IDENTIFYING POTENTIAL RUNOFF CONTRIBUTING AREAS IN A GLACIATED LANDSCAPE USING A GIS-BASED MODEL

By

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A Thesis
submitted in partial fulfillment
of the requirements for the degree

MASTER OF SCIENCE
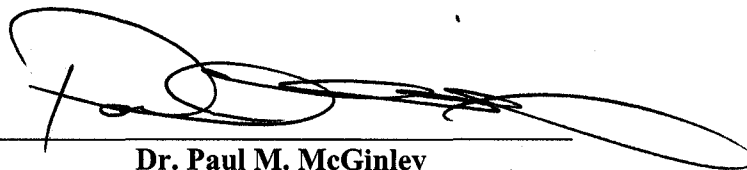
IN

NATURAL RESOURCES
(WATER RESOURCES)

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UNIVERSITY OF WISCONSIN
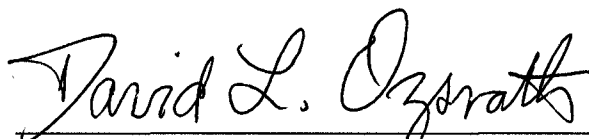**Stevens Point, Wisconsin**

December 2009

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ACKNOWLEDGMENTS

I would like to thank my graduate advisors Dr. Katherine Clancy and Dr. Paul McGinley for their insights and guidance and Dr. David Ozsvath for his recommendations and continued interest in the project. I would also like to thank all the folks at the UW Extension Center for Watershed Science and Education, notably George Kraft and Kevin Masarik, for keeping me entertained throughout the course of this study. And to my wife Ellie, whose endless patience and love provided limitless inspiration, thank you, from the bottom of my heart.

ABSTRACT

Hydrologic and water quality modeling require the characterization of runoff generating processes within watersheds. This necessitates not only the identification of runoff generating mechanisms, but also the delineation of areas within a watershed with the capability to provide runoff of streams, the latter being problematic in the Midwest where glaciations have left discontinuous areas of internal and disconnected drainage. This paper presents the results of an analysis using the PCSA (Potential Contributing Source Area) model to identify potential contributing areas, defined as areas from which runoff is physically capable of reaching a drainage network. The investigation was conducted to define the potential contributing areas of Upper St. Croix Lake, the headwaters of the St. Croix River, in north-west Wisconsin. The investigation included the use of the PCSA model to identify potential contributing and internally drained areas, a study of the Curve Number (CN) method to predict runoff volumes in the watershed, and an evaluation of the extent of potential contributing areas in relation to the minimum contributing area required to generate measured runoff volumes. Using the PCSA model, large areas of internal drainage were identified, comprising up to 70% of the catchments of tributaries to Upper St. Croix Lake. The streamflows of four tributaries were measured and the runoff portion of the hydrograph quantified to be compared with runoff estimates calculated using the potential contributing areas and the traditional catchment area. Runoff producing events occurred, but the use of tabulated CN values was unsuccessful in modeling runoff due to all precipitation depths during the study period falling below the initial abstraction. The extent of the minimum contributing area, estimated for a range of precipitation events, was found to be substantially less than the potential contributing areas, suggesting the PCSA model delimits the maximum boundary of potential contributing areas.

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INTRODUCTION

Watersheds define the boundaries of many hydrologic and water quality studies even though large regions of the United States have topographic features (karstlands, glaciated areas, and sandy areas) or climatic characteristics (excessively arid areas) that make delineating watershed boundaries difficult or impossible (Omernik and Bailey, 1997). Delineating watersheds is especially problematic in the Midwest where multiple glaciations have left a relatively flat landscape with many potholes, wetlands, and lakes topographically isolated from the drainage network. Precipitation falling on these internally drained areas may eventually reach a stream via groundwater, but runoff generated in these areas may never reach a stream except during the most extreme rain events.

Watersheds are often delineated with geographic information systems (GIS). The Arc Hydro GIS toolset is commonly used to delineate watersheds because it provides a consistent method of watershed delineation using publically available data (Maidment, 2002). Arc Hydro identifies watersheds using digital elevation models (DEMs) and streamlines. In order to delineate watersheds, a DEM must first be filled, a process of removing discontinuous slopes, to enable drainage from each point on the land surface to reach a stream. In glaciated regions, the process of filling the DEM can incorrectly connect internally drained areas to the stream network.

Hydrologic and water quality models are generally conceptualized by first determining the dominant process of runoff generation (e.g., saturation excess or infiltration excess flow) followed by identifying the areas in a watershed prone to generating runoff (Agnew et al., 2006). Identifying the areas that generate runoff but don't contribute to a drainage network (e.g. drain to a closed depression) is a process often neglected. Identifying the portions of watersheds that actually contribute runoff to

the waters of interest is necessary for correctly identifying the factors that affect water quantity and quality. Research has shown that including internally drained areas in water quantity and quality extrapolations can lead to the over estimation of runoff volumes and nutrient loads (Kirsch et al., 2002; Richards and Brenner, 2004).

Variable source areas, defined as the areas of a watershed that generate runoff and vary in extent and location depending on soil type, soil moisture conditions, storm intensity, and topography, have long been recognized as the primary source areas of runoff in many watersheds (Dunne and Black, 1970). Identifying variable source areas has historically been done through extensive field surveys requiring multiple site visits at various times of the year. Physically based hydrologic models, such as TOPMODEL (Beven and Kirkby, 1979) and the Soil Moisture Distribution and Routing (SMDR) model (Frankenberger et al., 1999), have been developed to model variable source areas through the use of topographic indices to identify areas prone to saturation on the landscape. These models require that the underlying assumptions be met and often require refined, high-resolution datasets and sub-daily precipitation measures (Woods et al., 1997; Agnew et al., 2006).

Although distributed models such as those mentioned above may correctly identify areas producing saturation excess runoff and can be calibrated to provide accurate streamflows (e.g. Guntner et al, 2004; Golden et al., 2009), these models are often passed over in favor of models which do not take into account the variable nature of areas that generate runoff, such the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1993). Models such as SWAT can also be calibrated to provide accurate streamflows, but the mechanism and distribution of runoff generation may be incorrectly represented (Lyon et al., 2006).

An efficient approach for identifying the areas that are hydrologically connected, and therefore, physically capable of supplying runoff to the drainage networks, has not been readily available. Methods such as identifying and removing "sinks" from the watershed can result in the delineation of many small (one to tens of grid cells in size) catchments that represent internally drained areas. This leads to the tedious task of either identifying catchment groupings of significance or determining a "fill" depth to apply to the DEM, thus eliminating small catchments altogether. The common practice of modifying a DEM by "burning in" (assigning lower elevations to) stream networks can eliminate some of these problems by creating more continuous stream flow paths, but the consequence is the creation of artificial riparian slopes.

The absence of an efficient model to identify the location of potential contributing areas prompted the development of the Potential Contributing Source Area (PCSA) model (Richards and Brenner, 2004). PCSA is a spatial analytic algorithm that uses a DEM and an initial contributing area, input as a raster grid, to identify all topographic areas with an uninterrupted slope to a the hydrologically connected areas of a drainage network. The DEM is not processed to fill sinks, which exist naturally in the hummocky topography of glaciated landscapes. The unprocessed DEM maintains the slopes and overland flow planes of a study area otherwise lost during DEM processing methods. The user-specified initial contributing area represents all areas directly connected to the stream network, including flood plains, wetlands, and anthropogenic drainage alterations such as ditches and road cuts. The output of the PCSA model is a spatially referenced ASCII grid which can be imported into GIS for analysis. PCSA has been used to investigate how anthropogenic changes to natural drainage systems could alter runoff rates by increasing the contributing area of streams and to identify critical areas for

nonpoint source pollution and recharge (Barlage et al., 2002; Richards and Brenner, 2004; Richards and Noll, 2006).

       The overall goal of this study is to use the PCSA model to identify the areas of a northwestern Wisconsin watershed physically capable of contributing runoff to the stream drainage network. Catchments with more developed drainage networks are expected to have larger potential contributing areas. A secondary goal of this study was use the NRCS-Curve Number method to evaluate if runoff volumes are better estimated using the potential contributing areas rather than the entire catchment area. The minimum area required to generate the measured runoff volume of various events was determined to evaluate the extent of the potential contributing areas identified using the PCSA model. The differences between the traditional watershed boundaries and potential contributing areas highlight the importance of identifying the distribution of internally drained areas on the landscape.

STUDY AREA AND METHODS

The study was carried out on the Upper St. Croix Lake watershed (latitude 46°22'N, longitude 91°48'W) in Douglas County, Wisconsin and model evaluations were performed on the catchments of Beebe Creek, Rock Cut Creek, Spring Creek and Leo Creek (Figure 1). These catchments were selected because there are no anthropogenic controls on streamflow (i.e., impoundments) which produce hydrographs that are not representative of natural baseflow conditions. The study catchments have areas that range from 4.28 to 19.77 km² and have similar topographies, land use and soils. Multiple glaciations have left a relatively flat landscape with pitted and hummocky areas and poorly developed drainage networks. The predominant land cover in the catchments is forests, covering 46-56% of the landscape, followed by wetlands (33-44%); the balance consists of grasslands and moderate development (Table 1). The soils vary in thickness, with some areas of exposed bedrock and shallow soils in the northwest. The soils are coarse loam- and sand-textured, derived from glacial tills and highly permeable outwash sands that range in thickness from <1 m in the west to 75 m in the east near Upper St. Croix Lake.

TABLE 1. Percentages of land cover type in the study catchments and throughout the entire Upper St. Croix Lake (USCL) watershed.

Catchment	Forest	Wetland	Developed	Ag.	Grassland	Water
Beebe Ck	46.3	43.7	7.1	2.1	0.6	0.1
Rock Cut Ck	55.8	33.8	7.4	2.3	.6	.2
Spring Ck	53.4	35.8	4.2	5.5	1.1	0.0
Leo Ck	50.0	32.5	5.2	8.2	3.2	.8
USCL Watershed	54.9	25.8	7.5	4.2	3.0	4.5

The designation of watershed boundaries for this area is difficult, primarily due to the complex glacial history and the sandy, well-drained soils of the region. Large, continuous areas and pockets of internal drainage exist throughout and are of sufficient local relief that surface flow does not contribute runoff to the stream network. Wetlands present in the subwatersheds often have no obvious topographic drainage divides, adding to the difficulty of delineating drainage boundaries.
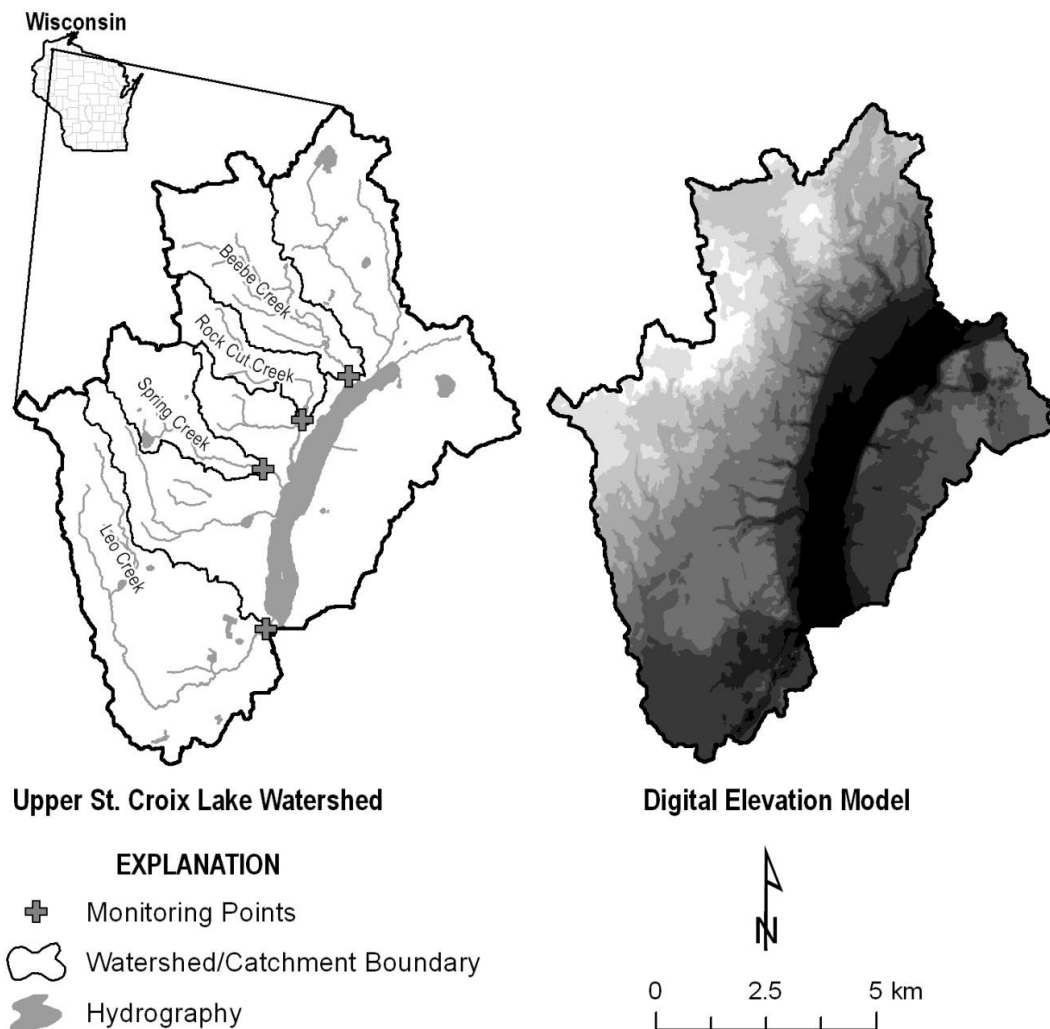

FIGURE 1. Location of the study catchments within the Upper St. Croix Lake watershed in Douglas County, Wisconsin. Monitoring points indicate the locations of stage recorders and the outlets of the study catchments. The darker regions in the digital elevation model correspond to lower elevations.

DATA DESCRIPTION

This study used readily available digital data from public agencies. Hydrography (lakes and perennial and ephemeral streams) at a 1:24000 scale were obtained from the Wisconsin Department of Natural Resources. Data obtained from the U.S. Geological Survey (USGS) include the 2006 National Land Cover Data (NCLD) (USGS, 2007) and a 10 m resolution digital elevation model (DEM). A 1 m resolution digital orthophoto from the National Agriculture Imagery Program (NAIP) was acquired from the WisconsinView website (WisconsinView, 2008). Information on soils was acquired from the Soil Survey Geographic Database (SSURGO). Watershed and catchment boundaries were delineated using ArcGIS 9.3 with the Arc Hydro 1.2 toolset. One hundred-year floodplains were digitized from geo-referenced FEMA maps using ArcGIS.

Stream stage was recorded at the outlet of each catchment with a pressure transducer (Levelogger model 3001; Solinst Canada, Ltd.) at 15 minute intervals during the 2008 growing season (May 1 through September 30). Streamflow was measured at various stages throughout the study period following the six-tenths depth method (Buchanan and Somers, 1984) using a SonTek FlowTracker acoustic Doppler velocimeter (ADV). Streamflows were used to develop stream rating curves (stage-discharge relationships) following USGS methods (Kennedy, 1984). The stream rating curves are in Appendix A. Hydrographs of mean daily flow were created by applying the stream rating curves to the recorded stages (Appendix B). The runoff and baseflow portions of the hydrograph were separated using the Web-based Hydrograph Analysis Tool (WHAT) and the local minimum method (Sloto and Crouse, 1996; Lim et al., 2005).

Daily precipitation data from May through September 2008 were obtained from the National Oceanic and Atmospheric Administration (NCDC, 2009) weather station in Gordon, Wisconsin, located 7 km southwest of the southernmost boundary of the Upper

St. Croix Lake watershed. The cumulative rainfall during the 2008 growing season was 43.38 cm, 7.72 cm below normal, which was preceded by 3 years of below normal rainfall. Independent precipitation events, defined as single-day events which produced storm hydrographs that were not influenced by subsequent rainfall, were identified from daily precipitation data and stream hydrographs. These independent events all have recurrence intervals of less than 1 year. Subsequent analyses were performed on the runoff volumes generated by these events (Table 2). Figure 2 shows the distribution of the events during the study period.

TABLE 2. Independent rainfall events selected for this study and associated hydrologic parameters and runoff generated in study catchments.

Event Date	Rainfall (mm)	Days since last rainfall	Antecendent rainfall (mm)	Direct Runoff (m³)			
				Beebe	Rock Cut	Spring	Leo
28-Jun-2008	22.1	5	0.3	1639.21	3156.08	244.66	4305.97
15-Jul-2008	17.0	2	22.9	538.25	611.64	318.05	685.04
29-Jul-2008	3.6	3	13.5	709.51	464.85	1174.36	733.97
4-Aug-2008	7.9	3	2.5	293.59	244.66	1370.08	3327.34
17-Aug-2008	3.0	3	9.9	318.05	195.73	73.40	293.59
24-Sep-2008	17.8	1	.5	4819.75	12526.47	954.16	4257.04
29-Sep-2008	16.5	2	20.3	2201.92	5602.66	1174.36	1565.81
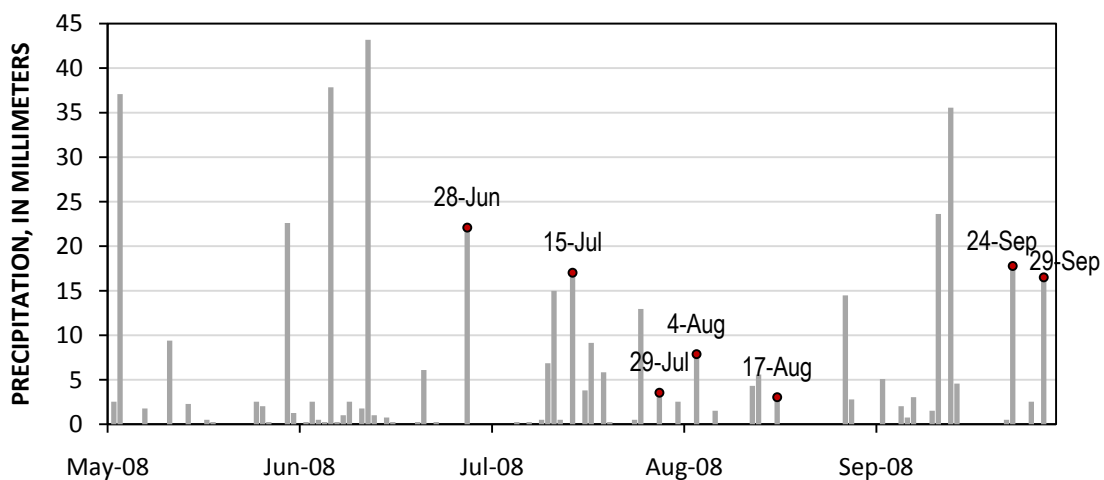
FIGURE 2. Size and temporal distribution of rainfall events occurring during the 2008 growing season in Gordon, WI. Independent rainfall events selected for this study are indicated by a dot and labeled with the date of the event.

IDENTIFYING POTENTIAL CONTRIBUTING AREAS

Minor changes were made to the PCSA code to create the model used in this study. Following procedures described by Richards and Denchev (SUNY Brockport, 2008, unpublished paper), the PCSA code was modified to allow for the input of larger raster grids and to perform more iterations. The number of iterations multiplied by the raster cell size determines the area around the initial contributing area that is assessed. For this study, 500 iterations were performed, thereby evaluating the topographic conditions a distance of 5000 m from the initial contributing area. The maximum size of raster grids that could be analyzed by PCSA was increased from 6000 columns and rows to 10,000 in order for the 10 m DEM to be utilized. Appendix C contains the modified PCSA source code.

The development of the initial contributing area (Figure 3) was the most labor intensive process of the PCSA model. The process involved using GIS to combine shapefiles and polygons of streams, lakes, wetlands, 100-year floodplains, and anthropogenic drainage systems into a single data set. The initial contributing area was first determined by using a GIS overlay method, or intersection, to select the hydrologic features mentioned above that are in direct contact with the stream network. The connectivity and extent of features were then verified by both referencing USGS topographic maps and digital orthophotos and conducting field surveys. Because of the complexities associated with wetland flow paths and the lack of obvious topographic drainage divides, the entire area of connected wetlands was included in the initial contributing area. Features not connected to the stream network were removed from the dataset. The dataset was then converted to a raster grid. The grid was required to have the same cell-size and spatial extent as the DEM and was formatted such that a value of 1

represented the initial contributing areas and a value of zero represented all other areas of the watershed.

The initial contributing network and DEM were loaded into PCSA as floating point grid files. Starting with the initial contributing network, PCSA evaluates adjacent raster cells to determine if they are higher in elevation. The cells are evaluated similarly to the D8 flow direction method, which assumes flow may enter a cell from the four side faces and diagonally from the four corners of adjacent cells (O'Callaghan and Mark, 1984). Cells that are upslope in any of the eight directions (as opposed to only the steepest path as with the D8 method) are added to the contributing area, and cells that are lower or at the same elevation as the contributing area cell are not added to the collection. This process is repeated using the new collection of contributing cells for the set number of iterations.
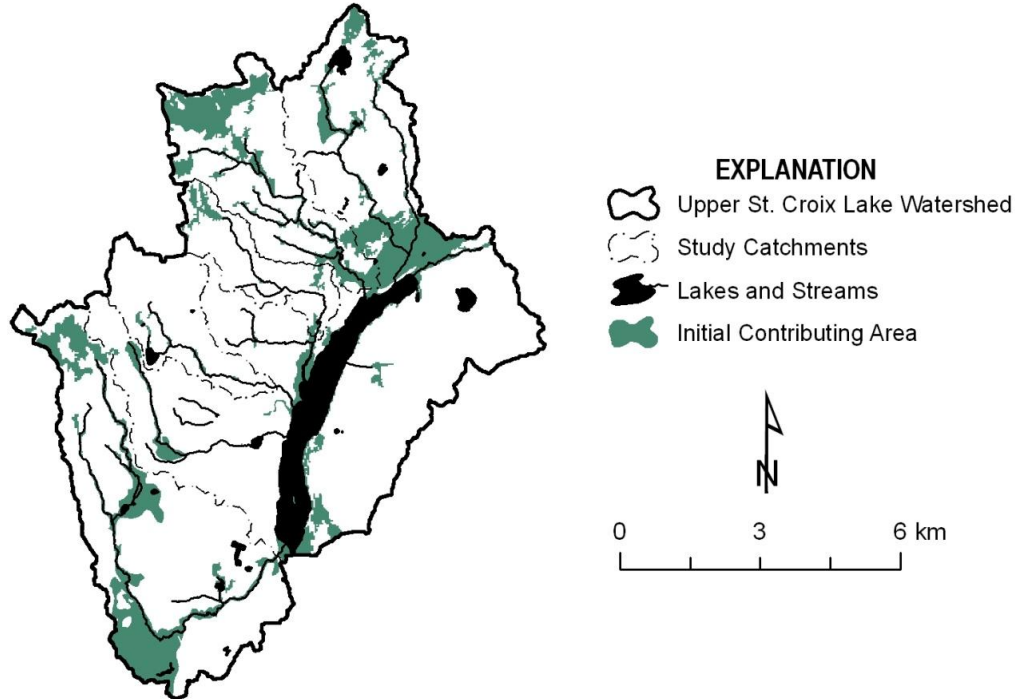
FIGURE 3. Initial contributing areas consisting of hydrologically connected stream network, wetlands, floodplains and anthropogenic drainage.

The PCSA output was converted to a raster and imported into ArcGIS for further refinement. The potential contributing areas sometimes extend beyond the traditional watershed boundary. This extension of the boundary occurs because the model selects all cells with an uninterrupted slope to the drainage network, which may include cells that are closer to and likely contributing to another drainage systems. To account for this, the potential contributing area was limited to the traditional watershed boundary. Each catchment was analyzed separately to identify if this overlap existed between the boundaries of the study catchments. Small areas (less than 50 m^2) of overlap were identified as well as areas where the potential contributing area followed a slope path that bridged the catchment boundary (e.g. around a hill) thus creating isolated areas which were subsequently deleted.

DATA ANALYSIS

Curve Number Analysis

The NRCS-Curve Number (CN) method (USDA-SCS, 1972) was selected to calculate the runoff volumes of various precipitation events for both the potential contributing area and traditional catchment area for comparison with the measured runoff volumes. The CN method was used because it is a simple and widely applied approach for determining direct runoff volumes from a precipitation event (Ponce and Hawkins, 1996; Garen and Moore, 2005). The CN method computes runoff volume (Q) in inches as

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \quad \text{for P} \geq 0.2\text{S} \tag{1}$$

$$Q = 0 \quad \text{for P} < 0.2\text{S}$$

$$\text{where } S = \frac{1000}{CN} - 10$$

In Equation (1), P is the depth of precipitation in inches, S is the potential maximum storage in inches, and CN is the curve number. The CN method was developed for watershed-scale use and does not identify the proportion of stream flow provided by each runoff generating mechanism or whether flow is generated from all or part of the watershed (Garen and Moore, 2005).

The area-weighted CN for each catchment and associated potential contributing area was identified using a GIS process similar to the methods of Zhan and Huang (2004). This process assumes a good hydrologic condition and antecedent soil-moisture condition (AMC) II. Unique values assigned for each combination of soil and land use were linked to a lookup table which assigns the appropriate CN for each combination. The CN values identified were adjusted to the associated AMC I CN values, the moisture conditions which prevailed throughout the 2008 study period. The web-based program L-THIA (available at: http://cobweb.ecn.purdue.edu/~watergen/) was also used to generate CN values for the study catchments. The L-THIA program uses STATSGO soils, which have a lower resolution than the SSURGO soils used in the GIS analysis. The CN values identified from these approaches can be found in Table 3.

Although runoff producing events were identified from hydrograph analysis, none were large enough to meet the CN method requirement of a precipitation depth greater or equal to two-tenths storage (S) depth when using the area-weighted CN. The inability to successfully determine CN values in forested watersheds using land use and soils data is paralleled in other studies (Hawkins, 1993; Ponce and Hawkins, 1996) and has been attributed to the large infiltration capacity of forest soils due to surface vegetation and debris coupled with thick and highly permeable organic horizons and root zones (Tedela et al., 2008). This suggests saturation excess is the likely source of runoff in forested watersheds.

The distributed CN approach was also used to estimate runoff. With the distributed CN method, runoff depth was calculated for each individual grid cell (30 m by 30 m) used for the area-weighted calculation of CN. The runoff depths for each grid cell were weighted by area and summed for the total runoff depth. Grove et al. (1998) found that the distributed CN method improves runoff estimates for smaller precipitation events in catchments with a wide range of CN values.

Hawkins (1993) proposed a method for the asymptotic determination CN values for gauged, forested watersheds, which was used to calculate the CN values for the study catchments. The precipitation and runoff depths were sorted separately in descending order and realigned to form pairs assumed to be of equal return periods during the study period. The CN for each catchment and potential contributing source area was solved for by first calculating S from the pairings using the following equation

$$S = 5[P + 2Q - (4Q^2 + 5PQ)^{1/2}] \qquad (2)$$

which in turn was used to calculate the CN. The few and relatively small rain events that occurred during the study period provided too few data points from which to discern whether the calculated CN values were approaching a constant value or to define an asymptotic behavior to the CN values. The average curve number and standard deviation for the events from which the CN was computed can be found in Table 3. Frequency matching of calculated CN values and precipitation depths are in Appendix D.

The primary mechanism of runoff generation in the study catchments was further investigated through an analysis of the saturated hydraulic conductivity of the soils in the catchments to estimate the recurrence interval of an event required to produce infiltration excess runoff (s*ensu* Walter et al., 2003). The average representative saturated hydraulic conductivity for soils in the study catchments, identified using SSURGO soils data, is estimated to be 17.2 cm·hr^{-1}. Assuming infiltration excess occurs when the rainfall

intensity exceeds the saturated hydraulic conductivity (synonymous with permeability) an event with a return period greater than 10 years is required to produce infiltration excess runoff, which suggests infiltration excess is not the dominant mechanism of runoff generation in the catchments investigated.

TABLE 3. NRCS-Curve Number values identified for the study catchments using various methods. The mean and standard deviation of CN values computed using the asymptotic method are presented; more and larger events are required for a complete asymptotic analysis.

Catchment	Traditional Catchment			Potential Contributing Areas	
	GIS	L-THIA	Asymptotic	GIS	Asymptotic
Beebe Creek	33	60	84.4 ± 8.3	34	84.5 ± 8.2
Rock Cut Creek	29	50	87.4 ± 6.2	29	88.0 ± 6.0
Spring Creek	31	59	84.4 ± 8.4	34	85.7 ± 7.7
Leo Creek	29	46	84.0 ± 8.6	31	84.6 ± 8.3

An example of the inability of the CN method to generate runoff is presented in Table 4. Recalling equation (1), if the precipitation depth (P) is less than two-tenths of the storage (S), no runoff is generated. The example uses the L-THIA derived CN for each watershed, the largest identified, and the largest independent rainfall event.

TABLE 4. Runoff calculated by CN method for each study catchment using largest rainfall event and highest CN value. All units except for CN (unit-less) are millimeters.

Catchment	Rainfall (P)	CN	S	0.2·S	Runoff
Beebe Creek	22.1	60	169.3	33.9	0
Rock Cut Creek	22.1	50	254.0	50.8	0
Spring Creek	22.1	59	176.5	35.3	0
Leo Creek	22.1	46	298.2	59.6	0

Minimum Contributing Area Method

To evaluate the extent of the potential contributing areas, the methods of Dickinson and Whiteley (1970) were used to quantify the minimum area that would yield the measured direct runoff if contributing 100% of the effective precipitation. This simple approach was chosen because of a lack of data required for estimating the fraction

of the watershed contributing runoff via other methods (e.g. Lyon et al, 2004). The independent precipitation events were used to determine the minimum contributing area which was calculated as:

$$R_a = \frac{V}{P_e} \qquad (3)$$

where R_a is the minimum contributing area, V is the volume of direct runoff as determined by hydrograph separation, and P_e is the depth of effective precipitation (Dickinson and Whiteley, 1970). Effective precipitation was approximated as the initial abstraction subtracted from the total event precipitation, where the initial abstraction represented the rainfall intercepted by vegetation, depression storage, and infiltration. A constant initial abstraction value of 1.5 mm was determined by identifying the maximum precipitation depth that produced no runoff during the study period. The runoff volume determined from hydrograph separation was used in Equation 3 to compute the minimum contributing area required for an event to generate the associated measured runoff.

RESULTS

POTENTIAL CONTRIBUTING AREAS

Figure 4 shows the distribution of potential contributing areas in the study area as determined by the PCSA model. The percent of the catchment area defined as potential contributing area is given in Table 5. The ratio of the potential contributing area to the catchment area was found to be positively correlated to the catchment drainage density (Figure 5). As expected, the relationship indicates that more developed drainage networks have larger potential contributing areas.
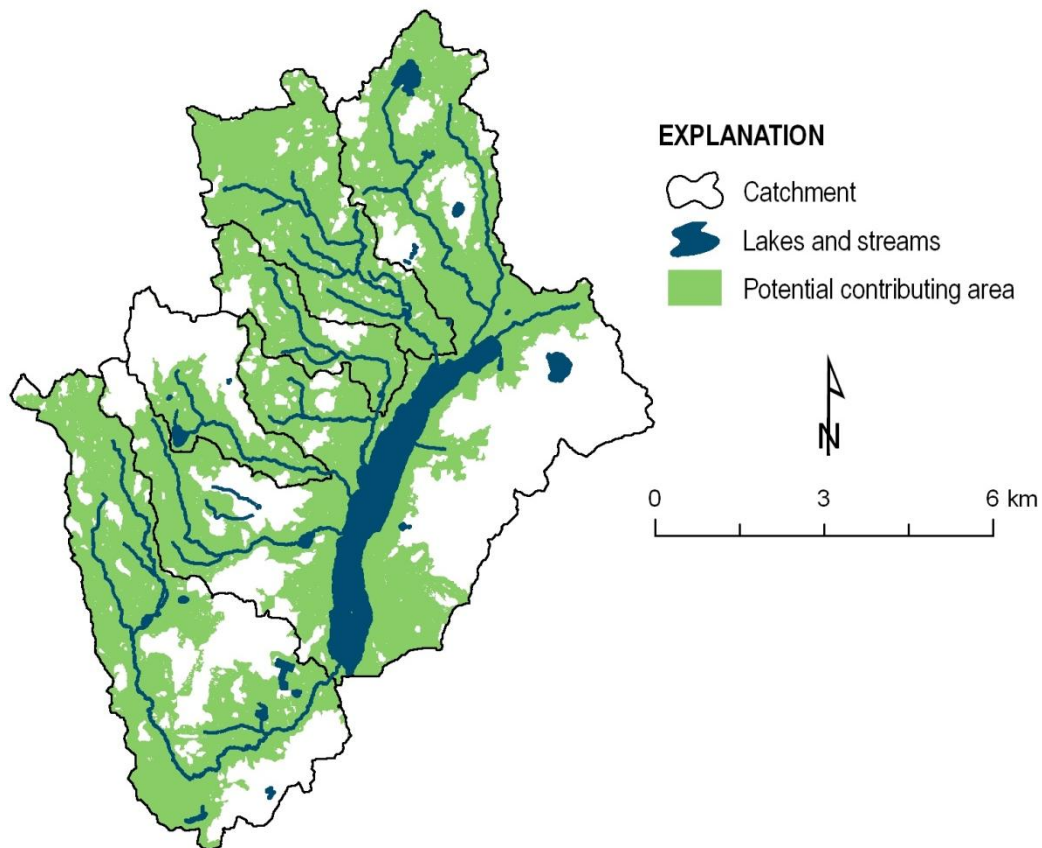
FIGURE 4. Potential contributing areas and stream network of the Upper St. Croix Lake watershed. The traditional watershed boundary for each study catchment is also shown.

TABLE 5. Extent of Upper St. Croix Lake (USCL) watershed, investigated catchments and potential contributing areas (PCA) and the percent of the catchment identified as potential contributing areas.

Catchment	Catchment Area (km^2)	Potential Contributing Area (km^2)	PCA : Catchment (%)
Beebe Ck	9.98	9.23	92.5
Rock Cut Ck	4.28	3.47	81.1
Spring Ck	5.56	2.65	47.6
Leo Ck	19.77	13.75	69.6
USCL Watershed	83.67	57.88	69.2
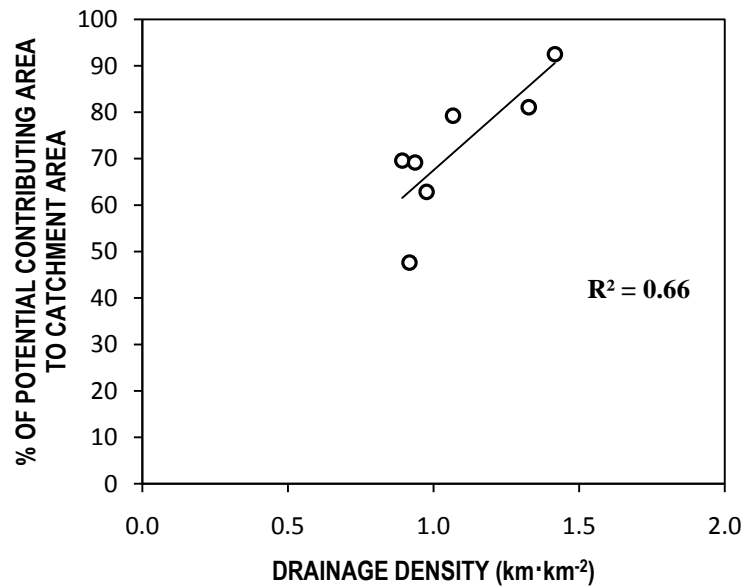
FIGURE 5. Correlation of the drainage density and ratio of the potential contributing area to catchment area, including two unmonitored catchments and the entire Upper St. Croix Lake watershed.

The land cover distribution within the potential contributing areas was extracted using ArcGIS 9.3 and found to be very similar to that of the catchment and watershed areas (Table 6). These results are similar to those of the Mallets Creek watershed in Michigan, where the minor differences between various landscape characteristics were attributed to a random distribution of the characteristics (Richards and Brenner, 2004).

TABLE 6. Percent change of land cover distribution between traditional catchment boundaries and potential contributing.

Catchment	% Difference by Land Cover Class					
	Forest	Wetland	Developed	Ag.	Grassland	Water
Beebe Ck	-0.4	-0.5	0.9	0.1	-0.1	0.0
Rock Cut Ck	-0.7	1.4	-0.3	-0.2	-0.1	0.0
Spring Ck	2.2	4.2	-3.0	-3.1	-0.3	0.0
Leo Ck	0.2	-2.5	0.5	0.7	1.5	-0.3
USCL Watershed	2.2	-2.8	0.1	0.4	1.9	-1.7

A negative relationship exists between the ratio of the potential contributing area to the catchment area and the baseflow index (Figure 6). The correlation was improved by including additional catchments from within and nearby the Upper St. Croix Lake watershed. The total catchment area has a stronger correlation with both the average baseflow (Figure 7) and the total event flow (baseflow plus runoff) than with the potential contributing area; however, for some events, the correlation between runoff volume and potential contributing area was higher than the correlation between the runoff volume and traditional catchment area.

The distributed Curve Number approach (*i.e.*, area weighted discharge) of calculating event runoff showed a slight improvement of the runoff estimate for independent events when using the potential contributing area rather than the catchment area (Figure 8). The distributed CN approach was successful in calculating some depth of runoff for all but the Spring Creek study catchments; however, the runoff volumes calculated for both the potential contributing area and catchment area were substantially less than measured runoff, only comprising at most 23% and 24% of the measured runoff, respectively.

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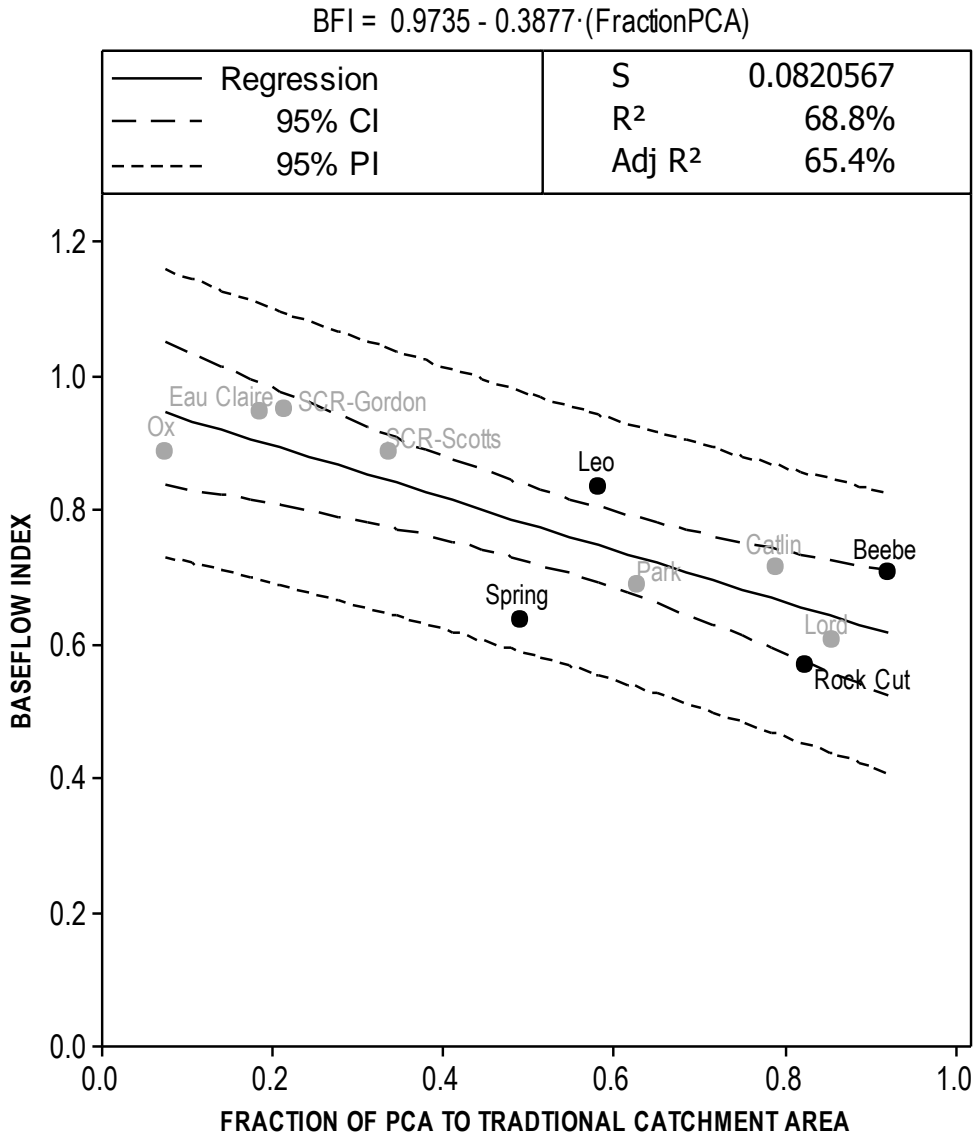
FIGURE 6. Correlation between the baseflow index and the fraction of potential contributing area to catchment area. Study catchments are indicated by the black circles; other catchments located within and near the Upper St. Croix Lake watershed are indicated by gray circles.
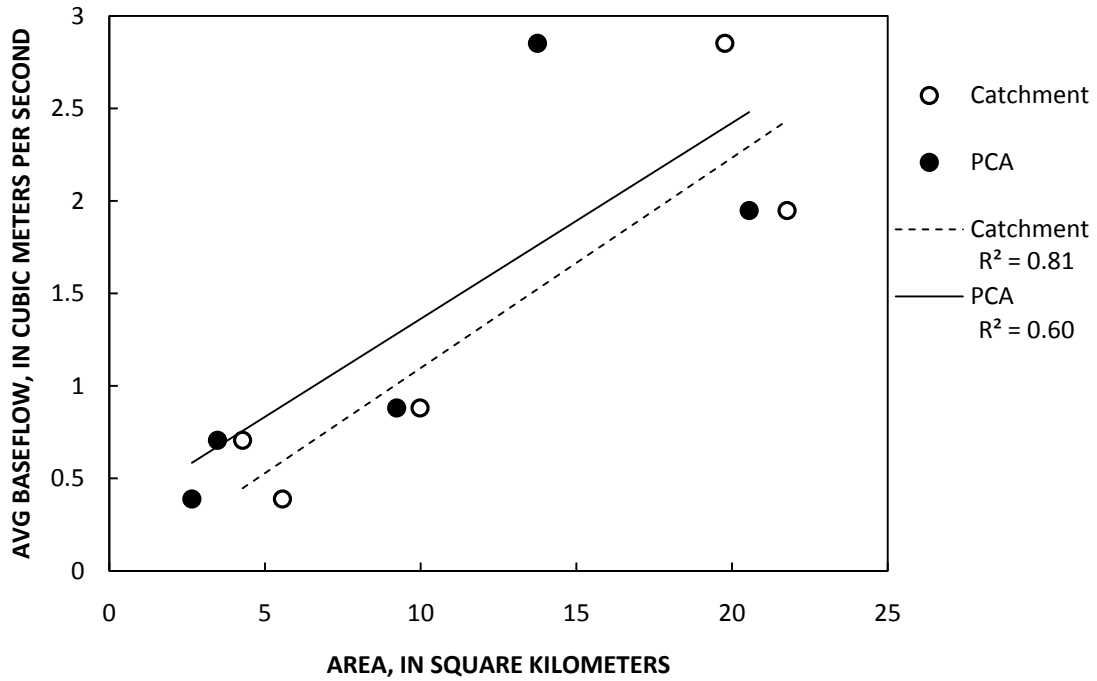
FIGURE 7. Correlation between average stream baseflow (18 May – 18 October 2008) and both catchment area and potential contributing area. To better express the trend, Lord Creek, a monitored catchment located adjacent to the Leo Creek catchment, is included.
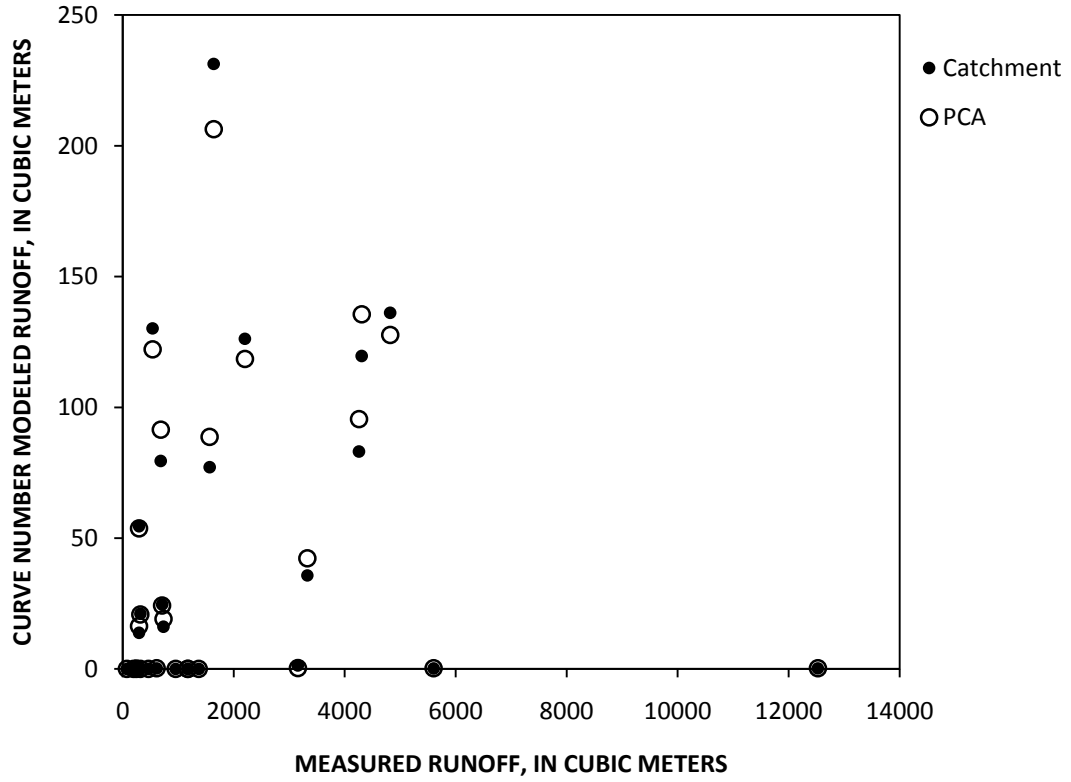
FIGURE 8. Field measured runoff versus Curve Number modeled runoff (using area weighted discharge) of both the potential contributing area and catchment area for independent events occurring during the study period. Note: the 1:1 line runs very close to the Y-axis.

EVALUATION OF POTENTIAL CONTRIBUTING AREA EXTENTS

The minimum contributing areas computed for independent precipitation events using Equation 3 are shown as a percent of the potential contributing area in Table 7 for comparison. All minimum contributing areas were found to be a small fraction of the potential contributing area. The Beebe Creek and Rock Cut Creek catchments responded similarly in terms of whether the minimum contributing area increased or decreased with respect to the previous event investigated. Spring Creek and Leo Creek responded differently than the other catchments investigated.

TABLE 7. Minimum contributing area computed for various events for each study catchment.

Date	Rainfall (mm)	Minimum Contributing Area as % of PCA			
		Beebe Ck	Spring Creek	Rock Cut Creek	Leo Creek
6/28/2008	22.1	.9	0.4	4.4	1.5
7/15/2008	17.0	.4	.8	1.1	.3
7/29/2008	3.6	3.7	21.6	6.5	2.6
8/4/2008	7.9	.5	8.1	1.1	3.8
8/17/2008	3.0	2.2	1.8	3.6	1.4
9/24/2008	17.8	3.2	2.2	22.2	1.9
9/29/2008	16.5	1.6	3.0	10.8	.8

DISCUSSION

The potential contributing areas identified by the PCSA model are essentially the topographic limits of areas that supply surface runoff to the drainage network. Runoff occurring in regions outside the potential contributing but area but still in the watershed likely flows to internally drained areas where it may provide stream baseflow via groundwater recharge to the drainage network. The variation in the percent of the study catchments' area identified as potential contributing area is related to the development of the drainage network.

The total catchment area is better correlated to the total event flow and baseflow than the potential contributing area. The relationship between baseflow index and the fraction of the catchment identified as potential contributing area is significant (Figure 6). This relationship suggests that catchments with a larger percentage of internal drainage have a larger percent of flow supplied by baseflow. The trend in Figure 6 may be influenced by impoundments and natural lakes located upstream of the gauging stations for five of the seven additional catchments, which, during dry periods, likely provide flow from storage in addition to the stream baseflow. The potential contributing area is better correlated, with respect to the catchment area, to the runoff volume more often than to the total event flow, indicating that the potential contributing areas are better representative of the runoff source areas than the source areas that provide the total event flow.

The accurate delineation of the spatial distribution of areas that provide runoff to stream networks has implications to hydrologic and water quality models. In this study, the differences between the extent of the potential contributing areas and the catchment areas are of sufficient size to have substantial effects on the extrapolation of nutrient yields (mass per unit area) and the calculation of runoff volumes. The land use

percentages within the potential contributing areas changed little from the traditional catchment boundaries in this study. The land cover distribution was expected to differ between the catchment and potential contributing areas, primarily because wetlands were inherently selected when developing the initial contributing area. The small changes in the land use percentages may be a reflection of a random distribution of land use in the Upper St. Croix Lake watershed. In watersheds with preferential land use distributions, for example agricultural or developed lands dominating near-stream areas, the location and contribution of runoff producing areas becomes an important issue, particularly when assigning a CN for hydrologic modeling.

An attempt was made to compare the runoff volumes of the potential contributing areas with the volumes of the traditional catchment using the NRCS Curve Number approach. In this study CN values, as determined using standard methods and tabulated values, did not predict runoff volumes. Runoff volumes were possible to compute using a distributed CN approach for all but the Spring Creek catchment. Although the runoff volumes computed using the potential contributing source areas were substantially less than the measured volumes, they were a slight improvement over runoff volumes computed using the entire catchment area.

Additional precipitation monitoring stations located within the study catchments would provide more accurate estimates of runoff. The data from the NOAA gauge used in this study differed from discontinuous rainfall data collected from within 2 km of the study catchments by as much as 23.6 mm during single precipitation events. Discrepancies of this magnitude are likely to have a strong impact on the estimated runoff volumes.

The minimum contributing areas within each catchment for seven precipitation events were calculated and found to be substantially smaller than the potential

contributing area identified by the PCSA model. A relationship between event size and the minimum contributing area did not exist, suggesting a variable nature to the runoff contributing areas in the study catchments. This implies that the modeled potential contributing areas encompass the variable sources areas of the catchments; however, the study occurred during a four year period of below normal precipitation, particularly dry during the summer months. The absence of larger events during normal (i.e. AMC II) conditions prevented the calculation of the minimum contributing areas for potentially larger runoff volumes. These results may also be skewed by a lack of precipitation data within the study catchments.

CONCLUSION

The main objective of this study was to use the PCSA model to identify the potential contributing areas of the Upper St. Croix Lake watershed. Delineating watersheds in glacially derived landscapes using common GIS methods can incorrectly identify the areas with the capability to contribute runoff during a precipitation event. This study also sought to evaluate the difference between measured runoff volumes and the runoff volumes estimated with the CN method using both the potential contributing areas and the entire catchment area. Although numerous runoff producing events occurred during the study period, the rainfall was of insufficient depth for estimating runoff using the standard CN method. The distributed CN method of estimating runoff did provide runoff volumes for the independent events and were, in general, better estimated using the potential contributing areas than the entire catchment area. The minimum contributing areas of independent events were calculated and found to be substantially smaller than the potential contributing area of the catchment. The CN method was found to be inappropriate for estimating runoff volumes in the study watershed.

The PCSA model identifies potential contributing areas, the areas with the physical capability to contribute runoff to waters of interest. The variation between the percent of the catchments identified as potential contributing areas is related to the development of the drainage network. A Curve Number approach is not appropriate. Runoff producing events were identified from hydrograph separation, but none were large enough for the estimation of runoff using the CN method.

FUTURE DIRECTIONS

The potential source area of neighboring watersheds was also investigated and some were found to have substantially smaller potential contributing areas than watershed area. These streams had either dams or natural lakes that buffered storm runoff at the monitoring sites, making hydrograph interpretation difficult. A study of the stream response to events above these artificial and natural controls would be beneficial to developing a more complete understanding the hydrologic response of streams with respect to the extent of potential contributing areas. This could be further researched using a CN-based model, such as SWAT, in a more appropriate agricultural setting. Creating separate hydrologic response units for potential contributing areas and internally drained areas will better represent the distribution of runoff generation and could potentially facilitate model calibration.

It would also be beneficial to investigate the internally drained areas identified using the PCSA model. The role internally drained areas play in stream baseflow and groundwater recharge could be investigated with a groundwater flow model. Incorporating the internally drained areas into groundwater recharge models may improve recharge estimates by accounting for topographic variability.

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APPENDIX A: Stream Rating Curves

BEEBE CREEK RATING CURVE

$Q = 4.444 \cdot H^{1.606}$
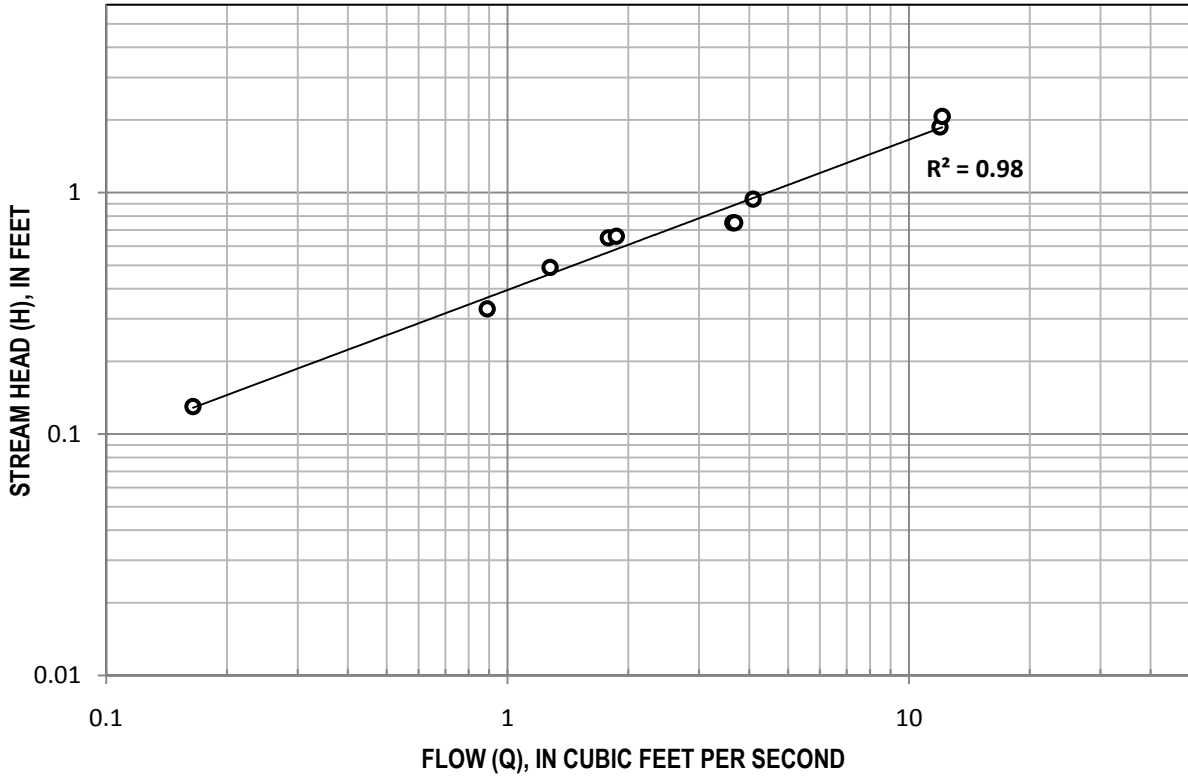
ROCK CUT CREEK RATING CURVE

$Q = 1.661 \cdot H^{2.608}$
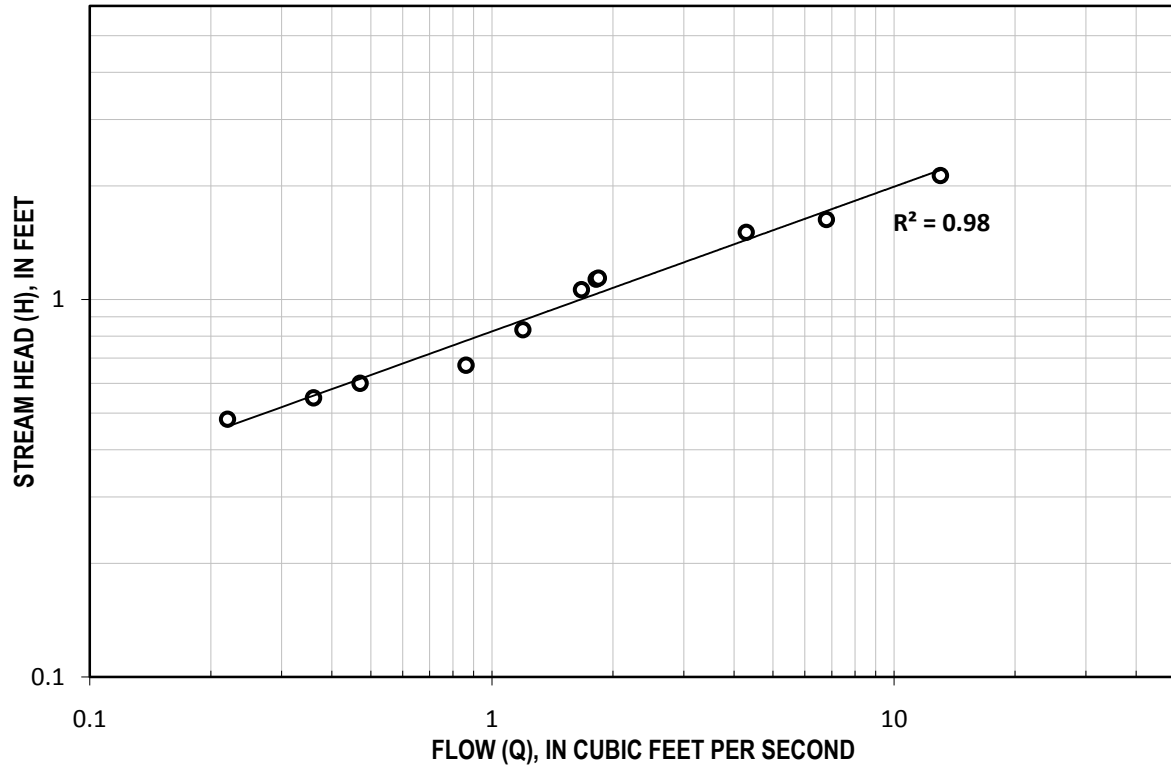
SPRING CREEK RATING CURVE

$Q = 7.921 \cdot H^{2.488}$
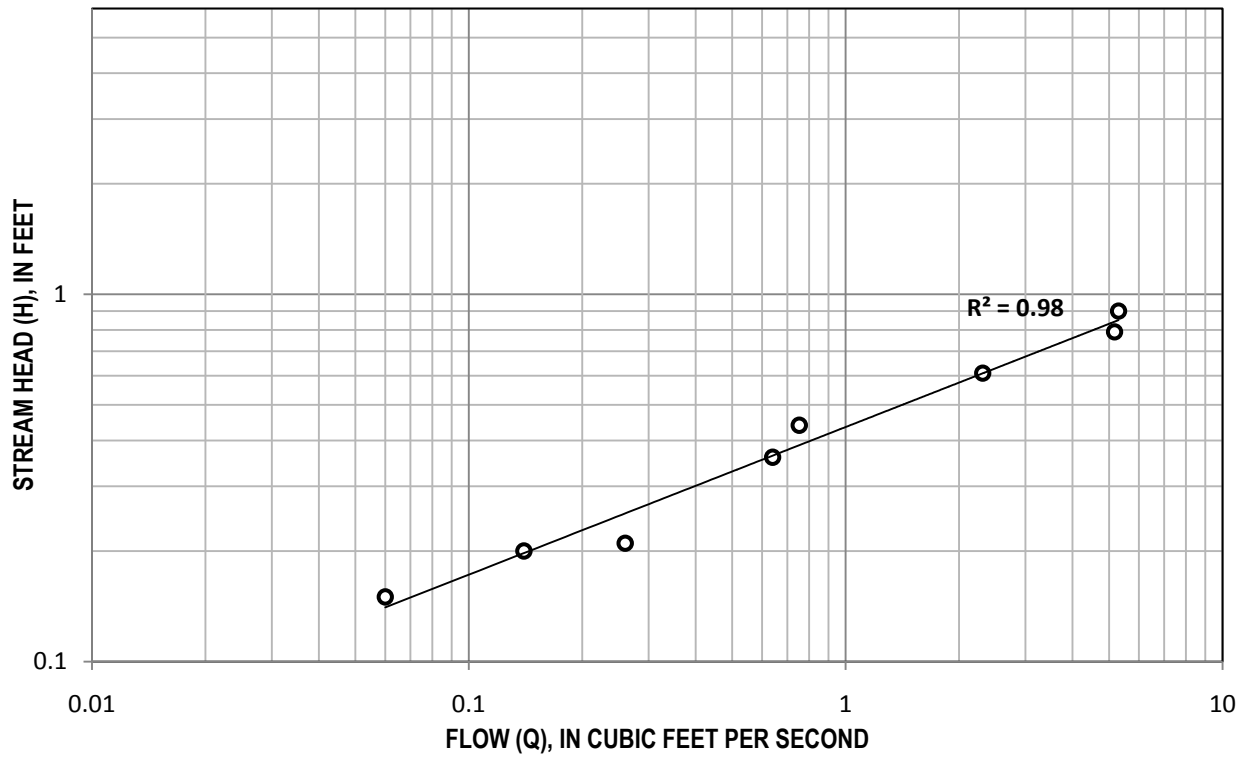
Appendix A-4

LEO CREEK RATING CURVE

$$Q = 0.922 \cdot H^{3.420}$$

STREAM HEAD (H), IN FEET

FLOW (Q), IN CUBIC FEET PER SECOND

$R^2 = 0.92$
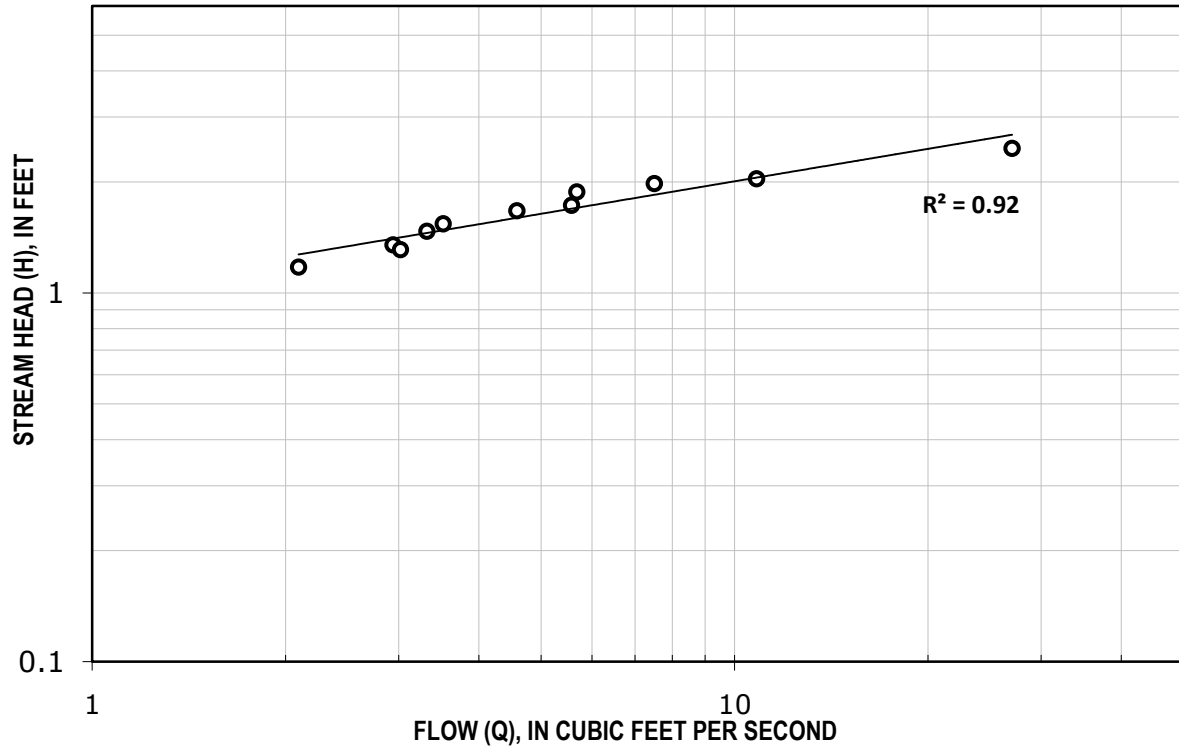
APPENDIX B: Stream Hydrographs

BEEBE CREEK AVERAGE DAILY FLOW
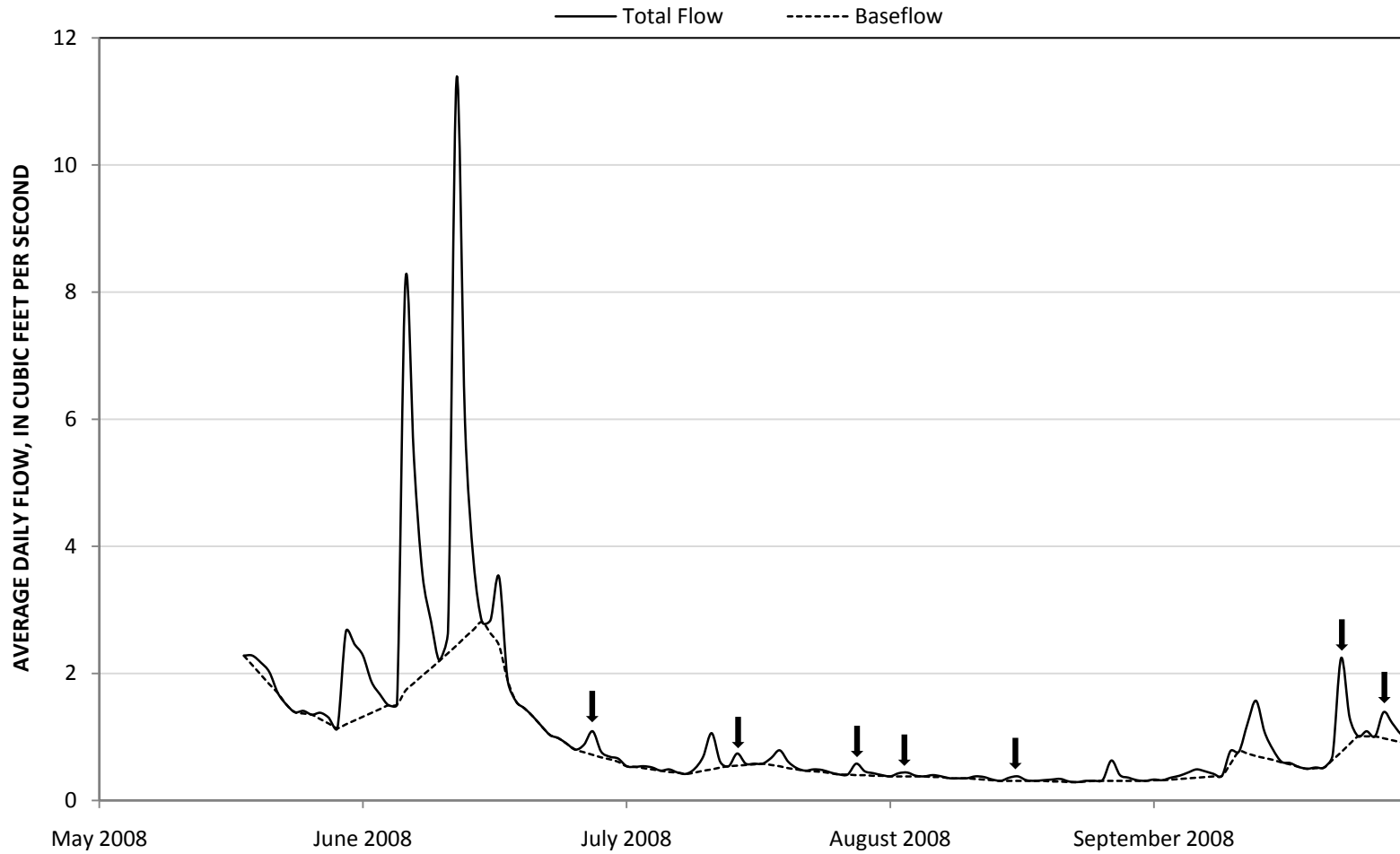
Note: Stage recorder malfunction May 1 to May 18.   Arrows identify independent events.

ROCK CUT CREEK AVERAGE DAILY FLOW
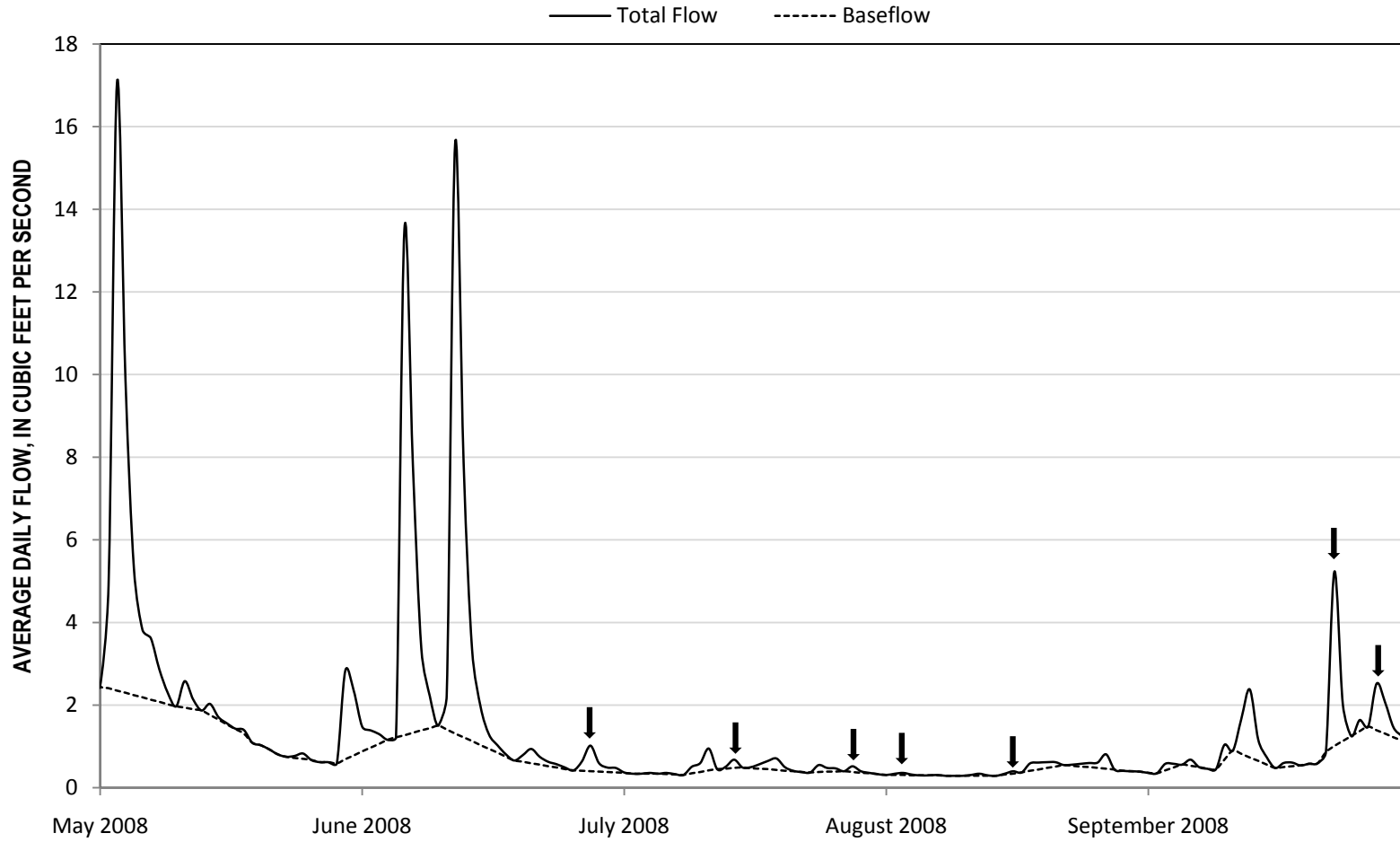
Arrows identify independent events.

Appendix B-3

SPRING CREEK AVERAGE DAILY FLOW
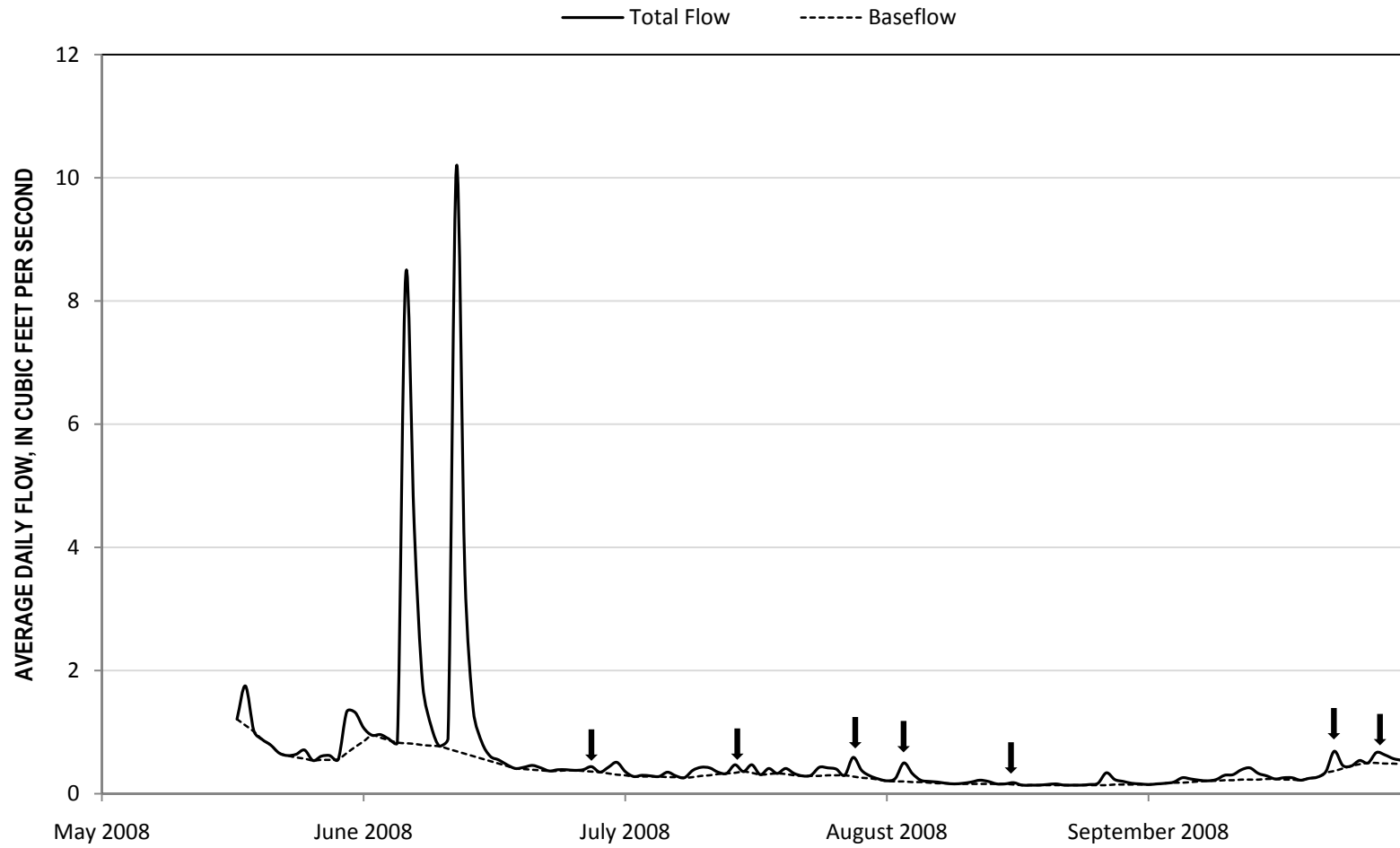
Note: Stage recorder malfunction May 1 to May 17.   Arrows identify independent events.

LEO CREEK AVERAGE DAILY FLOW
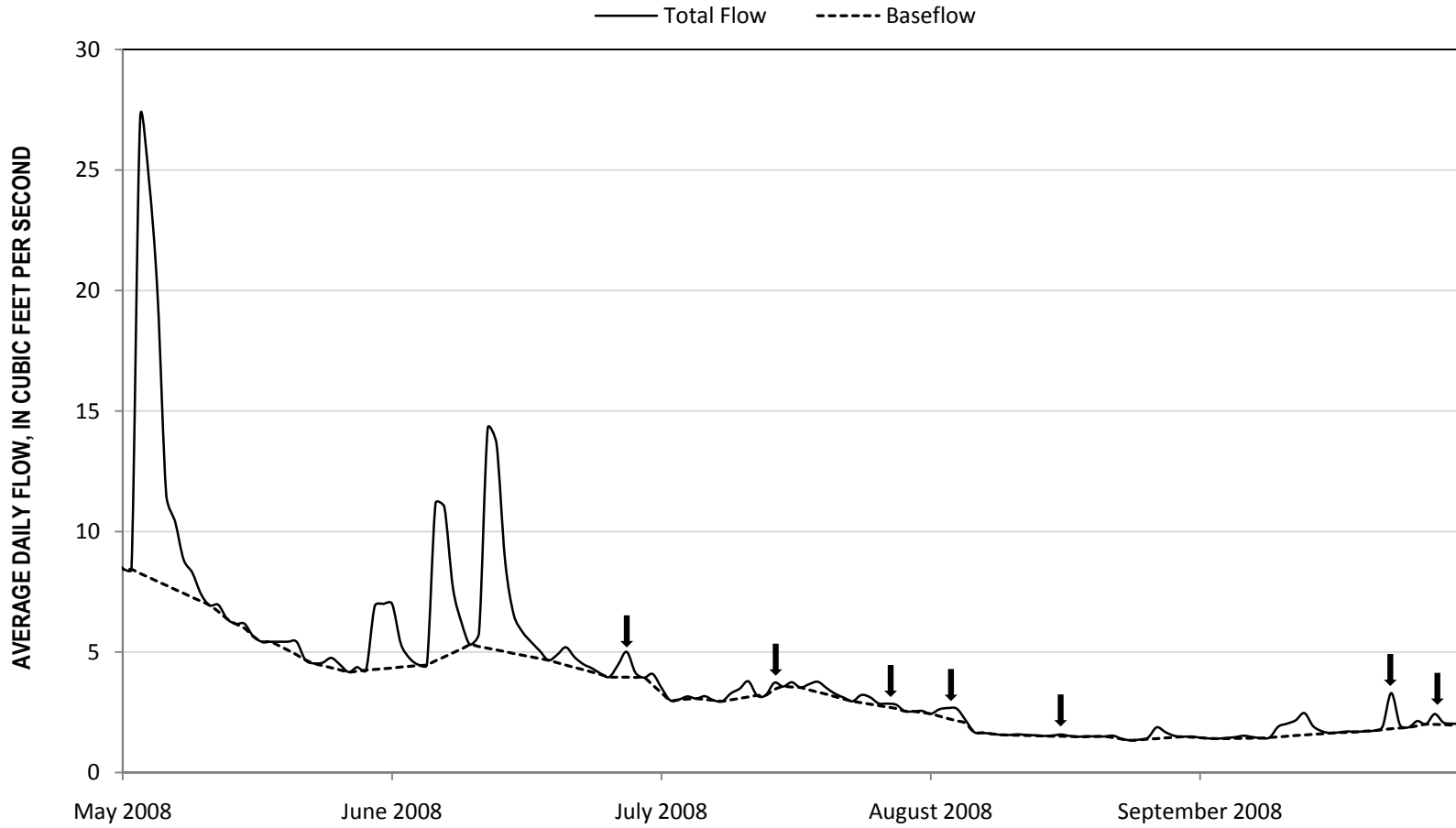
Arrows identify independent events.

APPENDIX C: FORTRAN Source Code for the PCSA Model

Code modifications are highlighted; compiled using Microsoft Visual Studio Fortran PowerStation v. 4.0.

```
      program PCSA
           USE MSFLIB
!        FORTRAN program to define
!      contributing source areas from dems
!         Written by Paul Richards 10/19,1998
!
!      Flood plain Version modified 2/16/99
!      Optomized by Vasil Denchev 1/15/2005
!      Fixed 'negative' flow error, Paul Richards 4/7/05
!        Full multidirection version
!      Modified to handle 10000 by 10000 grids, Jake Macholl 2/16/2009
!      Modified to increased Iterations to 500, Jake Macholl 2/16/2009
      implicit none
        integer :: g,h,i,j,ncols,nrows,inum,NODATA_value,start,active
        integer :: count,nrows1,ncols1
        real(kind = kind(1.0d0)) :: xllcorner,yllcorner,cellsize,dmax
        real(kind = kind(1.0e0)) :: raw_data(100000000),delev(8),temp(9)
        character*(512) :: block_data(281250)
        character*16 :: name
        character*13 :: fname, oname, dname
        character*8 :: byteorder
        integer(4) inumarg
        integer(2) status
        integer, ALLOCATABLE :: uphill(:,:)
        integer, ALLOCATABLE :: list(:)
       logical(1), ALLOCATABLE :: contrb(:,:),dir(:,:,:)
       real(kind = kind(1.0e0)), ALLOCATABLE :: dem (:,:)
!        namelist /a/ ls,nrows,xllcorner,yllcorner,cellsize
!      *,NODATA_value,byteorder

       equivalence (block_data,raw_data(1))


         inumarg=nargs()

C  request for command syntax
         if(inumarg.eq.1)then
              write(6,*) ''
              write(6,*) 'Syntax is...'
              write(6,*) ''
           write(6,*) 'PCSA [input file] [dem file] [output file]'
              write(6,*) ''
              stop ' '
          endif
          if(inumarg.lt.4)then
              write(6,*)
              write(6,*) 'Insufficient arguments'
              write(6,*) ''
              write(6,*) 'Syntax is...'
              write(6,*) ''
            write(6,*) 'PCSA [input file] [dem file] [output file]'
               stop ' '
           endif

C read in input filename
          call GETARG(1,name,status)

C  eliminate extension
        do 30 i=1,16
          if(name(i:i).eq.'.')then
             goto 31
          endif
          fname(i:i)=name(i:i)
 30      continue



C read in dem filename

 31    call GETARG(2,name,status)
```

```
C  eliminate extension
      do 32 i=1,16
         if(name(i:i).eq.'.')then
            goto 33
         endif
         dname(i:i)=name(i:i)
 32   continue

C read in dem filename

 33   call GETARG(3,name,status)

C  eliminate extension
      do 34 i=1,16
         if(name(i:i).eq.'.')then
            goto 35
         endif
         oname(i:i)=name(i:i)
 34   continue

C  Read in connected network file
35      open(1,file=TRIM(fname)//'.hdr',status='old')
10      format(14x,I8)
 11      format(14x,f16.6)
 12      format(14x,A8)
          read(1,10) ncols1
          read(1,10) nrows1
          read(1,11) xllcorner
          read(1,11) yllcorner
          read(1,11) cellsize
          read(1,10) NODATA_value
          read(1,12) byteorder

        write(6,*) ncols1,nrows1
        write(6,11) xllcorner
        write(6,11) yllcorner
        write(6,11) cellsize
        write(6,10) NODATA_value
        write(6,12) byteorder
        close(1)
          ncols = nrows1
          nrows = ncols1

!       nrows and ncols are switched due to accessing arrays by columns
!       load _net
!       read data in 512 byte blocks
         open (1,file=TRIM(fname)//'.flt',access='direct',
     *form='unformatted',recl=512)
         do g=1,nrows*ncols/128 + 1
         read(1,rec=g,err=102) block_data(g)
          enddo

102        ALLOCATE(contrb(nrows,ncols),list(4*nrows*ncols))
           active = 1
!    load data into contrb and build expandable list
        do j=1,ncols
          do i=1,nrows
            inum=(j-1)*nrows+i
            if(int(raw_data(inum)).eq.1) then
                    list(active) = i
                    list(active+1) = j
                    active = active+2
                    contrb(i,j) = .true.
               else
             contrb(i,j) = .false.
               endif
             enddo
        enddo
        close (1)
        write(6,*) 'Net placed in memory'
```

```fortran
106        format(<nrows>(i1,1x))
!      load dem data
!    read data in 512 byte blocks
         open (1,file=TRIM(dname)//'.flt',access='direct',
     *form='unformatted',recl=512)
         do g=1,nrows*ncols/128 + 1
         read(1,rec=g,err=107) block_data(g)
          enddo
107        ALLOCATE(dem(nrows,ncols))
!    load data into 2-d array
         do j=1,ncols
           do i=1,nrows
             inum=(j-1)*nrows+i
             dem(i,j) = raw_data (inum)
                enddo
         enddo
        close (1)
        write(6,*) 'Digital Elevation Model placed in memory'

         count = active
         start = 1
       do g=1,1
        write(6,*) 'iteration  ', g
         do  h = start, active,2
               i = list(h)
               j = list(h+1)
            if(contrb(i,j))then
!    assume first iteration that the first cell is
!    contributing
                if(g.eq.1)then
                        if(.not.contrb(i-1,j-1)) then
                            list(count) = i-1
                            list(count+1) = j-1
                            contrb(i-1,j-1)=.true.
                            count = count+2
                    endif
                        if(.not.contrb(i-1,j)) then
                            list(count) = i-1
                         list(count+1) = j
                            contrb(i-1,j)=.true.
                            count = count+2
                        endif
                        if(.not.contrb(i-1,j+1)) then
                            list(count) = i-1
                            list(count+1) = j+1
                            contrb(i-1,j+1)=.true.
                            count = count+2
                        endif
                        if(.not.contrb(i,j+1)) then
                            list(count) = i
                            list(count+1) = j+1
                            contrb(i,j+1)=.true.
                            count = count+2
                        endif
                        if(.not.contrb(i+1,j+1)) then
                            list(count) = i+1
                            list(count+1) = j+1
                            contrb(i+1,j+1)=.true.
                            count = count+2
                        endif
                        if(.not.contrb(i+1,j)) then
                            list(count) = i+1
                            list(count+1) = j
                            contrb(i+1,j)=.true.
                            count = count+2
                        endif
                        if(.not.contrb(i+1,j-1)) then
                            list(count) = i+1
                            list(count+1) = j-1
                            contrb(i+1,j-1)=.true.
                            count = count+2
```

```
                            endif
                                if(.not.contrb(i,j-1)) then
                                list(count) = i
                                list(count+1) = j-1
                                contrb(i,j-1)=.true.
                                count = count+2
                              endif
                            else
!    evaluate surrounding conditions
                        dmax = dem(i,j)
          if((i.ne.1).and.(j.ne.1).and.(i.ne.nrows).and.(j.ne.ncols))then
                            if((dem(i-1,j-1).le.dmax).and.(.not.contrb(i-1,j-1)))then
                                list(count) = i-1
                                list(count+1) = j-1
                                count = count+2
                                contrb(i-1,j-1)=.true.
                            endif
                            if((dem(i-1,j).le.dmax).and.(.not.contrb(i-1,j)))then
                                list(count) = i-1
                                list(count+1) = j
                                count = count+2
                                contrb(i-1,j)=.true.
                            endif
                            if((dem(i-1,j+1).le.dmax).and.(.not.contrb(i-1,j+1)))then
                                list(count) = i-1
                                list(count+1) = j+1
                                count = count+2
                                contrb(i-1,j+1)=.true.
                            endif
                            if((dem(i,j+1).le.dmax).and.(.not.contrb(i,j+1)))then
                                list(count) = i
                                list(count+1) = j+1
                                count = count+2
                                contrb(i,j+1)=.true.
            endif
             if((dem(i+1,j+1).le.dmax).and.(.not.contrb(i+1,j+1)))then
                                list(count) = i+1
                                list(count+1) = j+1
                                count = count+2
                                contrb(i+1,j+1)=.true.
             endif
             if((dem(i+1,j).le.dmax).and.(.not.contrb(i+1,j)))then
                                list(count) = i+1
                                list(count+1) = j
                                count = count+2
                                contrb(i+1,j)=.true.
             endif
             if((dem(i+1,j-1).le.dmax).and.(.not.contrb(i+1,j-1)))then
                                list(count) = i+1
                                list(count+1) = j-1
                                count = count+2
                                contrb(i+1,j-1)=.true.
             endif
             if((dem(i,j-1).le.dmax).and.(.not.contrb(i,j-1)))then
                                list(count) = i
                                list(count+1) = j-1
                                count = count+2
                                contrb(i,j-1)=.true.
             endif
                           endif
                         endif
            endif
               enddo
!     during next iteration process only items added during current iteration
               start = active
               active = count
           enddo
```

```
!     compute direction grid
        ALLOCATE(dir(8,nrows,ncols))
          do j=2,ncols-1
            temp(1) = dem(i-1,j-1)
                temp(2) = dem(i,j-1)
                temp(3) = dem(i+1,j-1)
                temp(4) = dem(i-1,j)
                temp(9) = dem(i,j)
                temp(5) = dem(i+1,j)
                temp(6) = dem(i-1,j+1)
                temp(7) = dem(i,j+1)
                temp(8) = dem(i+1,j+1)
          do i=2,nrows-1
            dmax = 0
            do h = 1,8
                      delev(h)=temp(9)-temp(h)
                      if(delev(h).gt.dmax)then
                  dmax=delev(h)
             endif
             enddo
                 temp(1) = temp(2)
                temp(4) = temp(9)
                temp(6) = temp(7)
                temp(2) = temp(3)
                temp(9) = temp(5)
                temp(7) = temp(8)
                temp(3) = dem(i+2,j-1)
                temp(5) = dem(i+2,j)
                temp(8) = dem(i+2,j+1)

c     All surrounding cells are same or lower
          if(dmax.le.0)then
            do h=1,8
                dir(h,i,j)=0
              enddo
              goto 700
          endif

c     One or more cells are higher
          do h=1,8
            if(delev(h).gt.0)then
                dir(h,i,j)=1
            else
                dir(h,i,j)=0
            endif
                enddo
700       enddo
        enddo
        write(6,*) 'Direction grid ready'
        DEALLOCATE(dem)
      ALLOCATE(uphill(nrows,ncols))
!              write out grid
        do j=1,ncols
         do i=1,nrows
           if(contrb(i,j))then
               uphill(i,j)=1
           else
               uphill(i,j)=0
           endif
               enddo
         enddo
         DEALLOCATE(contrb)

             count = active
             start = 1
             do g=1,500
        write(6,*) 'iteration  ', g
       if (start.ne.active) then
             do h = start, active,2
                   i = list(h)
                   j = list(h+1)
```

```
!   evaluate surrounding conditions
            if((i.ne.1).and.(j.ne.1).and.(i.ne.nrows).and.(j.ne.ncols))then
                if((i.ne.0).and.(j.ne.0))  then
                if(dir(1,i+1,j+1))then
                                dir(1,i+1,j+1) = .false.
                        list(count) = i+1
                        list(count+1) = j+1
                        count = count + 2
                            uphill(i+1,j+1) = 1
                endif
                     if(dir(2,i,j+1))then
                            dir(2,i,j+1) = .false.
                        list(count) = i
                        list(count+1) = j+1
                        count = count + 2
                            uphill(i,j+1) = 1
                endif
                      if(dir(3,i-1,j+1))then
                            dir(3,i-1,j+1) = .false.
                        list(count) = i-1
                        list(count+1) = j+1
                        count = count + 2
                            uphill(i-1,j+1) = 1
                endif
                if(dir(4,i+1,j))then
                                dir(4,i+1,j) = .false.
                        list(count) = i+1
                        list(count+1) = j
                        count = count + 2
                            uphill(i+1,j) = 1
                endif
                        if(dir(5,i-1,j))then
                            dir(5,i-1,j) = .false.
                        list(count) = i-1
                        list(count+1) = j
                        count = count + 2
                            uphill(i-1,j) = 1
                endif
                if(dir(6,i+1,j-1))then
                                dir(6,i+1,j-1) = .false.
                        list(count) = i+1
                        list(count+1) = j-1
                        count = count + 2
                            uphill(i+1,j-1) = 1
                endif
                if(dir(7,i,j-1))then
                                dir(7,i,j-1) = .false.
                        list(count) = i
                        list(count+1) = j-1
                        count = count + 2
                            uphill(i,j-1) = 1
                    endif
                    if(dir(8,i-1,j-1))then
                            dir(8,i-1,j-1) = .false.
                        list(count) = i-1
                        list(count+1) = j-1
                        count = count + 2
                            uphill(i-1,j-1) = 1
                endif
                        endif
                        endif
                 enddo
                start = active
                active = count
            endif
          enddo

          DEALLOCATE(list,dir)
          open(1,file=TRIM(oname)//'.asc',status='unknown')
```
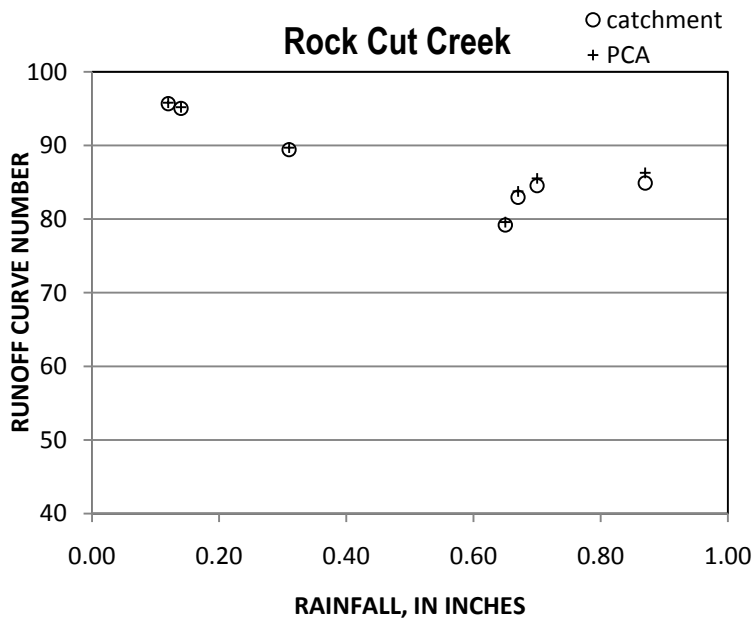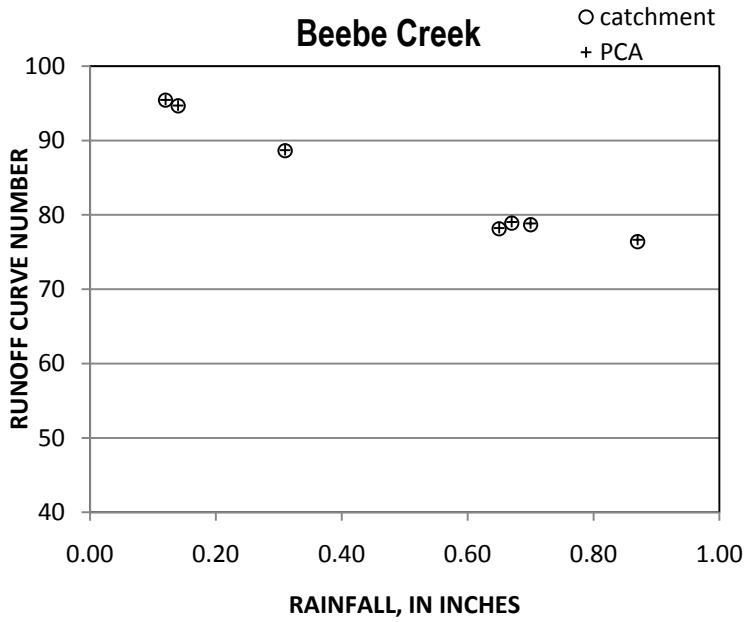
```
!  header file
      write(1,*) 'ncols          ', nrows
      write(1,*) 'nrows          ', ncols
      write(1,*) 'xllcorner      ', xllcorner
      write(1,*) 'yllcorner      ', yllcorner
      write(1,*) 'cellsize       ', cellsize
      write(1,*) 'NODATA_value  ', NODATA_value
      do j=1,ncols
         write(1,106) (uphill(i,j), i=1,nrows)
          enddo
        close(1)
      stop 'Contributing area delineated'
      end
```

APPENDIX D: Asymptotic Behavior of NRCS-Curve Number

Beebe Creek

○ catchment
+ PCA

RUNOFF CURVE NUMBER

RAINFALL, IN INCHES

Rock Cut Creek

○ catchment
+ PCA

RUNOFF CURVE NUMBER

RAINFALL, IN INCHES

Spring Creek

Leo Creek