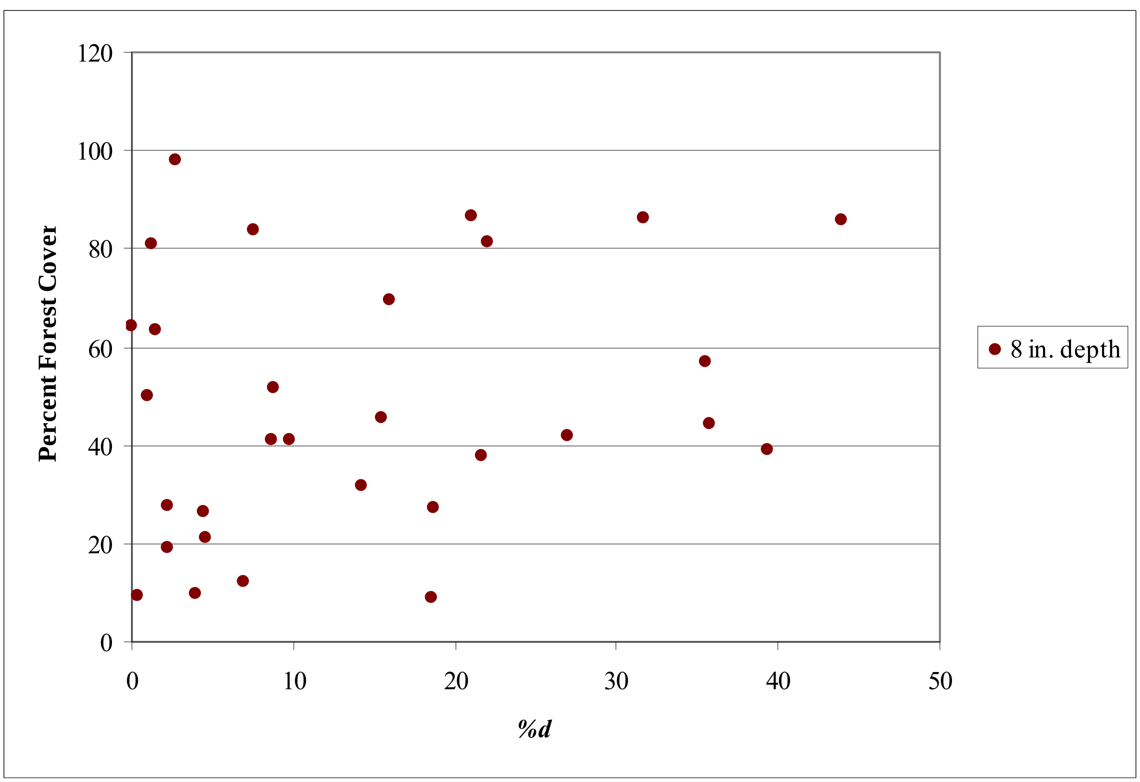


Figure 4-16: Relationship between *%d* and percent forest cover for 8-inch storm depth

4.6 Regression Results and Discussion

A regression model is being used to predict the percent change in routed discharge through the routing reach. The percent change in discharge due to routing through the reach is referred to as *CR* as documented in Equation (3-13). Examining how *CR* varies across cross-sections and relating this to the variation in overall peak discharge is the first step in developing an alternative method for estimating the sensitivity of overall peak discharge from the watershed to the cross-section location along the routing reach. Two issues that need to be examined are: 1) does the change in observed *CR* values predict the same watersheds as being the most sensitive to cross-section location as does *%d*? and 2) does the regression model used to predict *CR* also predict those same watersheds as being the most sensitive to cross-section location? The following sections describe and analysis the results from the regression method.

4.7 Observed CR and ΔCR Analysis

Determining sensitivity in the enumeration method involved examining the percent change between the minimum and maximum overall peak discharges for a watershed by storm depth. Because *CR* is already a percent further normalization of this quantity does not make sense. A meaningful way to examine the sensitivity of *CR* is to use the difference between the minimum and maximum *CR* values (referred to as ΔCR).

Figure 4-17 shows the observed ΔCR for each watershed for the 8-inch storm depth. Appendix E contains the plots for the 3 – 7-inch storm depths. Included are the same sensitivity threshold values used in the enumeration method presentation.

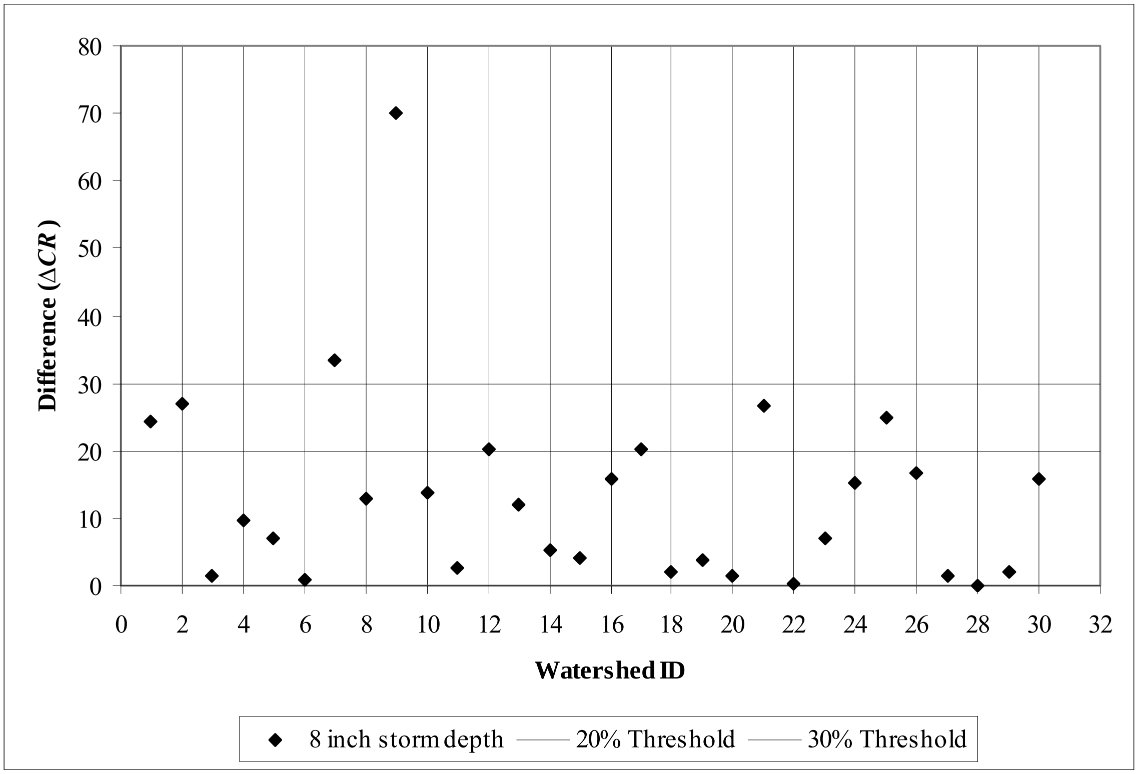


Figure 4-17: Sensitivity comparison using observed ΔCR by watershed for 8-inch storm depth

Table 4-6 contains a list of watersheds, by storm depth, that exceed the 20 percent and 30 percent sensitivity threshold values based on the observed ΔCR values.

Table 4-6: Watersheds exceeding sensitivity threshold values based on observed ΔCR by storm depth

Storm Depth	Watersheds Exceeding 20% Threshold	Percent of all Watersheds	Watersheds Exceeding 30% Threshold	Percent of all Watersheds
3-inch	16, 12, 21, 25, 17, 26, 4, 9, 1, 2, 24, 10, 8	43%	24, 10, 8	10%
4-inch	17, 8, 12, 26, 16, 21, 24, 1, 7, 4, 2, 9, 10	43%	4, 2, 9, 10	13%
5-inch	30, 21, 25, 24, 17, 1, 26, 12, 10, 16, 2, 7, 9	43%	7, 9	7%
6-inch	26, 25, 17, 21, 30, 1, 12, 2, 7, 9	33%	2, 7, 9	10%
7-inch	30, 17, 12, 1, 25, 21, 2, 7, 9	30%	7, 9	7%
8-inch	17, 12, 1, 25, 21, 2, 7, 9	27%	7, 9	7%

In general, the same watersheds are identified as sensitive across each of the storm depths. These watersheds should be considered as having a peak discharge with a high degree of sensitivity to cross-section location along the routing reach. In other words, these watersheds would be of greatest concern to the engineer if they were being used in a hydrologic analysis. A relationship between the ΔCR and *%d* sensitivity factors can also be examined.

A primary observation that is evident in Table 4-6 is the large difference between the number of watersheds that exceed the 20 percent sensitivity threshold and the number of watersheds that exceed the 30 percent sensitivity threshold. There are 20 to 30 percent more watersheds identified at the 20 percent sensitivity threshold than the 30 percent sensitivity threshold as being highly sensitive to the cross-section location. This compares to 5 to 15 percent in Table 4-2 when examining *%d*. The purpose of this comparison is to relate using ΔCR to *%d* as a tool for identifying watersheds with a high degree of peak discharge sensitivity to the cross-section location along the routing reach. This implies that the 30 percent sensitivity threshold may be too great when examining ΔCR values to determine the degree of the watershed sensitivity to cross-section location.

Next, it is important to compare which watersheds are observed to exceed the 20 percent sensitivity threshold value for both the *%d* and ΔCR factors. This comparison will establish a relationship between the *%d* sensitivity factor and the ΔCR sensitivity factor. Table 4-7 provides the comparison between watersheds that exceed the 20 percent sensitivity threshold for the *%d* criterion and observed ΔCR factor.

Table 4-7: Comparison results between watersheds identified as being highly sensitive to cross-section location by *%d* and by observed Δ*CR*

Storm Depth	Watersheds exceeding 20 percent threshold for *%d* and observed Δ*CR*	Watersheds exceeding 20 percent threshold for observed Δ*CR* and not *%d*	Watersheds exceeding 20 percent threshold for *%d* and not observed Δ*CR*
3-inch	1, 2, 4, 8, 10, 12, 16, 17, 24, 25, 26	9, 21	13
4-inch	1, 2, 4, 8, 10, 12, 16, 17, 21, 24, 26	7, 9	13, 25
5-inch	1, 2, 9, 10, 12, 16, 17, 21, 24, 25, 26, 30	7	4, 8
6-inch	1, 2, 9, 12, 17, 21, 25, 26, 30	7	8, 10, 16, 24
7-inch	1, 2, 9, 12, 17, 21, 25, 30	7	8, 24, 26
8-inch	1, 2, 9, 12, 17, 21, 25	7	24, 26

There are 3 watersheds that exceed the 20 percent sensitivity threshold based on Δ*CR* that do not exceed the 20 percent sensitivity threshold based on *%d* compared to eight watersheds that exceed the 20 percent sensitivity threshold based on *%d* and not based on Δ*CR*. Keeping in mind that *%d* defines the actual overall peak discharge sensitivity, I decided to be conservative for identifying watersheds with peak discharge sensitivity based on Δ*CR* and that a small number of watersheds may be identified via Δ*CR* that are not identified by *%d*. It is important on the other hand, that Δ*CR* identify all the watersheds as identified by the 20 percent sensitivity threshold for *%d*. By decreasing the sensitivity threshold for Δ*CR* used to identify watersheds that have peak discharges that are highly sensitive to cross-section location, the watersheds not previously identified would be. A sensitivity threshold value of, for instance, 10 percent would be more appropriate when using observed Δ*CR* to identify the watersheds with highly sensitive peak discharge values to cross-section location.

4.8 Observed ΔCR Relationships to %d and Watershed Characteristics

There are two different correlation analyses that are useful for determining how well observed Δ*CR* relates to *%d* in determining the sensitivity of peak discharge to cross-section location along the routing reach. In the previous section it was shown that a lower sensitivity threshold value was required for observed Δ*CR* than *%d* to capture the same degree of sensitivity to the cross-section location. A correlation matrix, Table 4-8, along with a scatter plot, Figure 4-18, can be used to compare the relationship between Δ*CR* and *%d*. A second correlation matrix relates Δ*CR* to the watershed characteristics in the same manner as was performed for *%d*.

Table 4-8: Correlation values between observed Δ*CR* by storm depth and *%d* by storm depth

Correlation Values	3-inch storm depth	4-inch storm depth	5-inch storm depth	6-inch storm depth	7-inch storm depth	8-inch storm depth
Observed Δ*CR* vs. *%d*	0.81	0.76	0.68	0.70	0.78	0.71

The correlation values found in Table 4-8 indicate a strong positive relationship between Δ*CR* and *%d*. This relationship is supported in the scatter plot shown in Figure 4-18. The scatter plot can be used to support the *%d* and Δ*CR* sensitivity threshold values as well. A sensitivity threshold value of 20 percent has been presented for *%d* when identifying watersheds with peak discharges sensitive to the cross-section location. The sensitivity threshold value presented for Δ*CR* is 10 percent. The scatter plot in Figure 4-18 shows that there are no watersheds with a *%d* greater than 20 percent that have an observed Δ*CR* less than 10 percent.

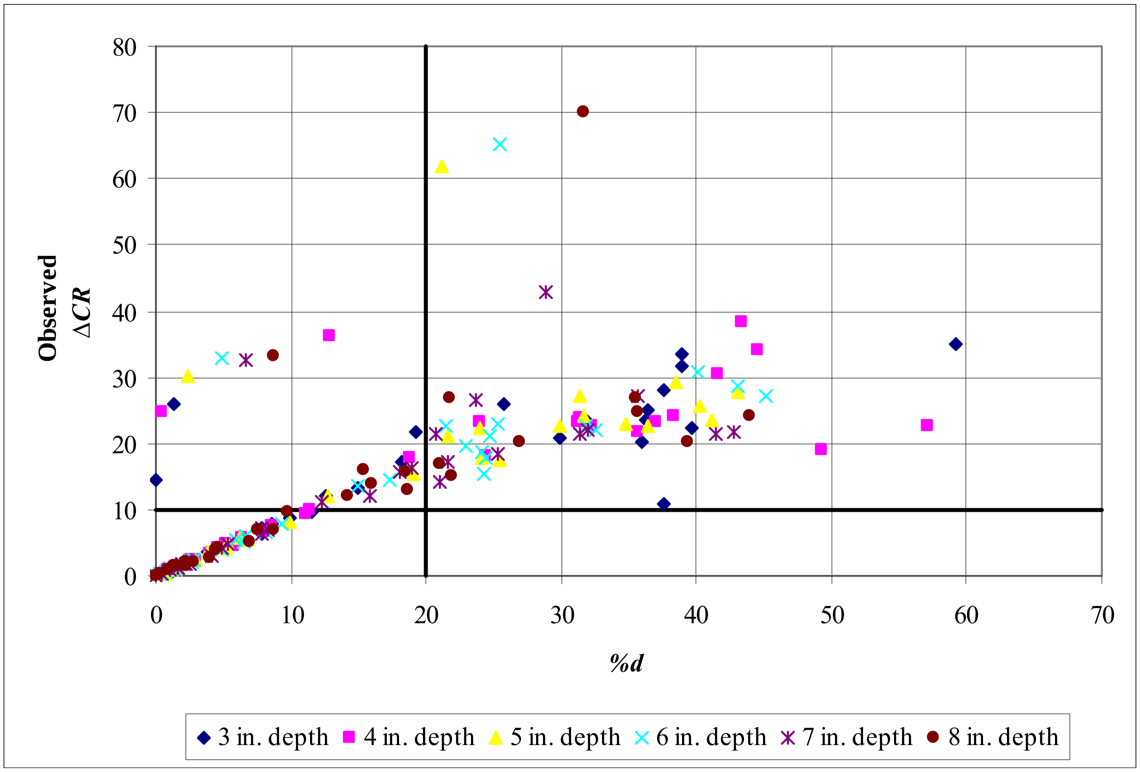


Figure 4-18: Scatter plot of *%d* vs. observed Δ*CR*

There are several points in the scatter plot that do not follow the relationship that a larger *%d* has a corresponding larger Δ*CR*. These points are of little concern based on the sensitivity threshold analysis previously discussed. A sensitivity threshold of 10 percent for Δ*CR* will identify the same watersheds as having peak discharge sensitive to the cross-section location as identified by the 20 percent *%d* sensitivity threshold. There may be additional watersheds identified as well, but there would be greater concern when validating the use of Δ*CR* if not all the watersheds were identified as having higher degrees of peak discharge sensitivity to cross-section location along the routing reach than identifying a minimal number of false positives.

The correlation matrix shown in Table 4-9 demonstrates the relationship between the observed Δ*CR* values and the watershed characteristics. Similarly as with the *%d* sensitivity value, Δ*CR* has a strong positive relationship with reach length. The remaining watershed characteristics have a stronger relationship with ΔCR than with *%d* indicating that the attenuation from reach routing is more closely linked to the reported watershed characteristics then the overall peak discharge to these characteristics at the watershed outlet. Both reach length and percent forest cover have positive relationships with ΔCR showing that as they increase the attenuation due to reach routing increases as well. The remaining watershed characteristics have negative relationships with ΔCR showing that as they increase the attenuation due to reach routing decreases.

Table 4-9: Correlation matrix between observed ΔCR by storm depth and watershed characteristics

Correlation Matrix	Observed ΔCR 3-inch storm	Observed ΔCR 4-inch storm	Observed ΔCR 5-inch storm	Observed ΔCR 6-inch storm	Observed ΔCR 7-inch storm	Observed ΔCR 8-inch storm
Reach Length	0.68	0.66	0.66	0.63	0.75	0.60
Channel Slope	-0.16	-0.25	-0.18	-0.21	-0.16	-0.20
Land Slope	-0.19	-0.29	-0.22	-0.25	-0.17	-0.23
Basin Relief	-0.16	-0.24	-0.17	-0.21	-0.16	-0.20
Percent Urban	-0.28	-0.27	-0.22	-0.24	-0.24	-0.22
Percent Impervious	-0.22	-0.19	-0.16	-0.19	-0.19	-0.18
Percent Forest Cover	0.22	0.28	0.32	0.30	0.25	0.30

4.9 Regression Equation Results

A power regression model has been developed to predict *CR* based on the 30 watersheds used in this study. The regression model has been updated as compared to the model developed and described in Chapter 3, equation (3-15). The precipitation predictor has been dropped as it was found to be insignificant (an exponent value of -0.002) when calibrated with the larger set of data from the 30 watersheds. Equation (4-2) is the result of the updated regression analysis.

$$CR = \Delta Q / Q_{in} = 0.0071 L^{0.3401} C^{-0.5518} S^{0.0972} \qquad (4\text{-}2)$$

Table 4-10 contains the goodness-of-fit statistics based on the regression analysis used to create Equation (4-2).

Table 4-10: Goodness-of-Fit statistics for *CR* regression analysis

0.0077	BIAS
0.0726	STANDARD ERROR OF ESTIMATE (Se)
0.1827	STANDARD DEVIATION OF Y (Sy)
0.3977	Se/Sy
0.9176	CORRELATION COEFFICIENT (R)
0.8419	EXPLAINED VARIANCE (R**2)
1.034	MEAN ABSOLUTE RELATIVE ERROR
6.258	STANDARD DEV OF ABSOLUTE RELATIVE ERROR

The goodness-of-fit statistics in Table 4-10 can be compared to the goodness-of-fit statistics in Table 3-3. The statistics found in Table 4-10 are slightly poorer than the statistics found in Table 3-3. This may be due to the increased number of watersheds making it more difficult to apply a regression model to fit the data. The data from the 30 watersheds used in the final study have greater variability than the data from the original 11 watersheds. Se/Sy increased approximately three percent and the explained variance decreased approximately two percent. These differences are small. The previous statements made in Chapter 3 regarding the goodness-of-fit statistics continue to hold true with this updated regression equation. The feasibility of using the predicted *CR* values to determine the peak discharge sensitivity to cross-section location will be explored below using similar methods as used above with the observed *CR* values.

Figure 4-19 shows the observed *CR* data vs. the predicted *CR* data at the 8-inch storm depth. The analysis pertains to all the data and a plot of these data may be found in Figure A-2 of Appendix A. The 45 degree axis represents a perfect match between observed and predicted data. Similarly to the findings from the regression analysis performed against the original subset of data, local biases are evident throughout the data. These biases can be attributed to specific watersheds in several cases.

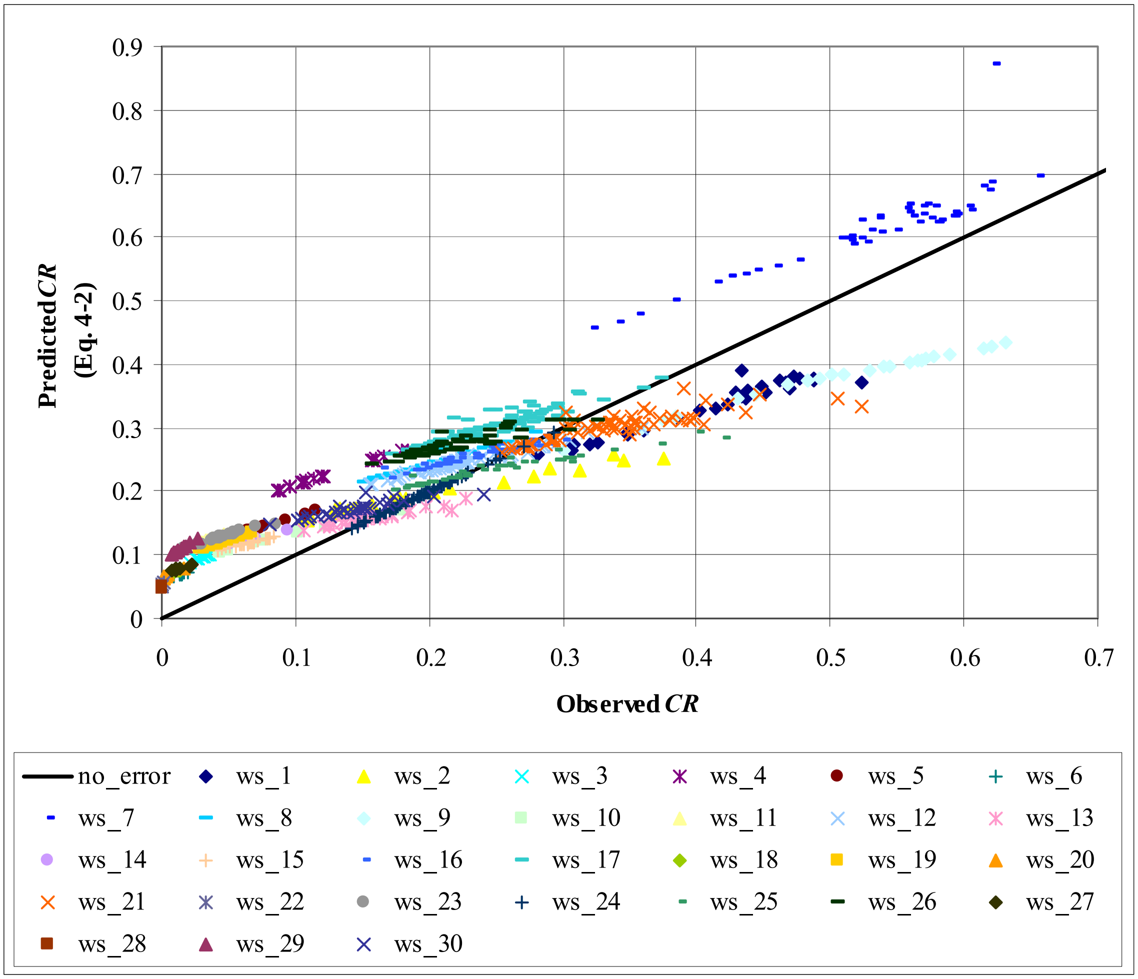


Figure 4-19: Observed *CR* against Predicted *CR* for Equation (4-2) regression results

Watersheds 6, 11, 18, 27, 28, 29, and 7 can be identified as watersheds whose *CR* values are all over-predicted. With the exception of watershed 7, these watersheds have reach lengths on the smaller end of the spectrum when compared to the range of reach lengths for the dataset and have relatively low *CR* values. These observations may be of interest when analyzing the sensitivities based on the predicted *CR* values. The sensitivity analysis is actually based on the difference in range of *CR* values within a watershed, therefore, the over prediction may not pose any concerns as it appears to be consistent. Watersheds 7 and 9 have interesting observed vs. predicted results at the larger *CR* values as well (see Appendix A for a presentation of observed *CR* vs. predicted *CR* for all the data). These two watersheds provide the largest *CR* values of the entire dataset. In addition they also have the largest under-predicted and over-predicted values. Both watersheds 7 and 9 are from the flat sloped data grouping, but they do not have any observable characteristics that separate them from the rest of the data in that grouping. The TR-20 results for these two watersheds identified a warning message that appeared for the small storm depths. TR-20 warns that the reach may require sub-division to avoid a large reduction of peak flow. The frequency of this message in TR-20 coincides with very similar or the same *CR* values regardless of cross-section. Based on the TR-20 warning and observed results, TR-20 implements a limit to the amount of attenuation that may occur from routing the hydrograph. The experimental method described previously was used consistently across all watersheds studied in my research such that each watershed was sub-divided into three sub-areas producing a single routing reach along which the cross-sections were measured. In so doing, this type of TR-20 warning was ignored for this study. In an actual hydrologic analysis, the engineer would be aware of this warning and might choose to alter how the specific analysis would be performed. Because the routing coefficient varies across these cross-sections within each watershed and because TR-20 limits the amount of attenuation, the predicted *CR* values are different from one another while the observed values remain the same.

Also of interest are the linear trends apparent in the observed vs. predicted *CR* values. These trends all appear to have a slope slightly less than one. Knowledge about the actual value for a single point could increase the prediction power of other *CR* values. Although the examination of these trends were out of the scope of this study, they may have bearing on future developments of a system using these methods for decision making purposes to assess the sensitivity of the peak discharge to cross-section location.

4.10 Predicted CR and ΔCR Analysis

The same analyses that were performed for the observed Δ*CR* values can be performed for the predicted Δ*CR* values. The predicted Δ*CR* values can be assessed to determine which watersheds produce peak discharges that are sensitive to the cross-section location. The determination of sensitivity can be based on a sensitivity threshold value in the same fashion as for observed Δ*CR* and *%d*. An initial analysis concluded that sensitivity threshold values of 20 percent and 30 percent for the predicted Δ*CR* values were too high to identify the same watersheds as identified by the *%d* sensitivity threshold values as having peak discharges with a high degree of sensitive to cross-section location. Table 4-11 contains the watersheds identified by a 15 percent sensitivity threshold for 3 – 4-inch storm depths and a 10 percent sensitivity threshold value for 5 – 8-inch storm depths. Using the watersheds identified by *%d* as having a moderate or high degree of peak discharge sensitivity to cross-section location along the routing reach as a baseline, a sensitivity threshold of 15 percent was found to be too large for the 5 – 8-inch storm depths.

The watersheds identified as having peak discharge sensitive to cross-section location in Table 4-11 match up well, although not perfectly, against the watersheds identified by the 20 percent sensitivity threshold for the observed Δ*CR* values in Table 4-6.

Table 4-12 compares the watersheds identified by observed and. predicted ΔCR values (Table 4-6 and Table 4-11 respectively) that exceed their respective sensitivity thresholds.

Table 4-11: Watersheds exceeding sensitivity threshold values based on predicted ΔCR by storm depth

Storm Depth	Watersheds Exceeding 15% Threshold	Percent of all Watersheds	Watersheds Exceeding 10% Threshold	Percent of all Watersheds
3-inch	8, 16, 25, 17, 26, 1, 12, 24, 2, 4, 21, 10, 7, 9	47%		
4-inch	2, 12, 1, 24, 21, 26, 7, 9	27%		
5-inch			25, 30, 2, 12, 26, 24, 17, 1, 21, 7, 9	37%
6-inch			12, 25, 26, 21, 17, 2, 1, 7, 9	30%
7-inch			12, 21, 25, 2, 17, 1, 7, 9	27%
8-inch			21, 2, 17, 1, 9, 7	20%

Table 4-12: Sensitive watershed comparison as identified by the observed and predicted ΔCR values

Storm Depth	Watersheds in Both Tables	In Predicted ΔCR not in Observed ΔCR	In Observed ΔCR not in Predicted ΔCR
3-inch	8, 16, 25, 17, 26, 1, 12, 24, 2, 4, 21, 10, 9	7	None
4-inch	2, 12, 1, 24, 21, 26, 7, 9	None	10, 17, 8, 16, 4
5-inch	25, 30, 2, 12, 26, 24, 17, 1, 21, 7, 9	None	10, 16
6-inch	12, 25, 26, 21, 17, 2, 1, 7, 9	None	30
7-inch	12, 21, 25, 2, 17, 1, 7, 9	None	30
8-inch	21, 2, 17, 1, 9, 7	None	12, 25

Table 4-12 indicates that a re-evaluation of the sensitivity threshold may be needed regarding the predicted ΔCR values. There are several watersheds across the six storm depths that are identified by the observed ΔCR values as having peak discharges with a high degree sensitivity to the cross-section location along the routing reach that are not identified by the predicted ΔCR values. Overall, and assuming the appropriate sensitivity threshold values are used, the biases and relative errors for the regression equation do not alter the identification of watersheds with peak discharges with a high degree of sensitivity to the cross-section location along the routing reach.

The relationship between observed and predicted ΔCR are demonstrated in Figure 4-20. Figure 4-20 demonstrates the tendency for predicted ΔCR to be less than observed ΔCR. This also supports the need for a smaller sensitivity threshold value when examining predicted ΔCR to determine if overall peak discharge is sensitive to the cross-section location along the routing reach. The smaller predicted ΔCR values are likely a result of the linear trend in the regression equation results discussed earlier as the difference between the minimum and maximum CR values will be smaller with a slope of less than one when compared to the observed values.

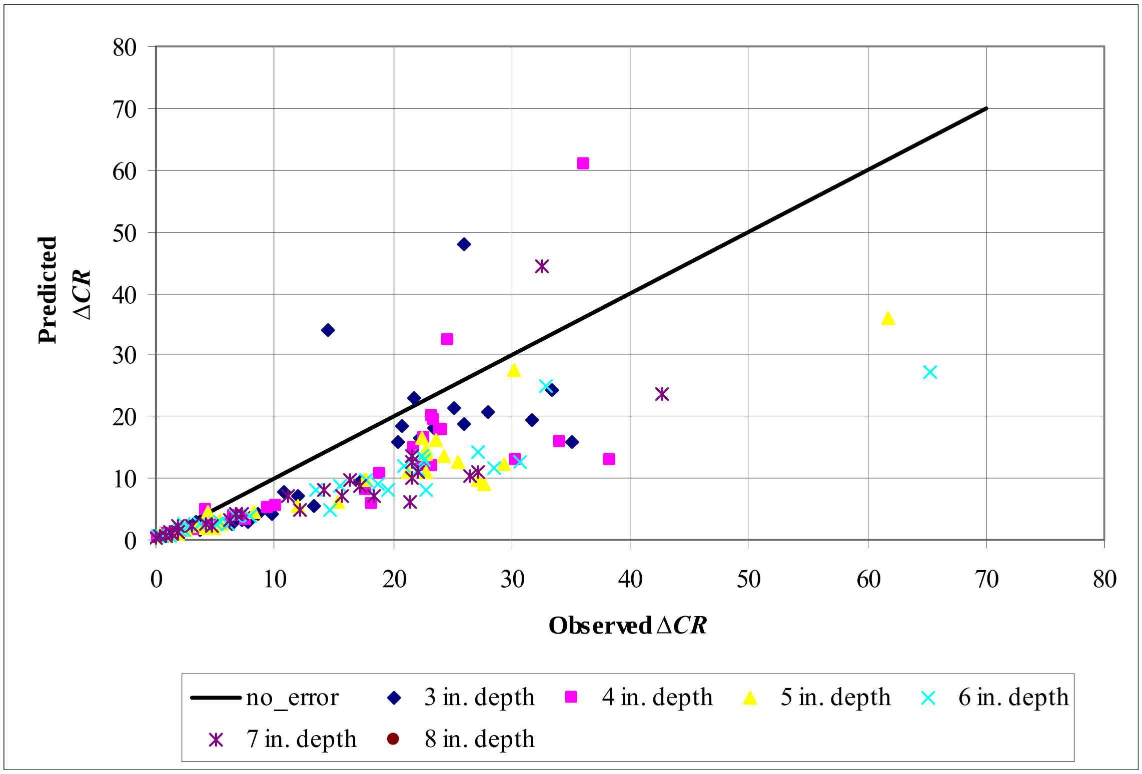


Figure 4-20: Plot of observed ΔCR vs. predicted ΔCR

A similar, and more useful comparison, can be made between the sensitivity thresholds for predicted ΔCR and the 20 percent sensitivity threshold value for *%d* in Table 4-2. Table 4-13 contains a list of watersheds by storm depth that were identified as having peak discharges sensitive to cross-section location via *%d*, but not by predicted ΔCR.

Table 4-13: Watersheds identified as sensitive via *%d*, but not predicted ΔCR

Storm Depth	Watershed ID
3-inch	13
4-inch	17, 16, 4, 10, 25, 8
5-inch	4, 8
6-inch	10, 16, 8, 24, 30
7-inch	30, 8, 26, 24
8-inch	26, 24, 25, 12

For the 4-inch storm depth, a sensitivity threshold value of 10 percent on the predicted ΔCR values will identify the watersheds listed in Table 4-13 as sensitive. For the 5-, 6-, and 7-inch storm depths a sensitivity threshold value of 8 percent identifies the listed watersheds as having moderately to highly sensitive peak discharges. The adjusted sensitivity threshold values would not add a significant number of watersheds identified as sensitive that are not contained in the Table 4-13 lists. For the 8-inch storm depth, a sensitivity threshold value of 7 percent would be required to identify the listed watersheds. This appears to identify an 8 percent sensitivity threshold for predicted ΔCR as the most appropriate sensitivity threshold to use for identifying watersheds with moderate to high sensitivity of peak discharge to the cross-section location. The engineer would want to invest additional resources in a given routing analysis when the regression results lead to a ΔCR value exceeding the 8 percent sensitivity threshold.

4.11 Case Study: Watersheds Analysis

A case study involving processing and analyzing three additional watersheds was performed. This case study was used to analyze the effectiveness of the regression equation to determine the sensitivity of peak discharge to the cross-section location. The watershed characteristics for the three case study watersheds are shown in Table 4-14.

Table 4-14: Watershed characteristics for three case study watersheds

Watershed ID	Area (mi^2)	Reach Length (ft)	Channel Slope (ft/mile)	Land Slope (ft/ft)	Basin Relief (ft)	Percent Urban	Percent Impervious	Percent Forest Cover
31	3.5	6265	9.7	0.009	20.7	2.1	0.9	74.2
32	3.8	6389	47.9	0.056	123.4	79.8	34.8	6.8
33	3.7	3661	271.5	0.148	573.9	13.7	3.4	58.1

Each region (flat sloped, moderate sloped, steep sloped) is represented by one of the watersheds from Table 4-14: watershed 31 (flat sloped), watershed 32 (moderate sloped), and watershed 33 (steep sloped).

Table 4-15 contains the *%d*, observed ΔCR, and predicted ΔCR values by storm depth for the three case study watersheds.

Table 4-15: Sensitivity parameters for three case study watersheds

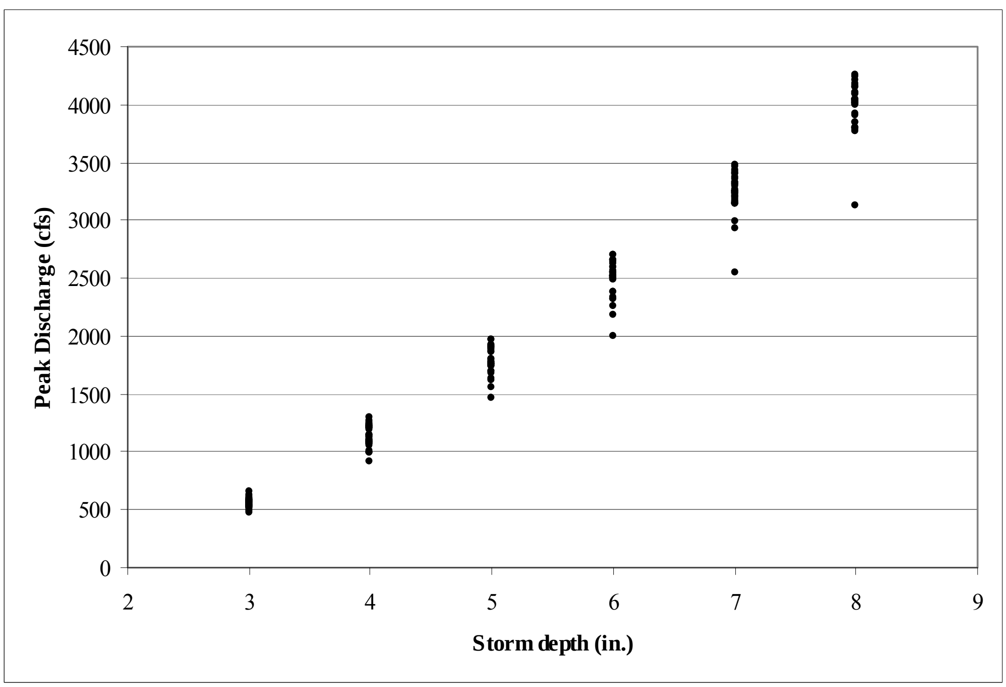
	Watershed 31			Watershed 32			Watershed 33		
Storm Depth	***%d***	**Obs. ΔCR**	**Pred. ΔCR**	***%d***	**Obs. ΔCR**	**Pred. ΔCR**	***%d***	**Obs. ΔCR**	**Pred. ΔCR**
3-inch	29.07	18.80	7.92	28.33	19.10	11.97	11.16	9.13	6.80
4-inch	12.25	8.58	3.54	29.56	20.00	9.53	11.03	8.84	5.02
5-inch	5.81	4.20	6.73	25.96	17.79	9.62	13.37	10.66	8.03
6-inch	15.25	11.30	4.86	26.20	18.16	10.06	11.65	9.30	5.85
7-inch	10.79	8.11	6.16	26.71	18.47	10.32	9.64	7.39	4.51
8-inch	10.04	7.79	5.22	26.53	18.01	9.26	7.28	5.48	3.65

A sensitivity threshold value of 20 percent will be used to determine sensitivity with *%d*, 10 percent will be used to determine sensitivity with observed ΔCR, and 8 percent will be used for predicted ΔCR. The overall relationship between the observed and predicted

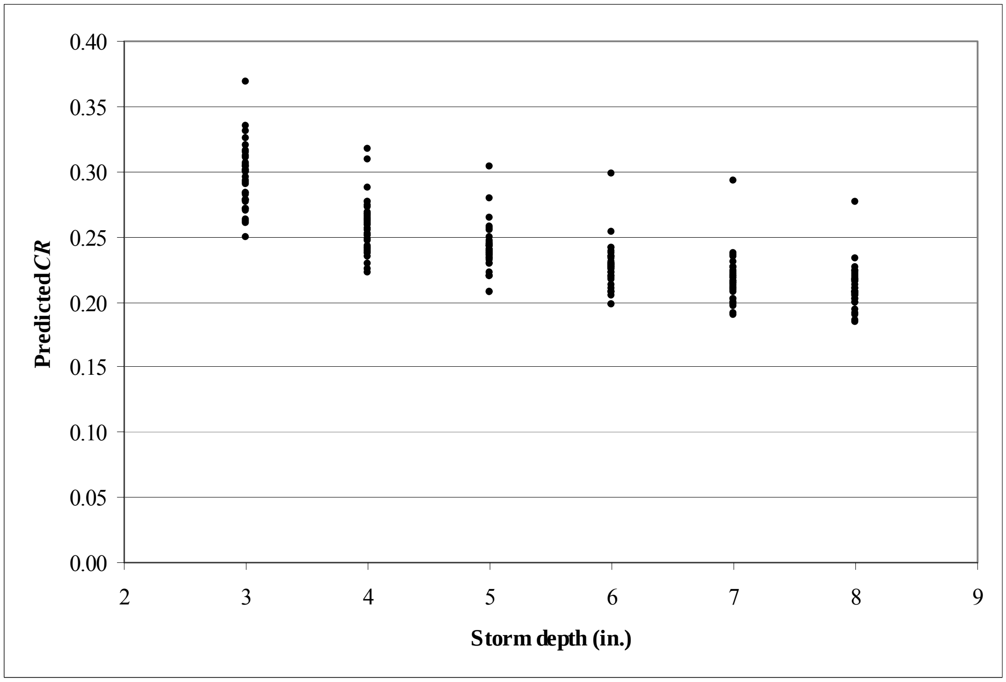
ΔCR values is consistent across the three case study watersheds with the exception of the 5-inch storm depth for watershed 31. The predicted ΔCR value for the 5-inch storm depth of watershed 31 is slightly greater than the observed ΔCR value. This is contrary to the trend observed for the remaining storm depths for all three watersheds. The data presented in Figure 4-20 show that there are occurrences where the predicted ΔCR value is greater than the observed ΔCR value, therefore, this occurrence is not unexpected.

With the exception of the 3-inch storm depth, watershed 31 has *%d* values below the 20 percent sensitivity threshold. The 3-inch storm depth *%d* value for watershed 31 is high due to several cross-sections producing watershed outlet hydrographs having two peaks. The two peak hydrographs result in a smaller minimum peak discharge and therefore a greater *%d*. The observed ΔCR values are all below the 10 percent sensitivity threshold with the exception of the 3- and 6-inch storm depths which are 18.80 and 11.30 percent respectively. The observed ΔCR values are all below the 8 percent sensitivity threshold value. Based on these findings for watershed 31, the regression (predicted ΔCR) values agree with the *%d* values with the exception of the 3-inch storm. Based on the regression analysis presented earlier these results are not surprising. These results indicate that watershed 31 does not have peak discharges that are highly sensitive to the cross-section location along the routing reach.

Watershed 32 has *%d* values that exceed the 20 percent sensitivity threshold for all storm depths. This implies that watershed 32 has peak discharges that are highly sensitive to the cross-section location along the routing reach, and that additional resources may be needed to determine the appropriate location for the cross-section. The observed and predicted ΔCR values support these findings based on the 10 percent and 8 percent sensitivity threshold values respectively. The data for watershed 32 should be examined for outliers that may inflate the *%d* and ΔCR sensitivity values. Figure 4-21(a) shows a plot of the peak discharge values by storm depth and Figure 4-21(b) shows a plot of the *CR* values by storm depth. Both Figure 4-21 (a) and (b) demonstrate how outlier data may influence the sensitivity results. For example, the *%d* value for the 8-inch storm depth is 26.53 percent. By dropping the single outlier point *%d* would be recalculated to 10.5 percent, and no longer show a high degree of sensitivity within peak discharge to cross-section location based on the 20 percent sensitivity threshold value for *%d*. A similar reduction in ΔCR is found once the outlier is removed. The 8-inch storm depth ΔCR value would be reduced from 9.3 percent to 4.6 percent and watershed 32 would no longer show a high degree of sensitivity within peak



(a)



(b)

Figure 4-21: Case study watershed 32 outlier figures (a) peak discharge by storm depth, (b) *CR* by storm depth

discharge to cross-section location based on the 8 percent sensitivity threshold for ΔCR.

Watershed 33 has *%d* values that are all below than the 20 percent sensitivity threshold. This implies that the peak discharge for watershed 33 is not highly sensitive to the cross-section location along the routing reach. Based on the 10 percent sensitivity threshold, the observed ΔCR values agree with this assessment with the exception of the 5-inch storm depth value. The predicted ΔCR values also agree with this assessment based on the 8 percent sensitivity threshold, with the exception of the 5-inch storm depth. The observed and predicted ΔCR values are on the borderline of their respective sensitivity thresholds at the 5-inch storm depth, and a judgment by the engineer would be needed in this case as to whether or not to spend additional resources researching the cross-section location.

When compared to the watershed characteristics the reach length is the characteristic of interest based on the earlier correlation analysis. The watersheds with the longest reach lengths vary in reach length between 7,300 and 10,400 feet. Based on these reach length values it may be expected that both watersheds 31 and 32 would be found to be on the border of having moderate to high degrees of peak discharge sensitivity to cross-section location along the routing reach and watershed 33 would not. This is true for watershed 32 but not so for watershed 31. The reach length for watershed 31 is deceptive in this case. This is due to how the data must be processed to create the necessary rating tables. Many of the available cross-sections for this watershed failed to create a rating table. These failures were due to the DEM processing not capturing the necessary information to create a proper rating table. Occasionally the flat terrain in the coastal regions present a problem for creating a rating table such that not all the discharge and cross-sectional area values increase as the stage increases. This situation is documented in Chapter 3 and must be considered when examining reach length as a measure for possible sensitivity.

The case study demonstrates how the regression equation may be used as a decision making tool for the engineer. Given the appropriate data necessary to compute the input parameters, the engineer can estimate the variability of estimated peak discharge related to the selection of the cross-section location along the routing reach. Assuming that a 20 percent difference between peak discharge values is of concern, if the ΔCR value calculated from the predicted CR values for a watershed were greater than 8 percent, there would be cause for further examination of the choice of cross-section location. Future development could use this information in a system designed to assist the engineer in the decision making process. This system could include the outlier analysis and incorporate relationships to reach length and rating table failures into providing relevant information to the engineer.

4.12 Summary

The primary motivation for this study is to provide guidance on developing routing reach cross-section characteristics to engineers, planners, and other professionals that use GIS to perform hydrologic rainfall-runoff modeling.

Based on the enumeration method and the regression method it was shown that there can be high degrees of sensitivity of peak discharge to the cross-section location along the routing reach. The two values used to examine the sensitivity were *%d* and ΔCR. *%d* is the percent difference between the minimum and maximum peak discharge values for a specific watershed. The ΔCR value is the percent change in peak discharge due to routing the hydrograph through the reach. In addition, correlations were drawn between these peak discharge sensitivity values and watershed characteristics.

The actual overall peak discharge sensitivity is derived from *%d*. The *%d* factor is a measure of the range of peak discharge values that may be found across all the cross-sections. The larger the *%d* factor, the greater the sensitivity of peak discharge to cross-section location. Although the significance of this factor may only be determined by the engineer, a sensitivity threshold value of a 20 percent difference was used in this study to identify sensitive watersheds. For larger storm depths this may mean a difference of 1000 cfs between the minimum and maximum peak discharge values. Several watersheds for each storm depth were identified as having peak discharges with high degrees of sensitivity to cross-section location along the routing reach based on the 20 percent sensitivity threshold. It was also noted that the spread of data should be taken into consideration. A large *%d* value may be based on one or two outlier points with the remainder of data well below the sensitivity threshold.

An estimate of the peak discharge sensitivity to cross-section location may be derived from the ΔCR factor as well. ΔCR represents the difference between the minimum and maximum *CR* values. The *CR* value represents the percent difference between the inflow and outflow peak discharges based on routing the hydrograph through the reach. A lower sensitivity threshold for ΔCR is required to identify the same set of watersheds as having a peak discharge sensitive to the cross-section location as identified by the *%d* analysis. There is not perfect agreement between ΔCR and *%d* in identifying peak discharges from watersheds with high degrees of sensitivity to cross-section location along the routing reach, however, for the sensitivity thresholds suggested in this study, agreement was generally greater than 90 percent of the watersheds studied. The results from the three independent case study watersheds supported the relationship between *%d* and ΔCR as well.

The correlation analyses were used to determine how well *%d* corresponded to ΔCR for predicting the peak discharge sensitivity to cross-section location, and how well these sensitivity factors related to the watershed characteristics. The *%d*, ΔCR correlation matrix along with the scatter plot of data demonstrated a strong relationship between both sensitivity factors, although different sensitivity threshold values are required. Reach length has the strongest relationship with the peak discharge sensitivity to cross-section location. Both sensitivity factors identified this as true. ΔCR on the other hand, has stronger relationships to the remaining watershed characteristics than *%d*, although still much weaker than with reach length.

The findings presented in this study can be used as the basis for an integrated system to aid the engineer in the decision making process when performing rainfall-runoff modeling. The cross-section location, and its relationship to the reach routing parameters, play a key role in determining the modeled peak discharge output. This system could include the regression equation as an analysis tool to estimate the sensitivity of peak discharge to the cross-section location along the routing reach. In addition, the system could include tools to analyze the reach length, possible rating table failures, and outlier data when computing ΔCR. These tools would provide the necessary information to provide guidance on developing routing reach cross-section characteristics to engineers, planners, and other professionals that use GIS to perform hydrologic rainfall-runoff modeling.

5 Conclusions

The objectives of this study as outlined in Chapter 1 are:

1. To develop a methodology to systematically quantify all the potential rating tables along routing reaches for input into a hydrologic rainfall-runoff model.
2. To quantify the sensitivity of peak discharge to the cross-section location along the routing reach within a watershed based on the methodology developed in objective 1.
3. To quantify the sensitivity of peak discharge to the cross-section location along the routing reach with changes in watershed characteristics (topography, precipitation magnitude, and routing reach length) using the methodology developed in objective 1.
4. To provide recommendations based on this study's findings that should inform the use of GIS in performing reach routing.

The development of the cross-section geometry is a fundamental input for performing reach routing in hydrologic modeling. Only a single cross-section measurement is often permitted as input to represent a routing reach. This study showed that the selection of the cross-section location can have significant impacts on the channel geometry measurements and resultant peak discharge from a rainfall-runoff model.

5.1 GIS Based Methodology to Quantify Potential Rating Tables

This study used GIS to systematically create all potential rating tables along a routing reach. This automated process established and implemented several methods that can be used by the engineer to produce a set of consistent cross-sections and related rating tables for use in the hydrologic modeling process. This methodology was used to produce the data for the 30 watersheds analyzed in this study plus the three case study watersheds used to validate the peak discharge sensitivity results. The GIS provides a mechanism for the engineer to quickly determine if additional resources are required when considering the cross-section location along the routing reach. Two different data analyses were used to measure the sensitivity of peak discharge to the cross-section location. The first data analysis was examining the TR-20 peak discharges returned for all potential cross-sections along a routing reach. The second data analyses were examining TR-20 routed hydrograph peak discharges returned for all possible cross-sections along a routing reach, and the formulation of a regression equation to model these results. The final results from both data analyses were compared to each other and to several watershed characteristics including reach length, channel slope, land slope, basin relief, percent urban, percent impervious, and percent forest cover.

5.2 Sensitivity of Peak Discharge from the Watershed Outlet to Cross-section Location

The enumeration method produced TR-20 output data for all possible cross-sections across the 30 watersheds for six different storm depths. Each watershed was assigned a sensitivity value, *%d*, by storm depth. *%d* is the percent difference between the minimum and maximum overall peak discharges at the watershed outlet based on processing each cross-section along the routing reach. A sensitivity threshold value for *%d* of 20 percent was used to identify specific watersheds where sensitivity of peak discharge to cross-section location may be a concern. At the largest storm depth of 8 inches, 9 of the 30 watersheds analyzed, or 30 percent, exceeded the 20 percent sensitivity threshold for *%d*. In other words, 30 percent of the watersheds returned a potential difference in peak discharge of at least 20 percent based solely on cross-section location along the routing reach. From the data produced in the enumeration method an alternative method was developed to examine the sensitivity of the peak discharge to the cross-section location along the routing reach.

5.3 Sensitivity of Routed Hydrograph Peak to Cross-section Location

The second method examined the sensitivity of the routed hydrograph peak to cross-section location along the routing reach. Two parameters emerged as the key components to this analysis, *CR* and *ΔCR*. *CR* is the percent difference between the input peak discharge at the top to the routing reach and the output peak discharge at the bottom of the routing reach excluding any contribution from the lower sub-area. *ΔCR* is the difference between the minimum and maximum *CR* values for a watershed and is used as a measure of sensitivity to cross-section location similar to *%d*. *ΔCR* was chosen as a second parameter to measure the peak discharge sensitivity to cross-section location along the routing reach for its ease of calculation. Given the necessary input data to compute a rating table and the development of a regression equation, an engineer can easily and quickly determine *ΔCR* and hence the sensitivity of the peak discharge to the cross-section location. Although not a direct measure of peak discharge sensitivity, the relationship between *ΔCR* and *%d* was successfully demonstrated.

The regression equation developed to estimate *CR* is based on the routing coefficient, reach length, and channel slope. The routing coefficient is a function of data derived from the cross-section channel geometry and is unique for each cross-section measured along the routing reach. On the other hand, the reach length and channel slope are watershed characteristics and remain the same across all cross-sections. An analysis of the goodness-of-fit statistics for this regression found that the regression equation showed promise for predicting *CR* and using *CR* in the decision making process when performing reach routing. Further analysis determined that a lower sensitivity threshold was required for *ΔCR* than for *%d* to identify the same watersheds as having peak discharges sensitive to the cross-section location along the routing reach. The sensitivity threshold identified for *ΔCR* calculated from predicted *CR* values was 8 percent. At an 8 percent sensitivity threshold and an 8-inch storm depth, the predicted *ΔCR* values identified essentially the same watersheds as being sensitive to the cross-section location along the routing reach as the 20 percent sensitivity threshold for *%d*. This analysis is the basis for the development of an integrated system of tools to provide guidance on developing routing reach cross-section characteristics to engineers, planners, and other professionals that use GIS to perform hydrologic rainfall-runoff modeling.

5.4 Sensitivity Relationships with Watershed Characteristics

Correlation matrices were generated between *%d*, *ΔCR,* and several watershed characteristics. In addition, several scatter plots of the sensitivity values and predictor variables were examined. The results of these analyses determined that *%d* has the strongest positive relationship with reach length when compared to the watershed characteristics which included channel slope, land slope, basin relief, percent urban, percent impervious, and percent forest cover. The remaining watershed characteristics showed weak correlation with *%d*. These findings were supported by the scatter plots.

The correlation matrix between the *ΔCR* calculated from predicted *CR* values and the watershed characteristics were overall stronger than for *%d*. This implies that the watershed characteristics analyzed in this study are more closely related to the attenuation of discharge due to reach routing than the overall peak discharge at the watershed outlet. Reach length again had the strongest correlation values when compared to the other watershed characteristics. This concept could be incorporated into an expert system as well.

5.5 Case Study Results

Three additional watersheds were examined in terms of *%d*, ΔCR calculated from observed *CR* values, and ΔCR calculated from predicted *CR* values. These watersheds were numbered 31, 32, and 33 respectively. The results from this case study supported the findings based on the analyses of the 30 watersheds. Based on the sensitivity threshold value of 20 percent for *%d*, only watershed 32 was identified as having peak discharges that are highly sensitive to the cross-section location along the routing reach. Both watersheds 31 and 33 had *%d* values below the 20 percent sensitivity threshold. This implies a lower risk to the TR-20 peak discharge results in relation to the selection of the cross-section location. Comparing the observed and predicted ΔCR values against their 10 percent and 8 percent respective sensitivity thresholds also identified watershed 32 as the only watershed as having highly sensitive peak discharges to the cross-section location along the routing reach. Further examination of the peak discharges and *CR* values for watershed 32 identified outlier data skewing the results. When these data were examined without the outliers, watershed 32 was no longer identified as having peak discharges highly sensitive to the cross-section location along the routing reach. Agreement concerning the need, or lack thereof, for further evaluation of cross-section location within the three watersheds provides the basis to support using the regression model as a planning and research tool.

5.6 Future Studies and Development

GIS provides an infrastructure for developing an integrated set of analytical tools, or expert system, that will aid the engineer in the decision making process. This study showed that the rainfall-runoff modeling processes can be sensitive to the reach routing process. Depending on the location where the channel cross-section is measured along a routing reach a range of rating tables can be produced. The range in rating tables and associated reach routing parameters can lead to large variations in the routed hydrograph peak. The regression equation for *CR* provides a quick and easy method for determining if the peak discharges from a watershed are sensitive to cross-section location along the routing reach provided a GIS and the correct set of input data. This could be considered the initiation of an expert system to aid the engineer in not only determining the sensitivity of the reach routing process to the cross-section location, but determining the location of the cross-section that best represents the routing reach. This expert system would initially require little or no additional input from the engineer when compared to current modeling implementations within a GIS. The prospect of determining the best cross-section location, or creating the most representative channel geometry, may require additional decision making from the engineer.

An examination of the patterns identified by the regression analysis when comparing predicted ΔCR to the observed ΔCR could provide additional insight within the expert system. There appear to be patterns within the predicted ΔCR values such that more sophisticated predictive models may improve the outcome of the regression. Although these patterns were identified, their analyses were beyond the scope of this study.

5.7 Closing Statement

The routing reach in the rainfall-runoff modeling process can only be represented by one channel cross-section geometry. A unique rating table and set of reach routing parameters can be created for each possible cross-section location along the routing reach. The resultant peak discharge may be sensitive to the cross-section location and the reach routing process as implemented in a GIS.

This study provides guidance and a methodology to assist the engineer in the decision making process regarding the cross-section location along the routing reach. This knowledge is obtained through a regression equation that predicts the sensitivity of the TR-20 peak discharge to the cross-section location. Given these findings, a GIS-based expert system proposed here could provide the engineer with essential information for making more informed decisions.

Appendix A Figures Depicting Observed *CR* vs. Predicted *CR* Values from the Regression Analyses

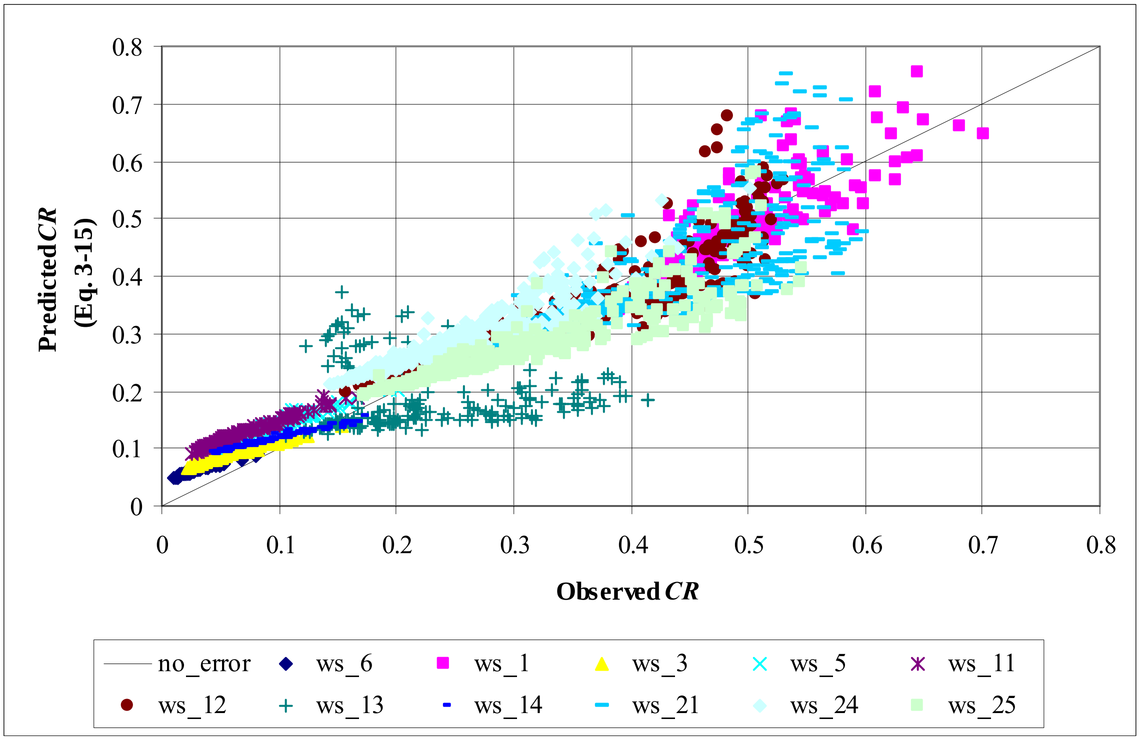


Figure A-1: Observed vs. predicted *CR* for based on regression model equation (3-15)

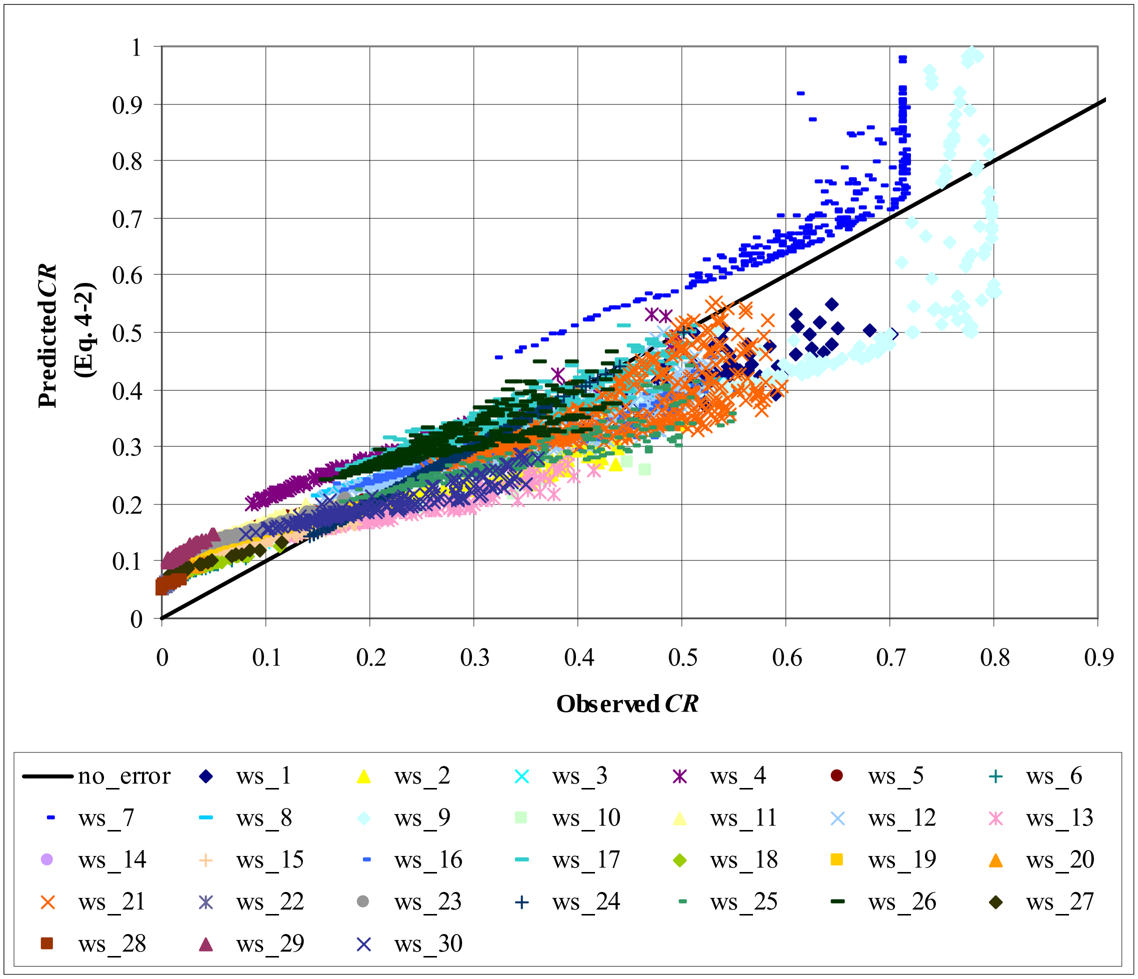


Figure A-2: Observed vs. predicted *CR* for based on regression model equation (4-2)

Appendix B 4 – 7-inch Peak Discharge Statistics Figures

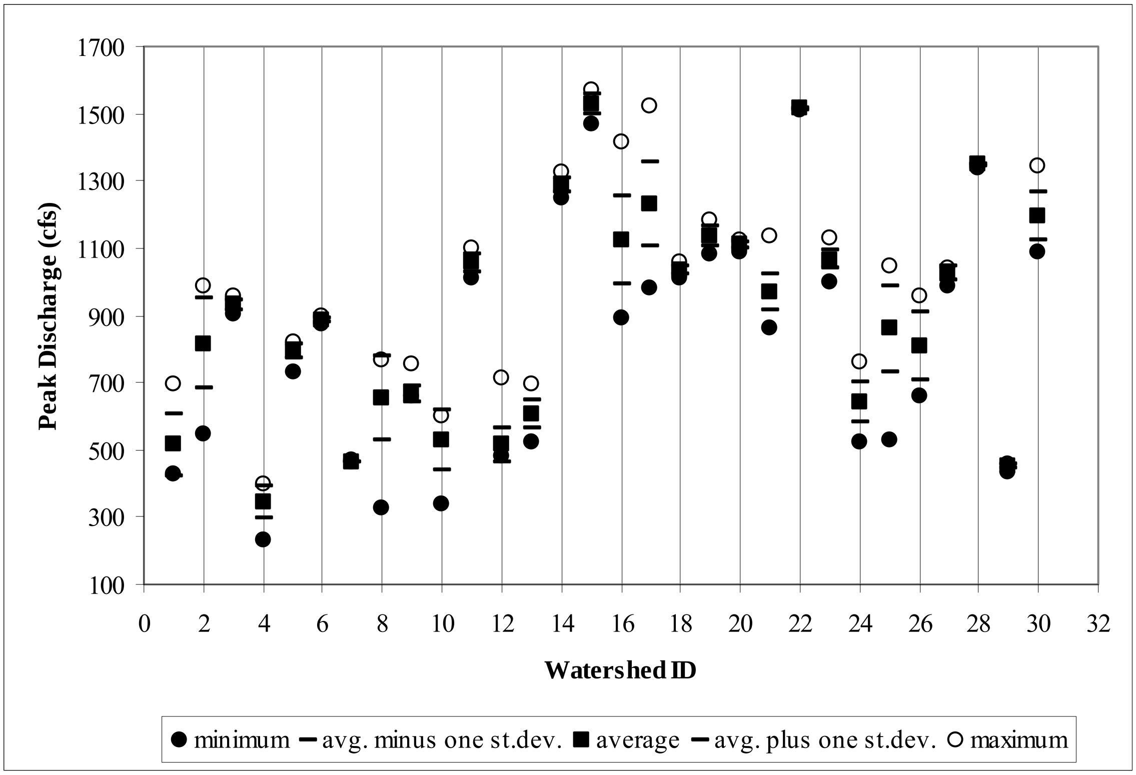


Figure B-1: 4-inch storm depth peak discharge statistics

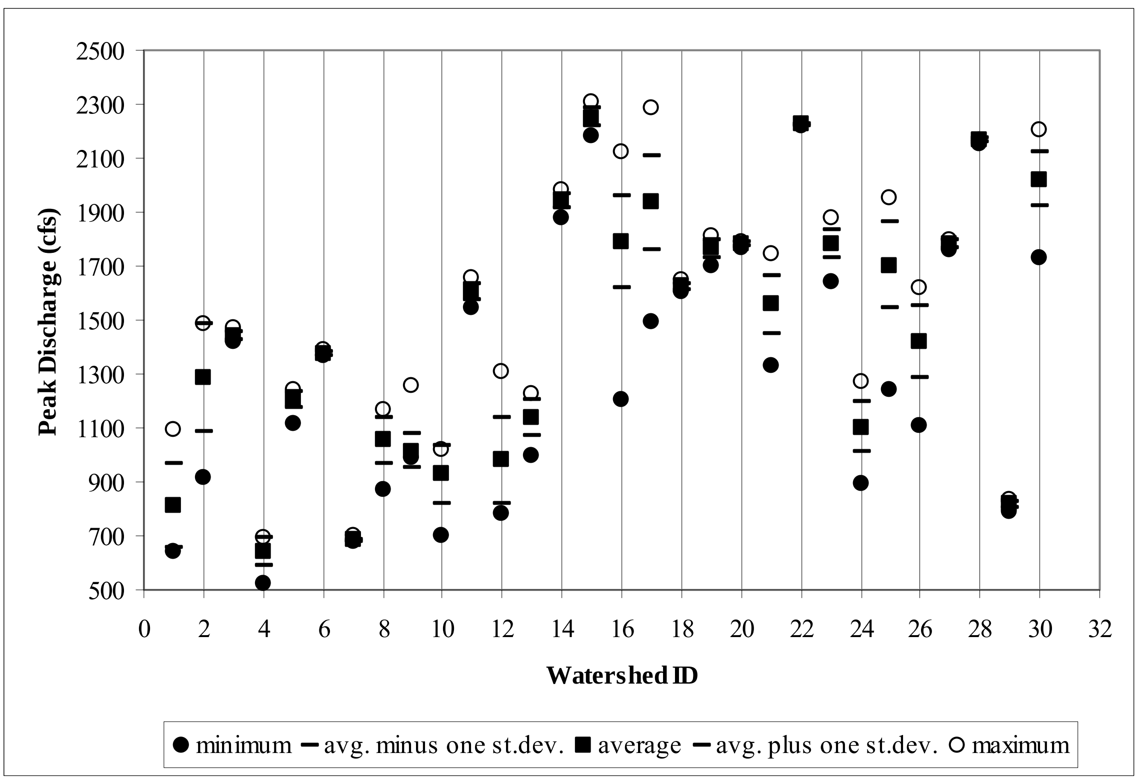


Figure B-2: 5-inch storm depth peak discharge statistics

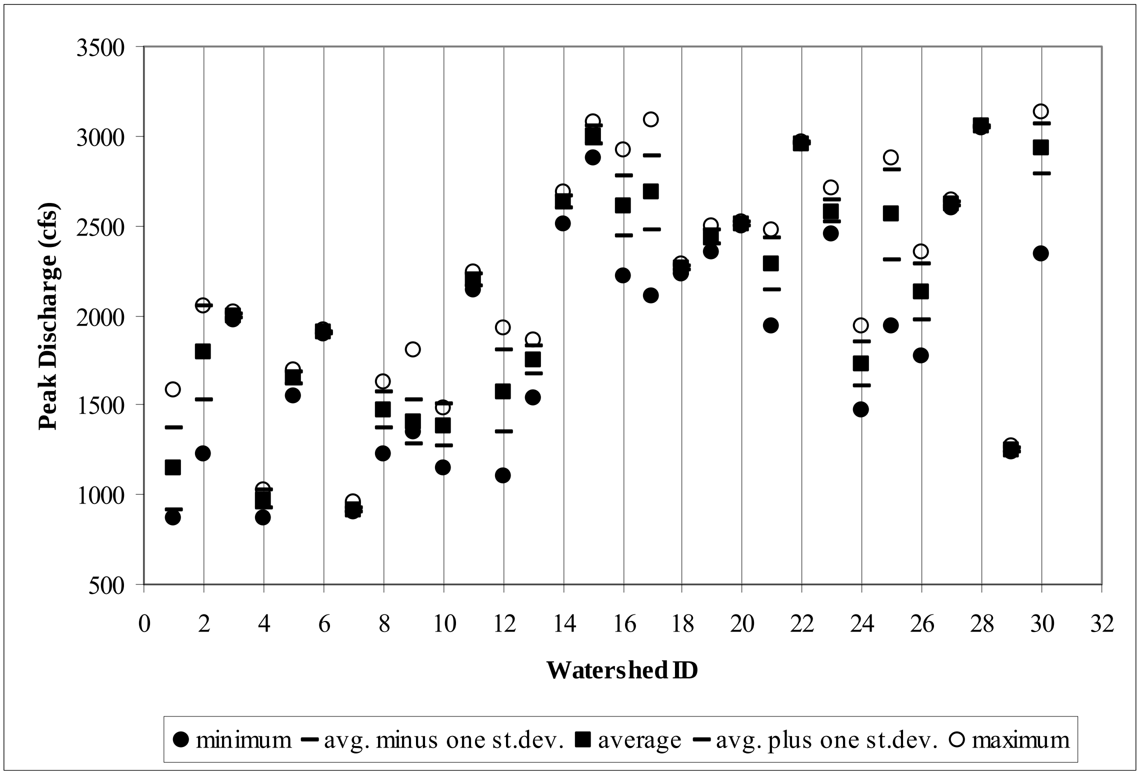


Figure B-3: 6-inch storm depth peak discharge statistics

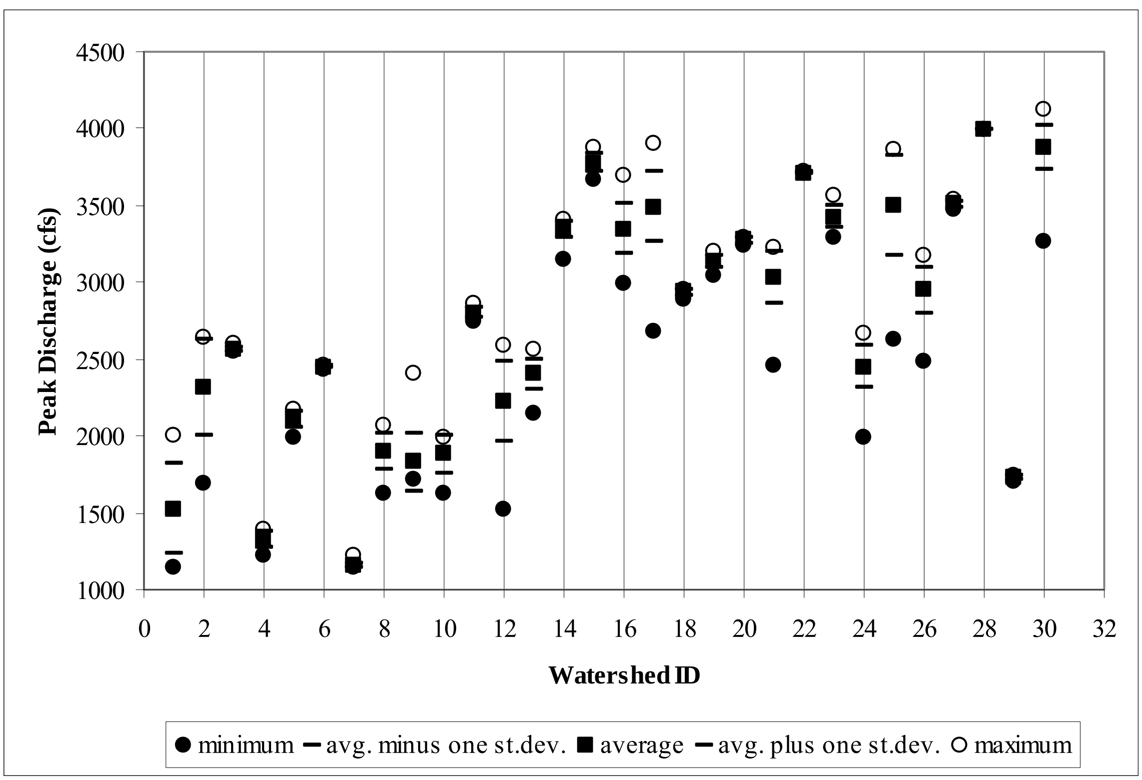


Figure B-4: 7-inch storm depth peak discharge statistics

Appendix C Figures Depicting the *%d* Sensitivity Factor by Watershed for the 3 – 7-inch Storm Depths

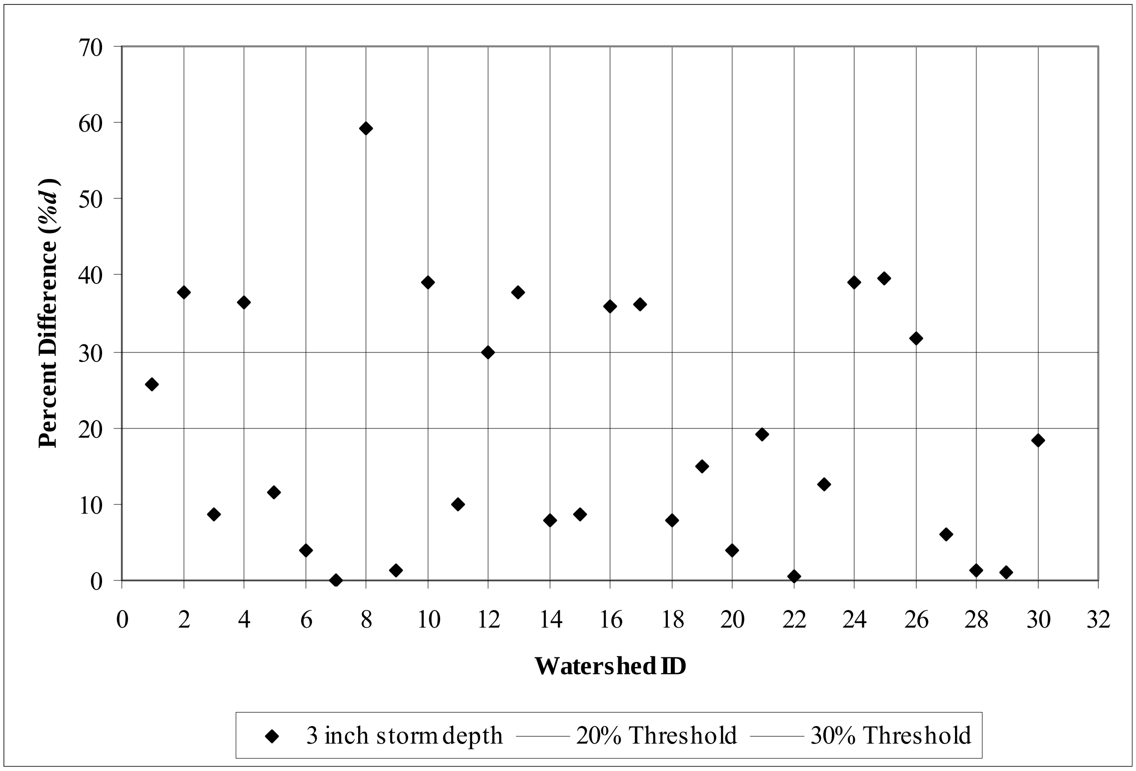


Figure C-1: Sensitivity comparison using *%d* by watershed for 3-inch storm depth

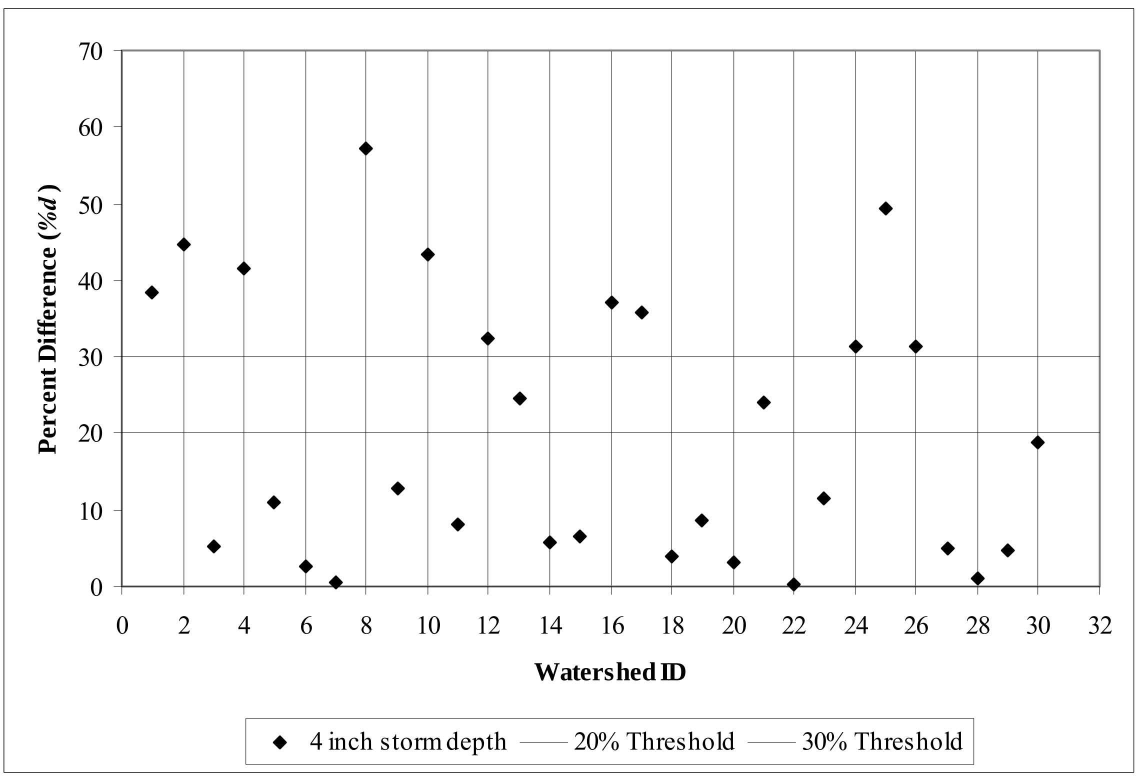


Figure C-2: Sensitivity comparison using *%d* by watershed for 4-inch storm depth

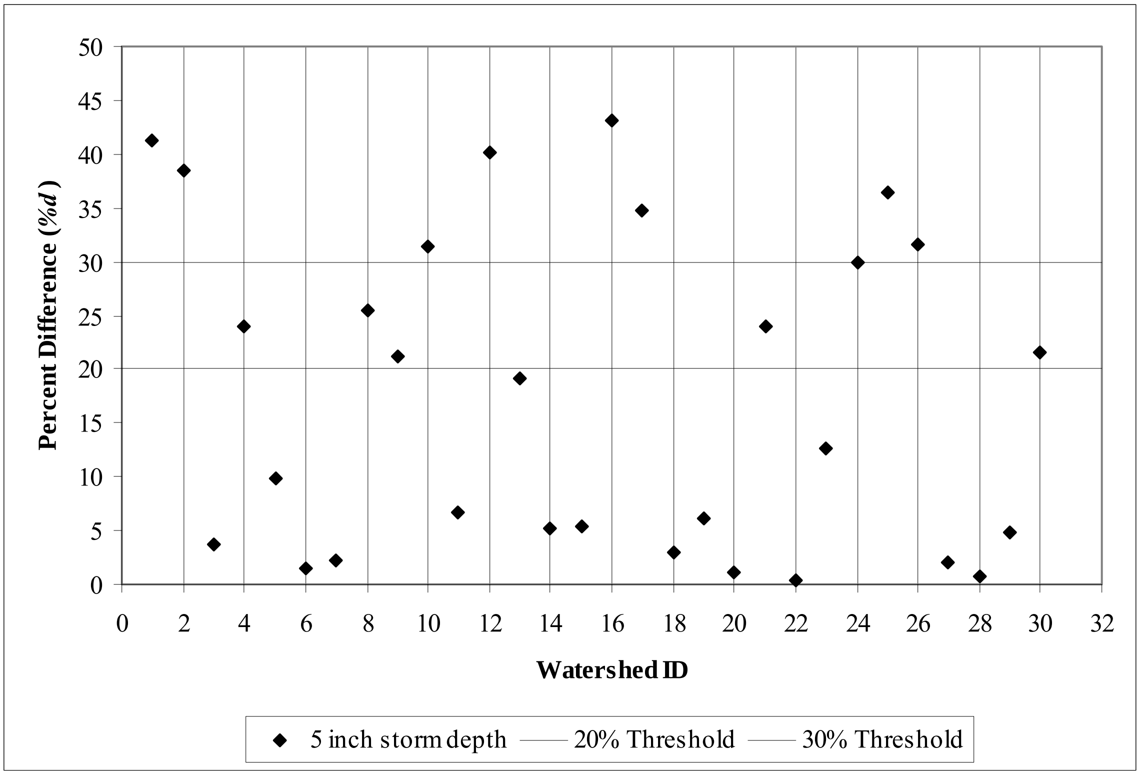


Figure C-3: Sensitivity comparison using *%d* by watershed for 5-inch storm depth

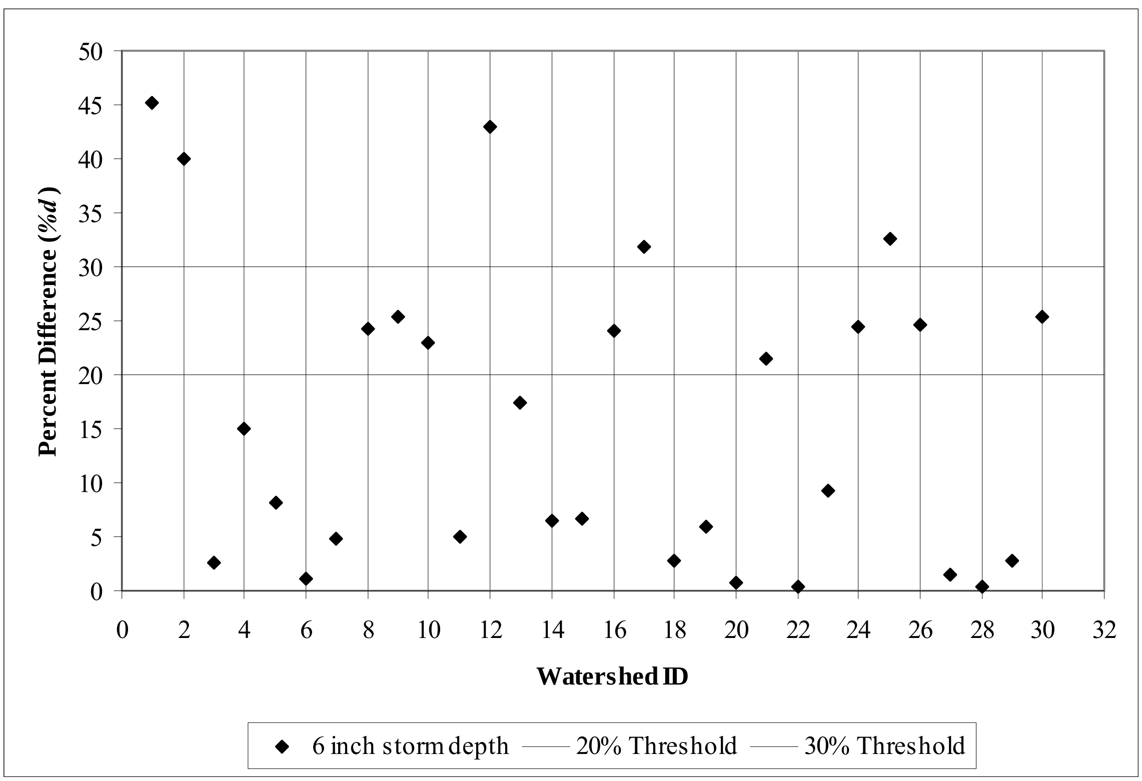


Figure C-4: Sensitivity comparison using *%d* by watershed for 6-inch storm depth

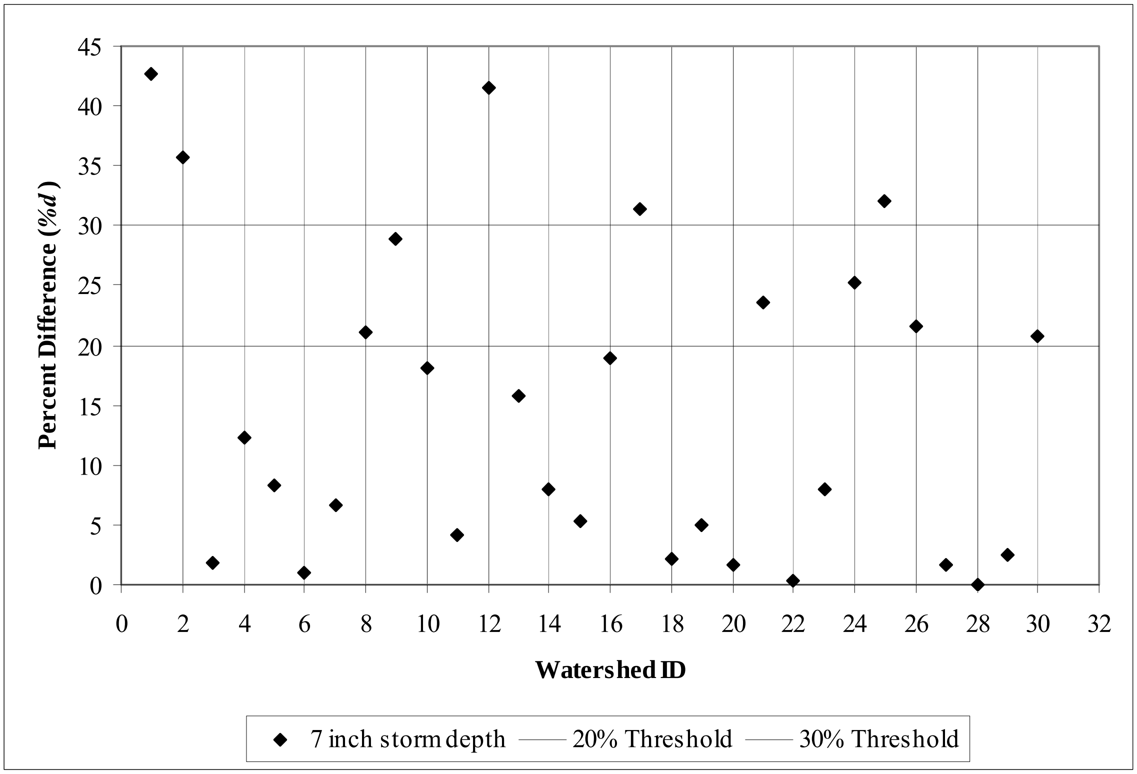


Figure C-5: Sensitivity comparison using *%d* by watershed for 7-inch storm depth

Appendix D Figures Depicting the *%d* Sensitivity Factor vs. Watershed Characteristics for all Storm Depths

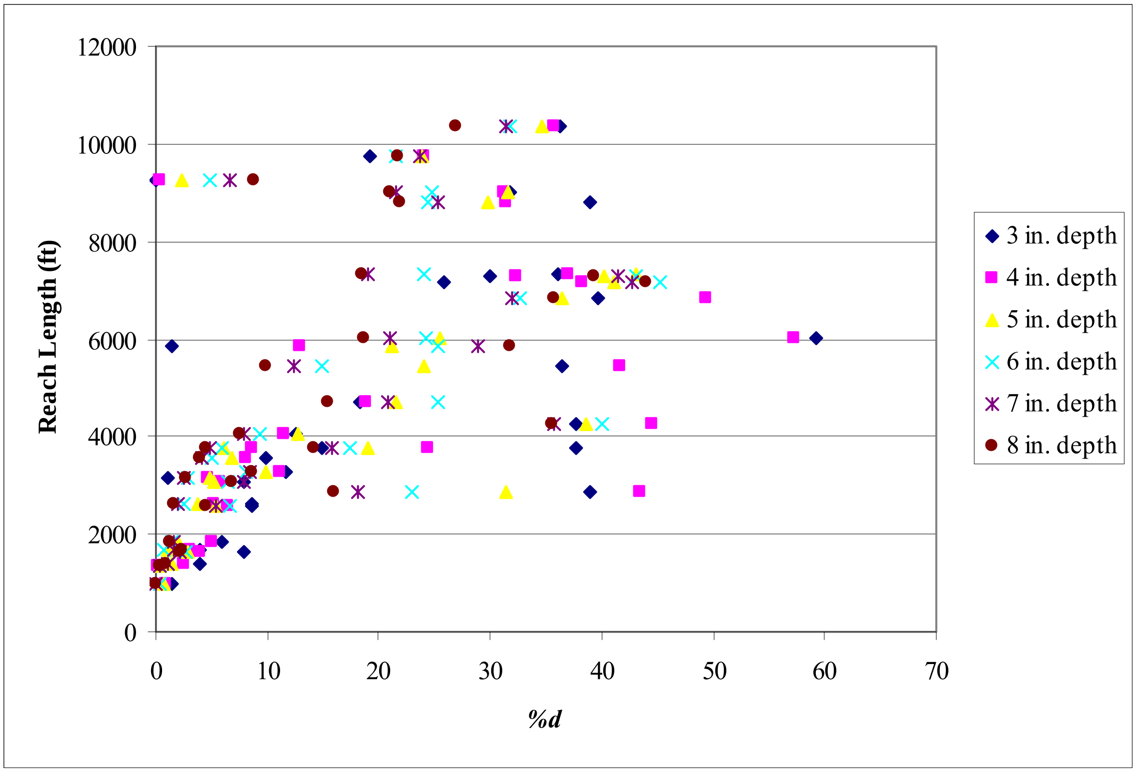


Figure D-1: Relationship between *%d* and reach length

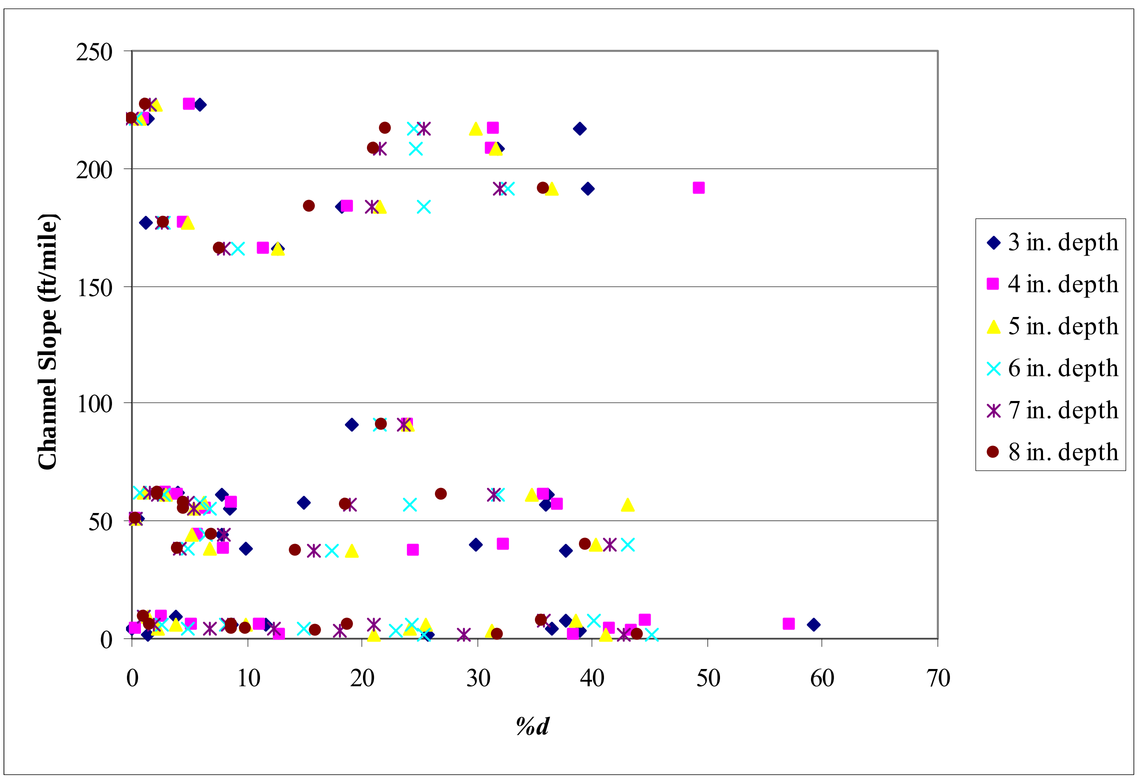


Figure D-2: Relationship between *%d* and channel slope

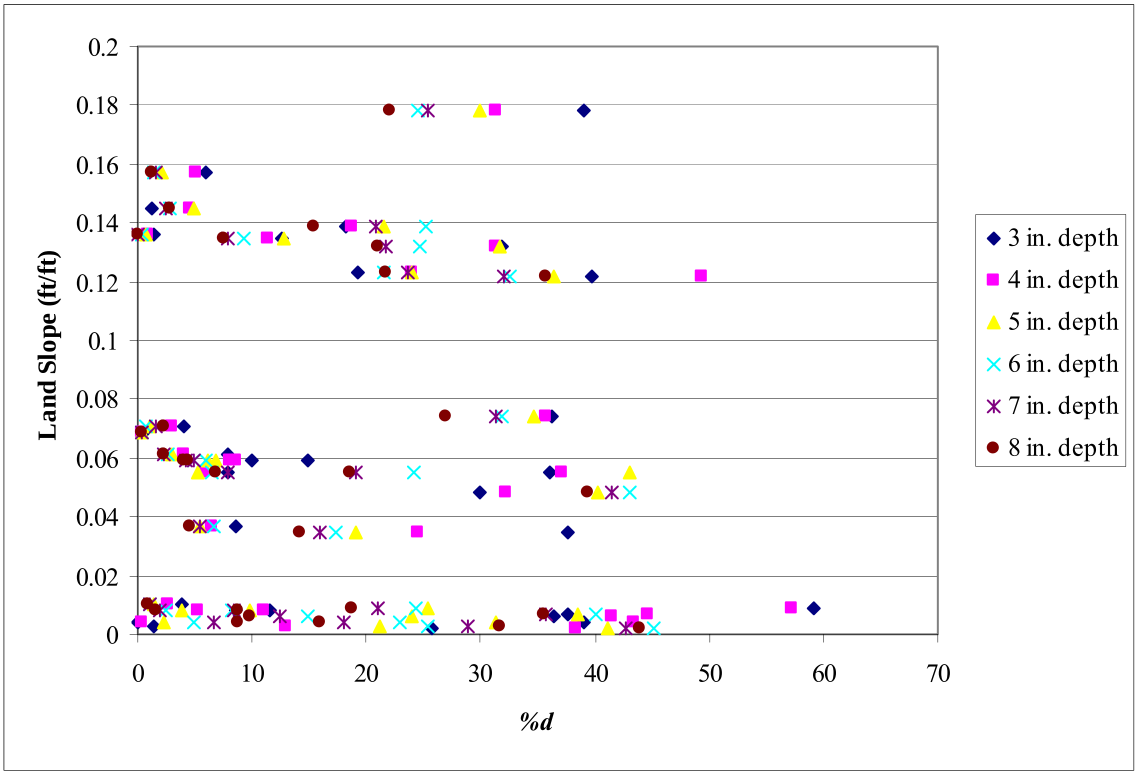


Figure D-3: Relationship between *%d* and land slope

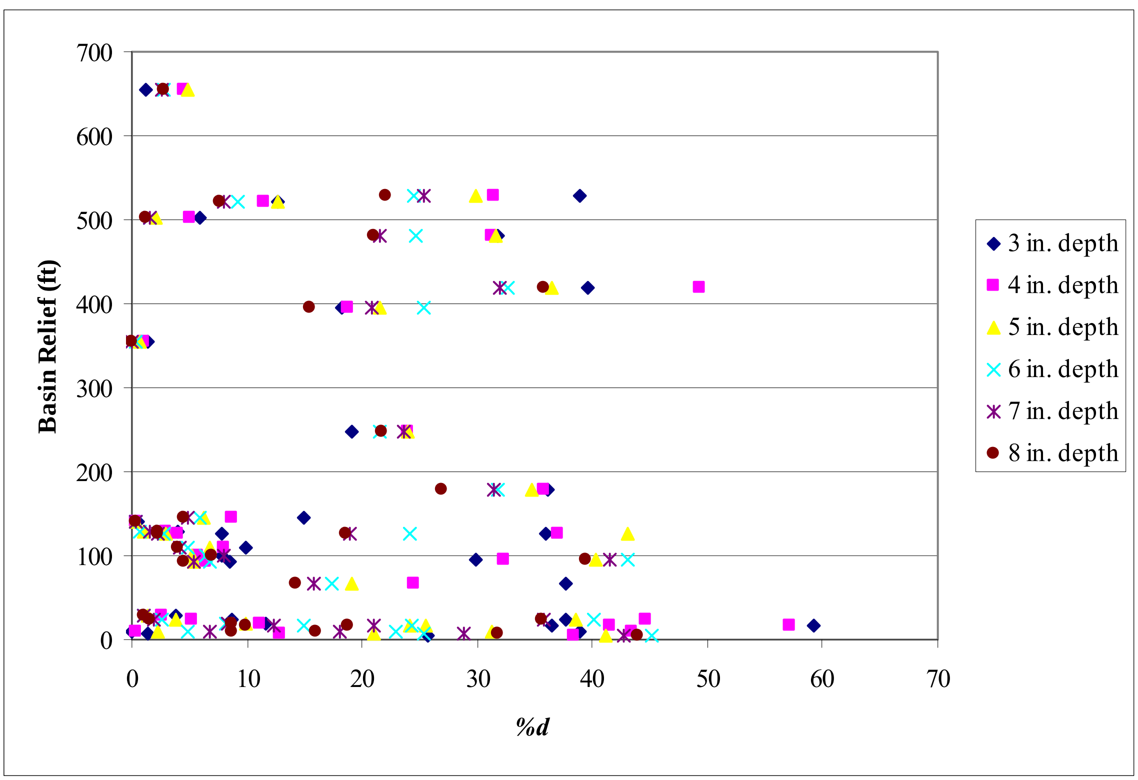


Figure D-4: Relationship between *%d* and basin relief

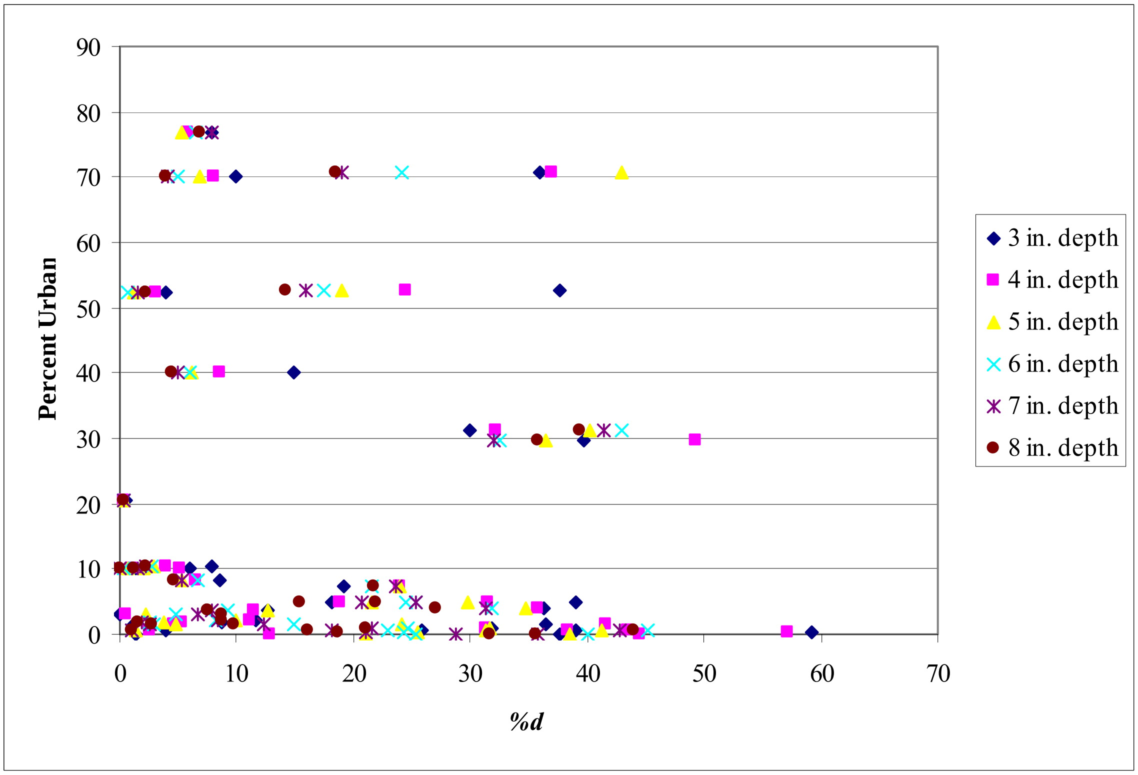


Figure D-5: Relationship between *%d* and percent urban

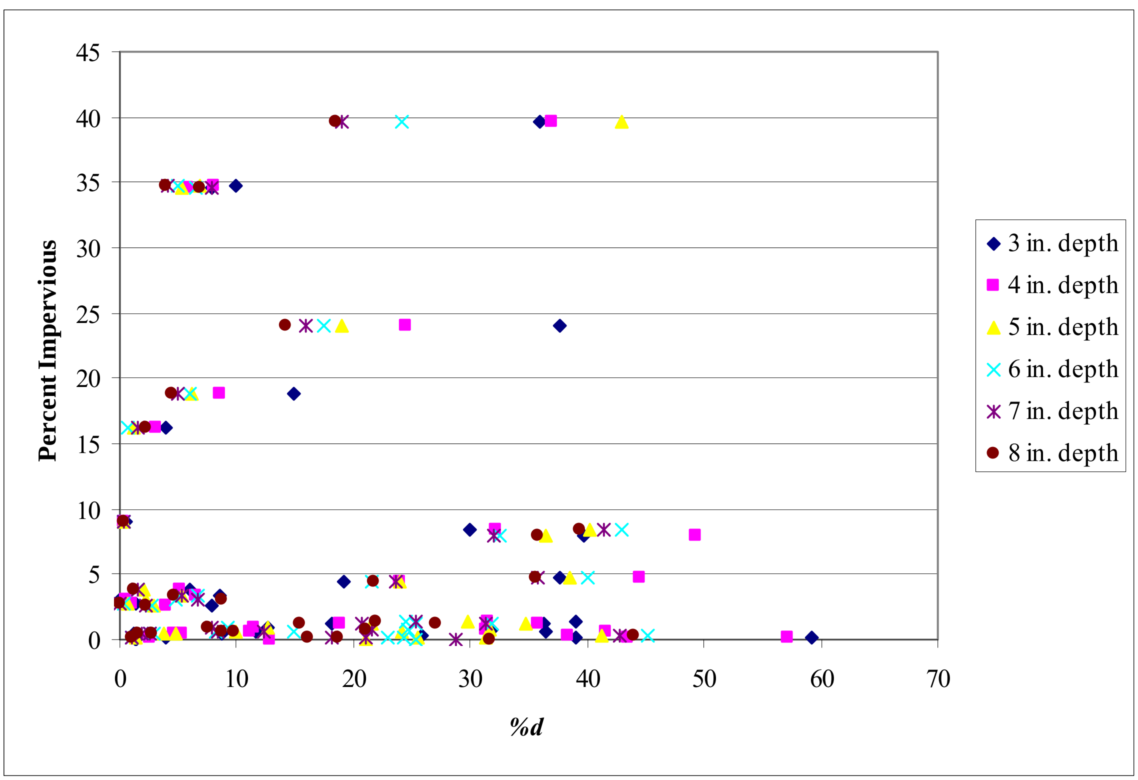


Figure D-6: Relationship between *%d* and percent impervious

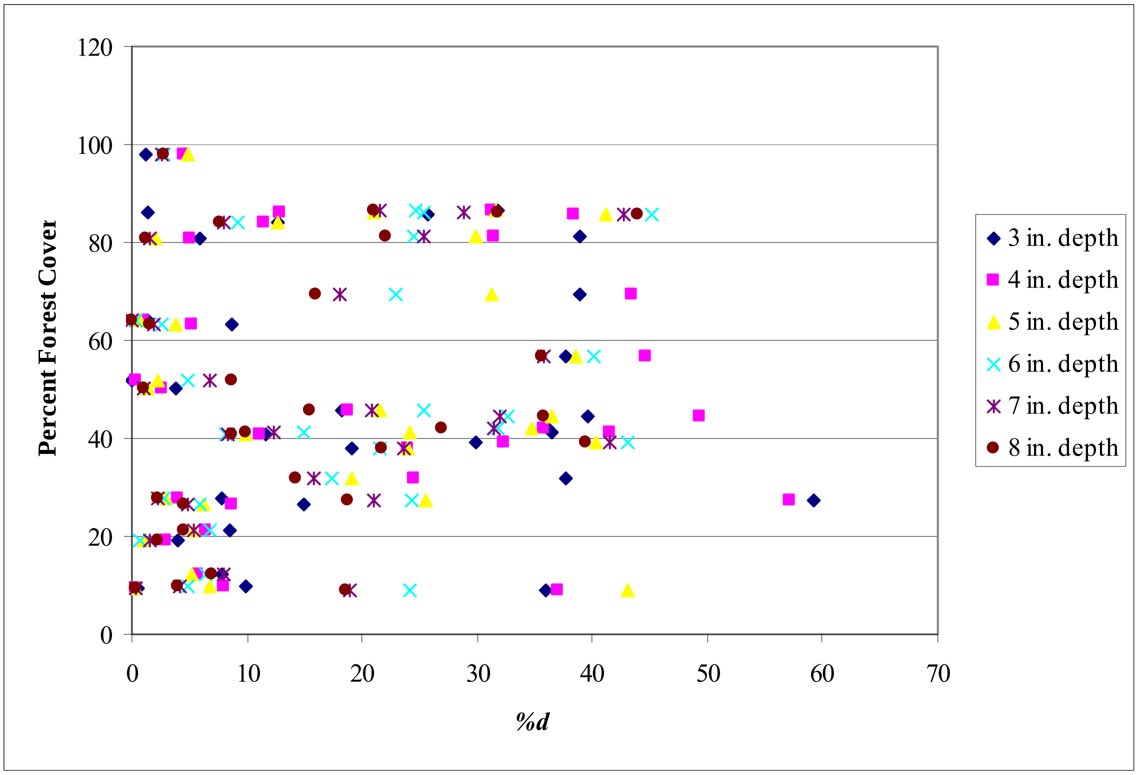


Figure D-7: Relationship between *%d* and percent forest cover

Appendix E Figures Depicting the ΔCR Sensitivity Factor by Watershed for the 3 - 7-inch Storm Depths

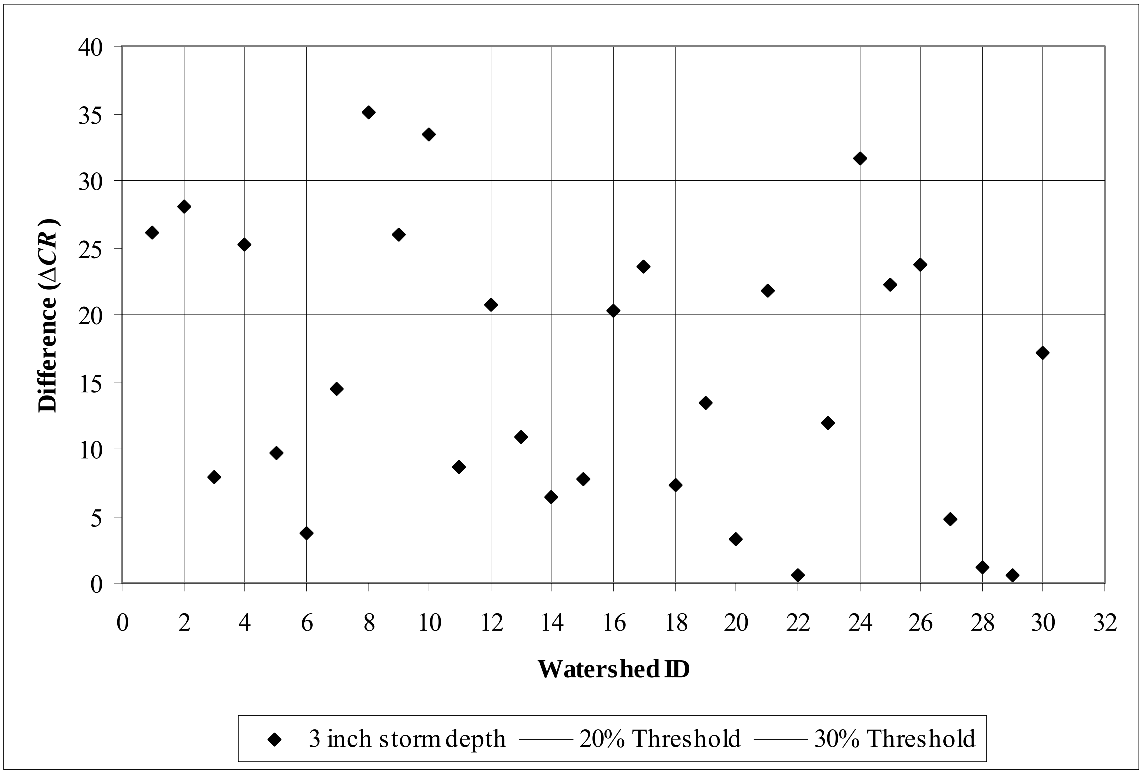


Figure E-1: Sensitivity comparison using observed *ΔCR* by watershed for 3-inch storm depth

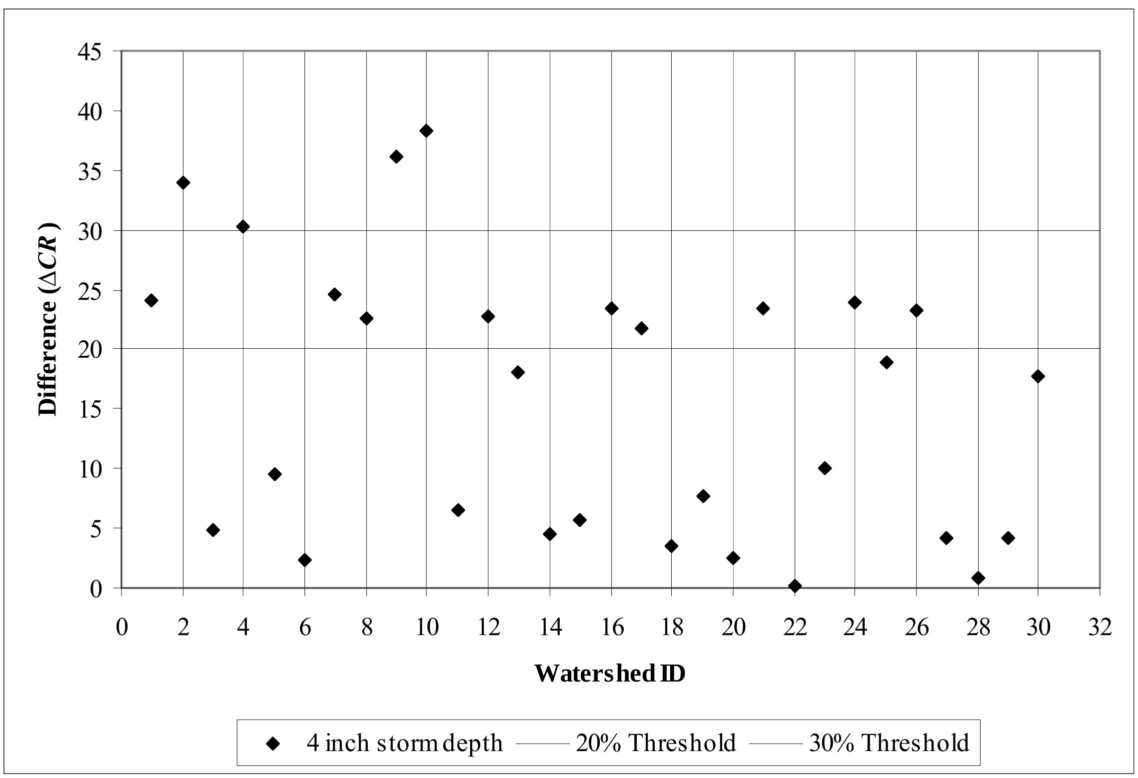


Figure E-2: Sensitivity comparison using observed Δ*CR* by watershed for 4-inch storm depth

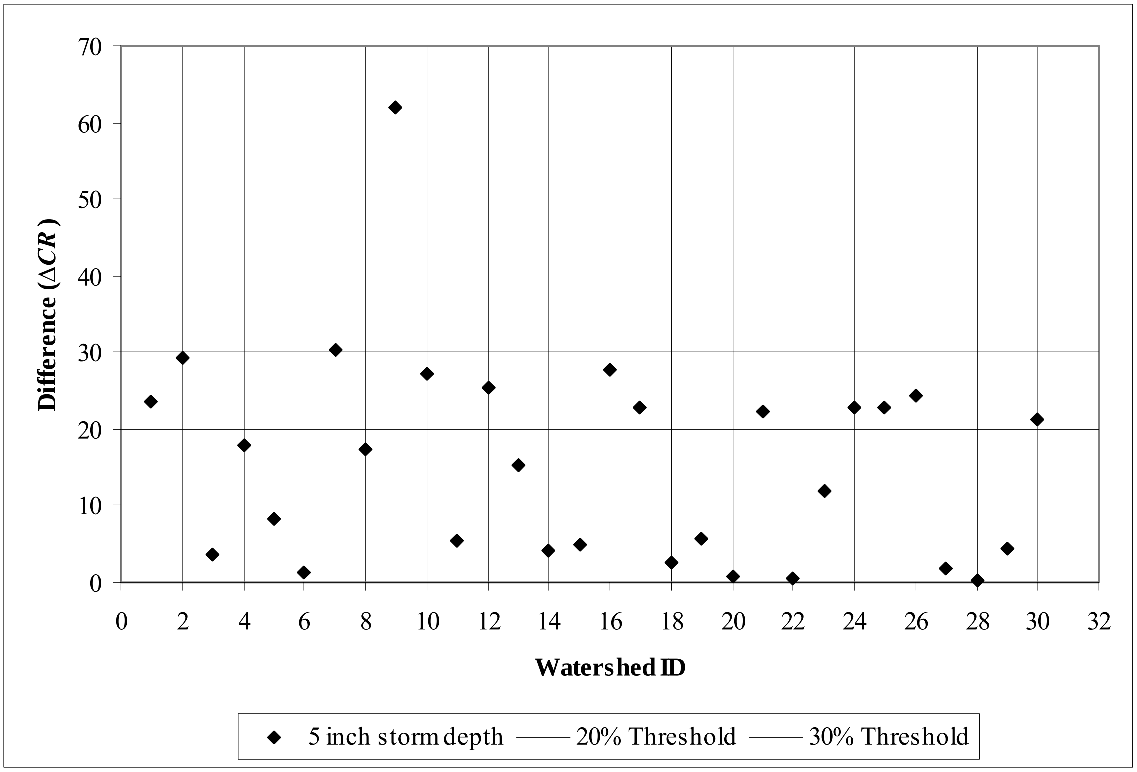


Figure E-3: Sensitivity comparison using observed Δ*CR* by watershed for 5-inch storm depth

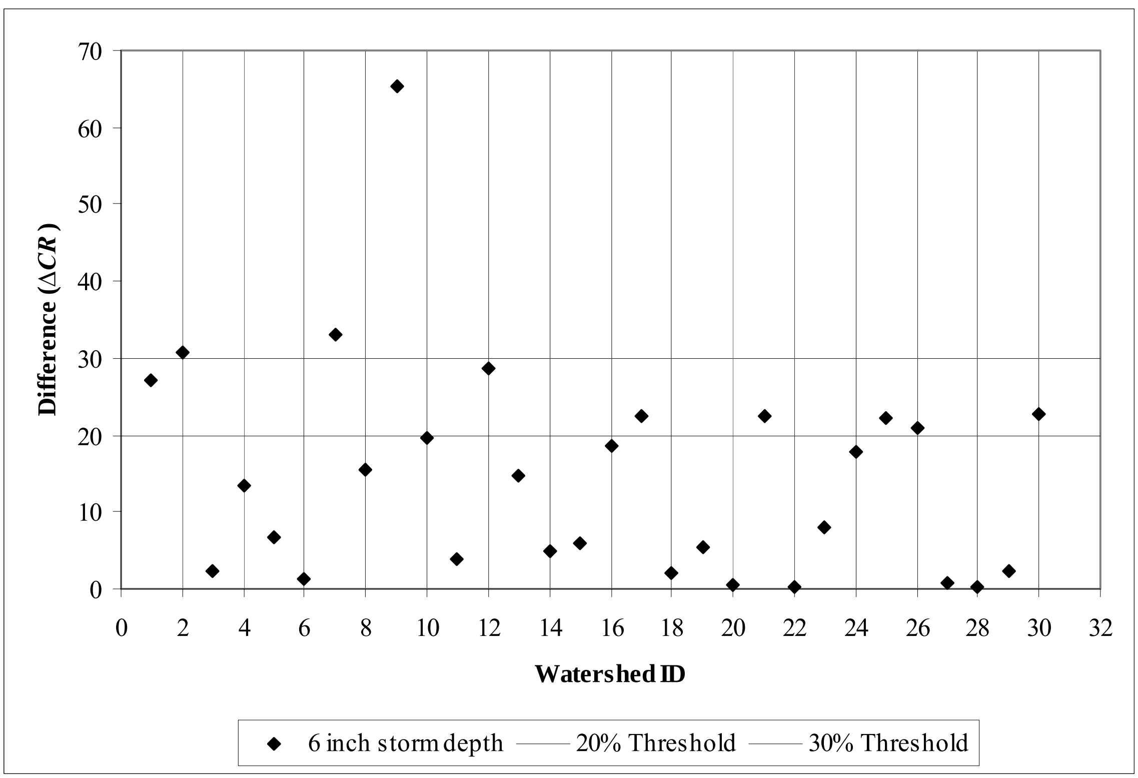


Figure E-4: Sensitivity comparison using observed Δ*CR* by watershed for 6-inch storm depth

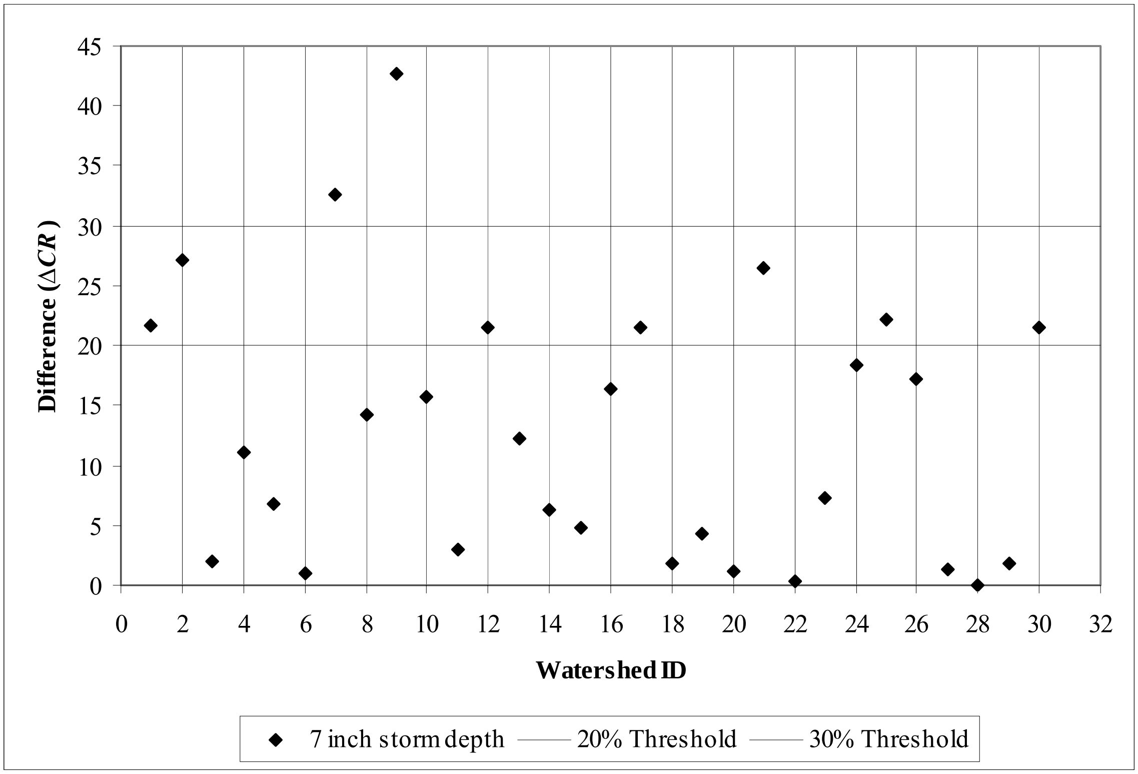


Figure E-5: Sensitivity comparison using observed Δ*CR* by watershed for 7-inch storm depth

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