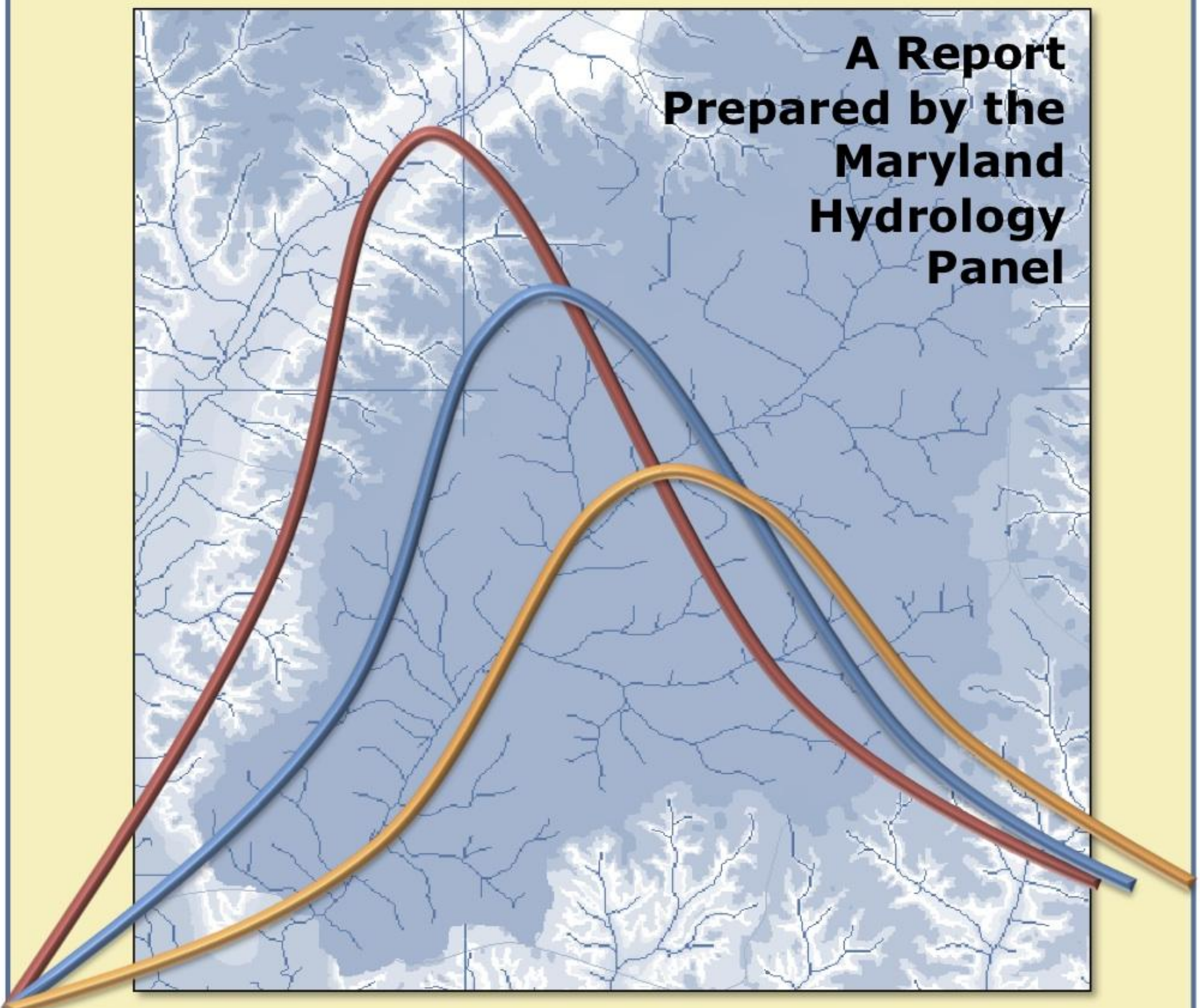
Application of Hydrologic Methods in Maryland

Third Edition, September 2010



A Report Prepared by the Maryland Hydrology Panel

Neil J. Pedersen
Administrator

Martin O'Malley, Governor

Jay G. Sakai
Director, Water Management Administration

SHA State Highway Administration
Maryland Department of Transportation

MDE

September, 2010

Subject: ***Application of Hydrologic Methods in Maryland***, Third Edition, September 2010

Users of this Manual:

On behalf of the State Highway Administration (SHA) and the Maryland Department of the Environment (MDE), we are delighted to endorse and recommend the use of this manual as it applies to hydrologic practices for State of Maryland projects. It is important to note that the manual will be the accepted criteria for all hydrologic efforts involving watersheds of approximately one square mile and larger in the State and not just for SHA highway efforts.

This manual is intended to aid the practitioner in the prediction of peak flow rates and flood hydrographs for Maryland streams as well as to offer techniques and tools that will improve the results of rainfall-runoff computer models. The procedures outlined in this manual guide the user toward the development of more reliable and consistent watershed models that better reflect the historic stream gage data for the Maryland region. This manual is to be used in conjunction with State and federal technical manuals, computer user manuals, and technical papers.

We recognize that the technology of hydrology computer programs, geographic information systems software and databases, and remote sensing data collection are continually being advanced. Although parts of this manual will be updated periodically to reflect current technology, data, and methods, it contains many guidelines, recommendations, limitations on procedures, analysis philosophies, and computational tools that will be valuable for the practitioner even as the science progresses.

We appreciate the effort of all who participated in the preparation and review of this manual and pledge our commitment to the continual improvement of the science and applications of hydrology in the State of Maryland.

Very truly yours,

Neil J. Pedersen, Administrator
State Highway Administration

Jay G. Sakai, Director
Water Management Administration
Department of the Environment

TABLE OF CONTENTS

APPENDIX 9	LINKS TO WEBSITES WITH HYDROLOGIC RESOURCES AND PROGRAMS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

In June, 1996, Maryland State Highway Administration (SHA) and the Maryland Department of Environment (MDE) appointed the Maryland Hydrology Panel (the Panel) to explore the development of improved procedures that would ensure an optimal balance between preserving the environmental quality of Maryland streams and the hydraulic performance of highway drainage structures. The Panel: 1) worked closely with the staffs of the two Departments; 2) extensively reviewed Maryland policies and design approaches, as well as those of other States; and 3) conducted extensive research directed toward improving the statistical and deterministic foundations of the two Department's hydrologic modeling procedures.

In February, 2001 the Panel issued a report entitled, Applications of Hydrologic Methods in Maryland. Adoption of the recommendations of the February 2001 report led to significant cost and time savings in the design/review processes of the two Departments through better utilization of computer and human resources. Of even greater importance, the implementation of the recommendations increased confidence in the design computations.

As the staffs of the two Departments gained experience and confidence with the procedures recommended by the Panel in 2001, they came forward with numerous suggestions that would lead to even better approaches. The Panel reconvened in the Fall of 2002 and, following the suggestions of the two Department's staffs, identified sufficient improvements to justify the publication of the second edition of the report in August 2006.

This September 2010 publication represents the third edition of the report entitled Application of Hydrologic Methods in Maryland. The report was updated to include the Windows version of TR-20 (WinTR-20), revised temporal rainfall distributions based on NOAA Atlas 14, and revised versions of the Fixed Region regression equations for selected hydrologic regions in Maryland. The Panel strongly believes that the procedures recommended in the present report, that have already been adopted by both Departments, positions Maryland as a national leader in cooperation to ensure that the hydrologic requirements of highway drainage structures and the environmental protection of streams are met.

Maryland correctly requires highway drainage structures to pass the floods from watersheds under both existing land use conditions as well as the floods that can be anticipated when the watershed land use changes to a future "ultimate development" condition. This mission must be met while providing a minimal environmental impact on the stream. The Panel recommends that the deterministic hydrologic model, WinTR-20, developed by the Natural Resource Conservation Service (NRCS) continue to serve as the base method for flood flow predictions. All deterministic hydrologic models, such as the WinTR-20, require the estimation of a number of input parameters that are developed through field and map investigations. These parameters are difficult to estimate and research conducted by the Panel shows that errors can cause significant problems. The Panel concluded that it was mandatory to provide guidance that would minimize the possibility of accepting errors in the

WinTR-20 input parameters and, thereby, ensure that the flood flows predicted are within the bounds of floods expected in Maryland. Thus, the Panel presents statistical methods that can be used to calibrate the WinTR-20 model using long term stream gage records collected in Maryland by the U.S. Geological Survey and regression equations documented in this report. The Fixed Region regression equations, originally documented in the August 2006 report, are the recommended statistical methods for ungaged watersheds and revised equations for some hydrologic regions are included in this report.

A key feature that ensures success is the Panel recommendation that requires the use of the software package GISHydro2000. State funding provided support for the development of GISHydro2000 by the Department of Civil and Environmental Engineering at the University of Maryland. GISHydro2000 provides the required hydrologic information by interfacing the recommended statistical and deterministic modeling procedures with a State-wide land-soil-topographic data base. Without GISHydro2000 the procedures recommended by the Panel would be too time and labor consuming to be implemented. With GISHydro2000 the approaches required by the Panel recommendations can be performed in a fraction of the time and with much more confidence and control than was possible with the traditional procedures of the late 1990's. Both Departments now use GISHydro2000. The confidence that the procedures are state-of-the-art and are being correctly applied has led to much shorter turn around time in the design/review/approval process with significant cost savings.

Websites have been created that allow GISHydro2000 to be downloaded at no cost or operated remotely as a web-based version that has the same functionality as the stand alone version. The software is also available at SHA headquarters for firms that are performing consulting work on state or county-funded projects.

This document presents a set of hydrologic modeling procedures that are designed to ensure an optimal balance between preserving the environmental quality of Maryland streams and the hydraulic performance and safety of highway structures. These procedures are recommended by the Maryland Hydrology Panel for use by the Maryland Department of Environment and the Maryland State Highway Administration for all watersheds of approximately one square mile and larger. Experience has shown that the procedures are also applicable for some watersheds smaller than one square mile if the watershed characteristics are within the application range of the approved equations.

THE MARYLAND HYDROLOGY PANEL
September 2010

This document presents a set of hydrologic modeling procedures that are designed to ensure an optimal balance between preserving the environmental quality of Maryland streams and the hydraulic performance and safety of highway structures. These procedures are recommended by the Maryland Hydrology Panel for use by the Maryland Department of Environment and the Maryland State Highway Administration.

Respectfully submitted:

Richard H. Berich, PE
Associate
Dewberry

William H. Merkel, PE
Hydraulic Engineer
USDA Natural Resources Conservation Service

Glenn E. Moglen, PhD
Professor
Virginia Tech

Michael Casey, PhD, PE
Assistant Professor
George Mason University

Wilbert O. Thomas, Jr. PH
Senior Technical Consultant
Michael Baker, Jr., Inc.

Donald E. Woodward, PE, PH
National Hydraulic Engineer (Retired)
USDA- Natural Resources Conservation Service

Dr. Arthur C. Miller of Pennsylvania State University and Mr. Michael Ports, then of Parsons, Brinkerhoff, served on the Panel through the publication of the February, 2001 Report. Dr. Robert Ragan, Professor Emeritus, University of Maryland, served on the Panel through the publication of the second edition of the report in August, 2006.

Communication between the Panel and the primary user agencies, the Maryland Department of Environment (MDE) and the Maryland State Highway Administration (SHA), was critical to the successful development of a usable system. David Guignet, PE, of MDE and Andrzej J. Kosicki, PE and Leonard N. Podell, PE, of SHA served as liaisons between their agencies and the Panel.

GLOSSARY OF EQUATION VARIABLES

Symbol	Definition	Units	Page of First Reference
A	drainage area	$miles^2$	3-6
A	drainage area of the watershed	acres	3-10
Ag	drainage area at the gaging station	$miles^2$	2-7
A_G	drainage area of watershed determined using GIS methods	$miles^2$	3-3
ai	the i^{th} increment of the watershed area	$miles^2$	3-8
A_M	drainage area of watershed determined manually from 1:24,000 scale maps	$miles^2$	3-3
ARC	antecedent runoff condition (1 indicates dry, 2 indicates average, 3 indicates wet)	--	4-5
A_{sf}	drainage area of the watershed	$feet^2$	3-9
Au	drainage area at the ungaged location	$miles^2$	2-7
c	the percent prediction interval in Student's t distribution (e.g. 5%)	--	2-9
DA	drainage area	$miles^2$	2-12
ΔD	duration of the unit excess rainfall	minutes	3-6
Δt	time increment for hyetograph	minutes	1-6
e	mathematical constant (equal to 2.718…)	--	3-15
FOR	percent of drainage area that is classified as forest	percent	2-12
G	average skewness for a given hydrologic region	--	2-4
ho	leverage, expresses the distance of the site's explanatory variables from the center of the regressor hull	--	2-9
i	rainfall intensity	inches/hours	3-11
Ia, I_a	initial abstraction	inches	1-7
IA	percent of the drainage area that is impervious as determined using NRCS imperviousness coefficients and the Maryland Department of Planning land use data (IA $\geq$ 10% is considered urban)	percent	2-12
K	peak rate factor	--	4-10
K	travel time constant in the Muskingum-Cunge routing method	minutes	5-6
Kx	the Pearson III frequency factor for recurrence interval, x and skewness, G	--	2-4
L	lag time, the time between the center of mass of the rainfall excess and the hydrograph peak	hours	3-8
L_h	hydraulic length of the watershed	feet	3-9
LIME	percent of the drainage area that is underlain by carbonate rock (limestone and dolomite)	percent	2-12
LSLOPE	average land slope calculated on a pixel by pixel basis	--	2-12

Symbol	Definition	Units	Page of First Reference
M	total length of the heavy line contours on a 1:24,000 topographic map	feet	3-9
n	number of gaging stations used in the analysis	--	2-9
N	contour interval between heavy line contours	feet	3-9
n	Manning's roughness	--	3-11
Ng	years of record at the gaging station	years	2-4
Nr	equivalent years of record for the fixed region regression estimate	years	2-4
p	number of explanatory variables used in the fixed region regression equation	--	2-9
P	precipitation depth	inches	3-4
P_2	2-yr, 24-hour rainfall depth	inches	3-11
Q	runoff volume	inches	3-4
q	overland flow discharge (assumed to be a power function of depth)	$feet^3$/seconds	3-11
q*	discharge in Figure 3.6	$feet^3$/seconds/inches	3-14
Qf	final estimate of the peak discharge at the ungaged site	$feet^3$/seconds	2-7
Qg	peak discharge at the gaging station based on observed data	$feet^3$/seconds	2-4
Qi	the runoff from watershed area i	Inches	3-8
q_p	peak discharge	$feet^3$/seconds	3-6
Q_p	peak discharge as estimated by WinTR-20	$feet^3$/seconds	3-14
Qr	peak discharge computed from the appropriate fixed region equation	$feet^3$/seconds	2-4
Qw	weighted peak discharge at the gaging station	$feet^3$/seconds	2-4
Qx	peak discharge for recurrence interval, x	$feet^3$/seconds	2-9
R	correlation coefficient	--	2-4
R	ratio of the weighted peak discharge (Qw) to the fixed region regression estimate (Qr)	--	2-7
R	hydraulic radius	feet	4-6
RCN	runoff curve number	--	1-7
$RCN_{(x)}$	runoff curve number for ARC=x, x=[1,3]	--	4-10
RCN_2	runoff curve number for ARC=2	--	4-10
R_h	hydraulic radius	feet	3-11
S	Potential maximum retention	inches	1-7
S	standard deviation of the logarithms of the annual peak discharges at the ungaged location	log(years)	2-4
S	channel slope	ft/ft	3-11

Symbol	Definition	Units	Page of First Reference
S_A	percent of the drainage area that is classified as NRCS Hydrologic Soil Group A	percent	2-12
S_D	percent of the drainage area that is classified as NRCS Hydrologic Soil Group D	percent	2-12
SD	standard deviation of estimates of Manning's n	--	3-15
SE_p	standard error of prediction of the fixed region regression estimates in logarithmic units	log(years)	2-4
t	the critical value of Student's t	--	2-9
T_c	time of concentration of the watershed	hours	3-6
T_o	travel time	hours	3-11
T_p	time to peak of the unit hydrograph	hours	3-6
T_t	travel time equal to the time of concentration	hours	3-11
T_{ti}	travel time from the center of ai to the point of reference	hours	3-8
V	overland flow velocity	Feet/minutes	3-11
x	parameter in Muskingum-Cunge routine method	--	5-6
xo	a row vector of the logarithms of the explanatory variables ata given site	log(various units)	2-9
$(X^TX)^{-1}$	covariance matrix of the regression parameters	log(various units)	2-9
Y	average watershed land slope	Percent	3-9
y	depth of overland flow	feet	3-11

CHAPTER ONE

1 INTRODUCTION

The Maryland State Highway Administration (SHA) has been using deterministic models, primarily the WinTR-20 developed by the Natural Resources Conservation Service, to synthesize hydrographs and to estimate peak discharges for both existing and ultimate development conditions for some time. However, there has been no way to ensure that the WinTR-20 results for a watershed are representative of Maryland conditions. Indeed, there is a belief among SHA and other designers that the WinTR-20 tends to over predict peak flow in many cases. This belief is supported by U.S. Water Resources Council (1981) tests on ten procedures that found that the WinTR-20 had a mean bias of approximately 60 percent high on attempts to reproduce the 100-year peak discharges. A report entitled “Analysis of the Role of Storm and Stream Network Parameters on the Performance of the SCS-TR-20 and HEC-1 Under Maryland Conditions,” by Ragan and Pfefferkorn (1992), concluded that the WinTR-20 could produce good results, but it was quite sensitive to the values selected for input parameters including the Manning roughness coefficients, representative cross sections, curve numbers, storm structure and storm duration. If the WinTR-20 was to continue to be used, the SHA wanted guidance that would lead to more dependable performance and confidence that the results would be consistent with Maryland stream flow records.

The Water Management Administration (WMA) of the Maryland Department of the Environment (MDE) has selected the WinTR-20 model or its equivalent as a standard deterministic method for computing flood flows in Maryland. However, the SHA wanted to make greater use of regional regression equations based on long term USGS stream gaging records. The WMA has been reluctant to accept a general use of regression equations for the following reasons:

- they do not account for ultimate development
- they do not reflect recent land use changes, and
- they do not account for changes in storage and times of concentration.

These are valid concerns in Maryland because of the rapid changes in watershed characteristics being produced by urbanization. However, since regression equations use USGS stream gaging stations in the region for definition, they can provide a reasonable indication of existing runoff conditions and, therefore, can provide a base for calibration of the WinTR-20 or similar deterministic models. Further, regional regression equations had been classified as non-standard models by the WMA. The WMA requires that for a model to be considered for use in estimating flood peaks the model must meet the following conditions:

- Be in the public domain.
- Be generally accepted by the hydrologic community.

- Be verifiable.

Regional regression equations derived from USGS stream gaging stations meet all three of the above criteria. First, the regional regression equations developed for Maryland are in the public domain. Second, the regression methodology is widely used and recognized as acceptable by the hydrologic community. And third, the original data, regression methodologies, and the resulting equations are published and, therefore, readily verifiable.

Standard hydrologic practice strongly recommends that all deterministic models, such as the WinTR-20, be calibrated against local data. Where sufficient actual, measured rainfall and runoff data are available, the WinTR-20 model should be calibrated and, if possible, validated prior to its application. However, the availability of on-site rainfall and runoff data is rarely the case in actual practice. In these more typical circumstances, regional regression equations developed from stream flow data may be used as a basis to "calibrate" the WinTR-20 model, providing the watershed conditions are consistent with those used to develop the equations.

Because of the need to improve confidence of the WinTR-20, the regional regression equation issues outlined above, and an array of other concerns being faced by the two organizations, the Maryland Water Management Administration and the Maryland State Highway Administration agreed to appoint a special hydrology panel. The Hydrology Panel (the Panel) was to be composed of professionals with extensive experience in Maryland who, at the same time, were nationally recognized for their substantial contributions to the practice of hydrology. Appointed in the fall of 1996, the Panel was chartered to operate independently of the SHA or other state agencies. The mission of the Panel was to:

> *Review Maryland hydrologic practices and make recommendations concerning peak flood estimating procedures that will best serve to satisfy agency needs, Maryland laws and regulations.*

The Panel met about six times a year as a formal committee. In addition, frequent meetings with SHA and WMA staff were held to discuss specific projects and procedures. Two versions of report entitled, "Application of Hydrologic Models in Maryland" were published in February 2001 and August 2006. Experiences with the application of recommendations presented in these reports, improvements in GIS technologies, and updates in TR-20 and the Maryland regional regression equations led to the publication of the third edition of the report dated September 2010. The following section presents the Panel's recommendations. Subsequent chapters explain the basis for these recommendations and the procedures required for their accomplishment.

1.1 RECOMMENDATIONS

The Panel recommends the use of the software package, GISHydro2000 and future upgrades, for hydrologic analysis in the State of Maryland. GISHydro2000 includes internal delineation of the watershed boundaries, curve number computation and direct interfaces with both the regression equations and the WinTR-20. Use of this software ensures reproducibility of watershed characteristics based on the topographic, land cover, and soil databases that are integral to GISHydro2000. Automated reporting that is built into GISHydro2000 allows reviewers at the Maryland Department of the Environment to independently confirm analyses submitted for their review. Consistency in analysis presentation also helps to streamline the review process.

GISHydro2000 is available for download at no cost at the following website:

http://www.gishydro.umd.edu

The Panel recognizes that although GISHydro2000 is free, the GIS software required to support this program can represent a significant expense for some firms. To give broader access to this software, the SHA makes GISHydro2000 available in two ways:

1. A web-based version of the software is available at:

   http://www.gishydro.umd.edu/web.htm

   This web-version contains the exact same functionality as the stand-alone version of the software.
2. The software is also available at SHA headquarters for firms that are performing consulting work on state or county-funded projects. To obtain access, please contact Mr. Andrzej J. Kosicki at the Maryland State Highway Administration at 410-545-8340.

1.1.1 Overview of the Modeling Process and the Calibration Requirements

The hydrologic analysis of Maryland State Highway Administration bridges and culverts must evaluate the behavior of the structure and local stream under both existing and ultimate development watershed conditions. Because two land cover and flow path conditions are involved, the basis for these hydrologic analyses must be a deterministic model that can simulate the runoff processes that occur during and after the storm. The deterministic model will be the WinTR-20 or an approved equivalent. The recommended first step is to calibrate the deterministic model using field and map defined input parameters so that the model adequately describes the runoff processes under existing watershed conditions. After the designer is satisfied that the calibrated deterministic model provides a realistic representation of the existing watershed conditions, the impact of ultimate development will be simulated by adjusting the input parameters to reflect the planned land cover and flow path modifications.

The Panel discussions focused on watersheds having drainage areas larger than one square mile. Hydrologic analyses for all watersheds having drainage areas larger than one square mile will be supported by field investigations and the design discharges will be determined utilizing two hydrologic models: (1) a probabilistic method based on a local USGS gaging station or approved regression equations that are developed through statistical analyses of USGS stream gage records (Chapter 2); and (2) a flood hydrograph deterministic procedure such as the WinTR-20 or its equivalent. The objective is to use the probabilistic method based on long-term stream gage records to ensure that the WinTR-20 produces peak discharges that are consistent with Maryland conditions. As described in Chapters 3 and 4 of this report, the sensitivity of the WinTR-20 to the values assigned to its input parameters and the uncertainties associated with the selection of these parameters are such that calibration against USGS historical data is mandatory. The calibration methodology will be utilized in the following order of priority to determine peak flow:

1. Use a gage located at the site with the frequency curve of record being weighted with the regional regression estimates using the approach presented by Dillow (1996) or future procedures once they become available. The discharges reported will be the weighted estimate and an error bound of plus one standard error of prediction. The stream gage frequency curves are to be developed following the procedures in the Interagency Advisory Committee on Water Data Bulletin 17B "Guidelines For Determining Flood Flow Frequency" (1982). Bulletin 17B is the standard reference for the preparation of flood flow frequency curves for gaged watersheds.

2. If there is no gage at the site, but there is a gage on the same stream that can be transposed, (the gage's data can be transposed $\pm$ half the gaged area upstream or downstream), the gaged record will be transposed to the site following the approach recommended by Dillow (1996). The discharges reported will be the estimate and an error bound of plus one standard error of prediction.

3. If there is no gage on the stream and the watershed characteristics are within the bounds of those used to derive the approved regional regression equations, the regression equations will be applied to the watershed. The discharges reported will be the regression equation estimate and an error bound of plus one standard error of prediction.

The region between the "best estimate line" of the regional regression equations and the upper bound of plus one standard error of prediction will be defined as the "**calibration window**" for the purposes of these recommendations.

If the peak discharge of the hydrograph synthesized for the design storm is within the calibration window, the analysis will be accepted as a reasonable representation of the runoff for existing watershed conditions, providing that the WinTR-20 input parameters are within the bounds of sound hydrologic practice. The model then forms the basis for simulating the watershed under ultimate development conditions.

If the peak discharge estimated by the deterministic model is outside the calibration window, additional investigations and simulations will be conducted to determine:

1. Are the watershed conditions consistent with those of the USGS stream gages used to develop the approved regional regression equations?

2. Are the regional regression equations appropriate for use on this watershed?

3. Even though the averaged watershed characteristics are consistent with those of the USGS stream gages used to develop the regression equations, are there specific conditions such as extensive stream valley wetlands, a deeply incised channel or other factors that would cause unusually low or high peak discharges?

4. Are the deterministic model parameters defining the curve number, time of concentration and storage attenuation appropriate for the field conditions being simulated? If not they can be adjusted in accordance with Chapter 4. Some parameter adjustment is allowed because the WinTR-20 is quite sensitive to the assigned values and it is very difficult to select quantities that best represent the watershed conditions. Any adjustments must be justified with supporting documentation and **MUST BE WITHIN THE BOUNDS OF SOUND HYDROLOGIC PRACTICE**.

If there is no term in the regional regression equations that reflects the degree of urbanization and the watershed is greater than 10% impervious, then the WinTR-20 calibration process for existing conditions will be a two-step process. First, the designer will estimate the pre-developed land cover distribution and calibrate to the regression equations for this pre-developed condition. These WinTR-20 discharges will then be adjusted by revising the input parameters to reflect the increased curve numbers and the drainage network of the existing condition. The process is described in section 4.6 of this report. The Panel believes that the uncertainties associated with a “pre-developed calibration” are less than those associated with an approach that requires the designer to select WinTR-20 input parameters without any opportunity for calibration.

If the WinTR-20 peak discharges do not fall within the calibration window of the regression equations, the designer should explain why the existing watershed conditions are significantly different from those defining the regression equations or why the WinTR-20 model is not applicable to this particular watershed. The designer will then select and justify the most appropriate method for the specific watershed.

The focus of the Panel’s efforts was the development of procedures for use on watersheds having drainage areas larger than one square mile. Subsequent experience on SHA projects has shown that GISHydro2000 and the calibration procedures using the regression equations can often be applied on much smaller watersheds. When applying the procedures on basins smaller than one square mile, the user must be especially careful to ensure that the watershed boundary generated by GISHydro2000 is consistent with that indicated by the USGS 1:24000 Topographic Maps. GISHydro2000 develops the watershed boundary from USGS digital elevation data spaced on a 30 meter grid. As the watershed area becomes smaller, the number of elevation points used by GISHydro2000 to generate the boundary decreases. The consequence is an increasing risk that the boundary generated by the computer delineation may differ from that indicated by topographic maps.

An example of when it might not be possible to get the WinTR-20 peak discharges to fall within the calibration Window of the regression is in the Blue Ridge physiographic region. In this region, the area of limestone geology is a predictor variable in the Fixed Region regression equations. The area of limestone geology was compiled from geologic mapping from several sources and is not known with precision. A slight shifting of the limestone geology boundary could significantly change the estimated percentage of limestone in a watershed with boundaries intersecting both limestone and non-limestone areas. The uncertainty in estimated limestone geology becomes larger as overall watershed area gets smaller. Errors and uncertainty in percent limestone geology can have a significant effect on the resultant flood discharges estimated by the Fixed Region regression equations. Because of the uncertainty associated with the determination of limestone geology, the WinTR-20 model estimates should NOT be calibrated to the Fixed Region regression equations for watersheds when there is a significant percentage of limestone (greater than 25 percent) in the watershed. For these watersheds, the WinTR-20 model estimates should be used for the design discharges. Although the WinTR-20 model estimates will be somewhat conservative, the Hydrology Panel believes this is a better alternative than underestimating the design discharges.

There may be situations where the WinTR-20 estimates are not applicable in the limestone areas, such as when the percentage of limestone area in the watershed is greater than 75 percent. Based on comparisons to gaging station data, the WinTR-20 estimates can be very conservative when the percentage of limestone area exceeds 75 percent. If there is a gaging station near the watershed outlet (within 50 percent of the drainage area of the watershed being studied) and the percentage of limestone in the watershed is greater than 75 percent, the analyst should use a weighted average of the gaging station estimates and the Fixed Region regression estimates for existing development conditions following the approach described later in Section 2.3, Estimates for Ungaged Sites near a Gaging Station. If there is no gaging station nearby, then the analyst should use the Fixed Region regression estimates for existing conditions. In each instance, the flood discharges for existing conditions should be adjusted for ultimate development based on the ratio of uncalibrated TR-20 flood discharges for the ultimate development and existing development conditions.

1.1.2 Issues Concerning the Selection of WinTR-20 Input Parameters

The first step is to use map and field investigations to select input parameters that are consistent with established hydrologic practice and give a reasonable simulation of existing watershed conditions. If inputs give results that are outside the calibration window, the designer will review the parameters used as inputs to define the WinTR-20 simulation. If the review indicates that a parameter may be incorrect, additional field and map investigations will be used to support any corrections. **In no instance will WinTR-20 inputs be accepted that are outside the bounds of standard hydrologic practice.**

Before attempting to revise input parameters in a WinTR-20 calibration against one of the three approaches listed in Section 1.1.1, the designer should carefully study Chapter 3 of the present report and MD-SHA AWO92-351-046, "Analysis of the role of storm and stream parameters on the performance of SCS-TR-20 and HEC-1 under Maryland Conditions" (Ragan and Pfefferkorn, 1992).

Normally, watersheds having drainage areas larger than one square mile will be delineated using the digital terrain modeling capabilities of GISHydro2000 or manually on 1:24000 USGS quad sheets. Special care must be taken in locating the ridgeline on the eastern shore or in other areas of low relief. The designer should always perform a map check of the automatic boundary delineation of GISHydro2000 that uses 30-meter resolution USGS digital terrain data.

The WinTR-20 model will be run using the latest precipitation-frequency information from NOAA Atlas 14 (Bonnin and others, 2006) and center-peaking NRCS hyetographs as design storms. The volumes and temporal structure of these design storms will be defined from the NOAA Atlas 14 web site. The Panel recognizes that changes in the duration and/or structure of the design storm used as an input to the WinTR-20 produces significant changes in the magnitude of the peak discharge and shape of the runoff hydrograph. More research is needed to finalize a synthetic storm structure and duration to be used for specific frequencies and locations in Maryland. Until new research on storm structure is complete, the designer should use design storms developed in WinTR-20 or GISHydro2000 from NOAA Atlas 14 data. Twelve- and 6-hour durations may be developed from data contained in the 24-hour storm distribution. Table 1.1 shows the acceptable storm durations that may be used to calibrate the WinTR-20 model and develop final design peak discharges. The storm duration selection is based on the total time-of-concentration (T_c) to the point of study. In general, the duration of the design storm should in no case be less than the total T_c of the watershed.

Preliminary analyses indicate that the flood producing rainfalls in the Appalachian Plateau are considerably shorter than those in the rest of the State. Until completion of further studies, if reasonable agreement with the regional regression equations cannot be achieved, Appalachian Plateau flood estimates may be developed using the 6- and 12-hour storm durations.

Table 1.1: Acceptable Storm Durations (hrs) for Total Watershed Tc.

Time of Concentration	*2-yr*	*5-yr*	*10-yr*	*25-yr*	*50-yr*	*100-yr*	*> 100-yr*
<6 hrs	6/12/24	6/12/24	6/12/24	12*/24	12*/24	12*/24	24
6-12 hrs	12/24	12/24	12/24	12*/24	12*/24	12*/24	24
12-24 hrs	24	24	24	24	24	24	24
>24 hrs	48	48	48	48	48	48	48

*Appalachian Plateau only

An example of development of 6-hour and 12-hour duration design storms for Howard County, Maryland is presented in Appendix 7. A spread sheet was developed to calculate the 6, 12, and 24-hour storm distributions for locations within Maryland. In all instances, the hyetograph time increment, Δt, shall not exceed 6 minutes (0.1 hour).

Intensity-Duration-Frequency (IDF) curves are developed from point measurements. The spatial distribution of rainfall within a storm generally produces an average depth over an area that is a function of watershed area and storm duration. Figure 3.11, reproduced from USWB-TP-40, illustrates this phenomenon. The Panel recommends that the hydrologist adjust the design storm rainfall to reflect spatial distribution. If the hydrologist is using GISHydro2000, the adjustment is automatic. If the hydrologist is conducting a study outside the GISHydro2000 environment, the adjustment for spatial distribution should be made using the graph in Figure 3.10.

The NRCS presents runoff curve numbers for many hydrologic soil-cover complexes as a range covering "good", "fair" and "poor" – conditions that may be difficult to determine. Also, as discussed in Chapter 3, the assumption that $I_a = 0.2S$ is fundamental in the calculation of runoff volume in terms of a Runoff Curve Number (RCN). Figure 10-1 of USDA-NRCS-NEH, Part 630, Chapter 10, (2004) presented in this report as Figure 3.2, shows that there is significant scatter in the data used to support the assumption that $I_a = 0.2S$. Thus, the Panel recommends that the designer be granted a reasonable degree of latitude in the selection of RCN values for individual land parcels during the calibration process providing the values remain within the range recommended by NRCS and the decision be justified in writing. Adjustments must be made on a parcel-by-parcel basis and cannot be made by simply changing the overall watershed RCN.

The commonly used peak rate factor of 484 in NRCS dimensionless unit hydrograph (DUHG) is known to vary for different terrain. The designer will use those of Table 3.1.

The NRCS lag equation to estimate the time of concentration should not be used on watersheds having drainage areas in excess of five square miles. The hydraulic length in the equation should be longer than 800 feet because shorter lengths result in artificially short lag times.

The lag equation is not included as a recommended procedure in USDA-NRCS, WinTR-55, “Hydrology for Small Watersheds” (2002). Thus, the Panel recommends that the lag equation not be used in urban ($\geq$ 10 percent impervious) watersheds until additional research becomes available. It should be noted that the lag equation was developed using data from agricultural watersheds.

The Panel recommends that the velocity approach of NRCS be used to estimate the time of concentration in urban and suburban watersheds. The NRCS velocity approach is based on estimating the travel times of the three segments of flow – overland, shallow concentrated, and open channel – through the watershed. The NRCS kinematic wave equation should be used to estimate time of overland flow travel with a maximum flow length of 100 feet. Because the quantity of flow and, therefore, the hydraulics are different for each storm frequency it is logical to expect that the time of concentration will be different for a 2-year storm than for a 100-year storm. The Panel recommends that bankfull conditions that many consider to approximate the 2-year storm conditions be used to estimate the time of travel through the main channel.

Use GISHydro2000 or 1:24000 scale USGS 7.5 minute quadrangle sheets to estimate channel length. It is recognized that this scale cannot adequately represent meanders and, therefore, estimated length may be too short and slope too steep. When field investigations or more detailed maps indicate that such is the case, the designer may increase the estimated length, providing the increase is justified in writing.

As illustrated by Equation 3.16, it is difficult to estimate the correct Manning roughness coefficient. Variations in the estimate of the Manning roughness can produce significant changes in the time of concentration and, therefore, the estimated peak discharge. The designer should exercise extreme care in estimating the main channel roughness and use discharge comparisons with the statistical approaches of the regression equations to improve the estimates.

As stated earlier, velocities at “bankfull” conditions are to be used in estimating the time of travel through the main channel. Selection of the representative bankfull hydraulic radius is difficult because the bankfull cross section varies along the length of the channel. A “best estimate” should be made using field and map investigations and then brought into agreement with the calibration window through corrections justified by additional field and/or map investigations.

When the watershed is divided into sub-basins, the routing cross sections and the channel and overbank roughness coefficients are difficult to estimate and can have a significant impact on the attenuation simulated by the routing procedure. The hydrologist must select a routing cross section that is representative of the overall channel length. The digital terrain modeling capabilities of GISHydro2000 provide a rapid way to explore the variations of cross sections along the channel.

In situations where errors can result in loss of life or major economic damage, routing cross sections should be developed through detailed mapping along the stream.

When the economics of a project do not justify detailed surveys along the length of a stream, reasonable modeling results can be produced with:

- Bankfull cross sections developed from regional regression equations that relate channel depth and width to the drainage area above the cross section; (Equations for use in Maryland are presented in Appendix 4.)

- Routing sections developed by drawing perpendicular transects to the channel across the contours, as is the approach followed by GISHydro2000;

Regression equation and map transect estimates of cross sections should be supported by field investigations to ensure that the sections are realistic for the watershed involved.

If there are culverts or other storage producing structures along the stream, the attenuation should be reflected in the inputs to the WinTR-20.

Where available, comprehensive planning maps, as opposed to zoning maps, should be used to predict future land cover. The planning maps incorporate key elements of time and spatial distribution that are not apparent on zoning maps.

1.2 RATIONALE

1. Each watershed will be analyzed by two widely accepted approaches, one statistical (local gage or regional regression equations) and one deterministic (WinTR-20 or equivalent). In the past the effort associated with such an approach would have been prohibitive. With the current capabilities of GISHydro2000 that includes internal delineation of the watershed boundaries, curve number computation and direct interfaces with both the regression equations and the WinTR-20, the tasks can be performed in considerably less time than was required by conventional techniques.

2. Studies have shown that uncalibrated WinTR-20 models often predict peak discharges that are not consistent with the peaks that have been measured at Maryland stream gages. A major contributor to this problem is the fact that it is very difficult to select the curve number, the Manning roughness coefficients and the "typical" cross sections that represent the watershed conditions. Small errors in the selection of these parameters can lead to incorrect estimates of the volume of runoff, time of concentration, storage attenuation and, therefore, lead to peak flow predictions that are too high or too low. Calibration against a USGS gage, or regression equations that are based on statistical analyses of regional USGS stream gages, can aid the designer in the selection of appropriate hydrograph input parameters that will usually produce estimated peaks that are consistent with

Maryland conditions. The calibration will also provide a confidence that the WinTR-20 is not over predicting to cause unnecessary construction costs and not under predicting to cause unnecessary flooding risks.

3. The recommended procedures are consistent with accepted practice, especially with AASHTO (1991) that states, "What needs to be emphasized is the need to calibrate to local conditions. This calibration process can result in much more accurate and consistent estimates of peak flows and hydrographs… Should it be necessary to use unreasonable values for variables in order for the model to produce reasonable results, the model should be considered suspect and its use carefully considered." An example of an inappropriate use of the WinTR-20 would be to use an NRCS dimensionless hydrograph peak factor of 484 on the Eastern Shore of Maryland where the recommended peak factor is 284.

4. The recommended procedure is to make use of the USGS stream flow records as the cornerstone for calibrating the hydrograph model. The USGS based methods are utilized to ensure that the deterministic model provides a realistic representation of existing watershed conditions. Once confident that the WinTR-20 model represents the existing conditions, the designer can vary the input parameters to simulate changes in the land cover and drainage network associated with ultimate development and be fairly confident in the final results.

5. It is not the intent of this report to recommend that the calibration of the deterministic model be accomplished at the upper bound of the calibration window. Rather, the prediction limits can be used to provide an indication of the level of risk associated with the discharge selected. Assuming that the regional regression equation estimates are unbiased, 50% percent of the peaks measured on watersheds having these characteristics will be higher and 50% will be lower than the expected value. Approximately 68% of the peak discharges will fall between plus and minus one standard error of the expected value. Thus, there is an approximately 84% chance that the peak discharge for this type of watershed will not exceed that indicated by the upper bound. Similarly, there is an 84% chance that a measured peak flow for this type of watershed will be greater than that indicated by the lower bound. **For purposes of "calibrating" the WinTR-20 model, the model parameters can be adjusted, within the bounds of sound hydrologic practice, so the estimated flood discharge falls within a calibration window defined by the regression estimate (expected value) and the upper bound of plus one standard error of prediction.**

1.3 NEED FOR CONTINUING RESEARCH

As described in Chapter 5 of this report, there are many areas of hydrology that require additional research if we are to improve our confidence in the modeling process. It is imperative that a continuing, well-conceived and adequately funded research program be implemented to address a number of problems, especially,

1. Improving the structure and duration of the design storms;

2. Using the time-area curve available from the digital terrain data to generate geomorphic unit hydrographs that are unique for the watershed being modeled;

3. Until procedures for the future use of geomorphic unit hydrographs can be implemented, research must continue on the regionalized peak factors to be used with the NRCS dimensionless unit hydrograph;

4. Improving methods for estimating times of travel through the watershed;

5. Peak discharge transposition of gaging station data;

6. Estimating confidence levels that are appropriate for WinTR-20 adjustments;

7. Providing improved statistical alternatives to develop estimates of the 2- to 500-year peak discharges for rural and urban streams in Maryland;

8. Defining guidelines for the application of the Muskingum-Cunge routing module in the NRCS-Win TR-20 on watersheds above roadway drainage structures.

9. Developing guidelines for estimating NRCS runoff curve number from information on planning and zoning maps.

CHAPTER TWO

2 STATISTICAL METHODS FOR ESTIMATING FLOOD DISCHARGES

2.1 INTRODUCTION

The Maryland State Highway Administration (MSHA) has a long history of using statistical methods for estimating flood discharges for the design of culverts and bridges in Maryland. MSHA has funded four regional regression studies over the last 30 years, Carpenter (1980), Dillow (1996), Moglen and others (2006) and the revised regression equations documented in Appendix 3 of this report.

Carpenter (1980) developed regression equations for three hydrologic regions (North, South and Eastern) in Maryland by relating flood discharges based on Bulletin 17A (U.S. Water Resources Council, 1977) at 225 rural gaging stations (114 in nearby states) to watershed and climatic characteristics. Carpenter (1980) also used short-term rainfall-runoff data collected at eight small stream sites to calibrate a watershed model and simulate annual peak discharges at these stations using long-term rainfall data. The simulated annual peak discharges were analyzed using Bulletin 17A guidelines to estimate the design flood discharges at each station. For 17 other small stream stations in the Appalachian Plateau and Piedmont Regions with only observed data for the period 1965-76, Carpenter adjusted the flood discharges based on comparisons to nearby long-term stations to be more representative of a longer period of record.

Dillow (1996) developed regression equations for five hydrologic regions in Maryland (Appalachian Plateau, Blue Ridge, Piedmont, western and eastern Coastal Plains, see Figure 2.1). Dillow's study superceded the study by Carpenter (1980). Dillow (1996) used flood discharges based on Bulletin 17B estimates (Interagency Advisory Committee on Water Data (IACWD), 1982) at 219 rural gaging stations (112 in nearby states) in developing his regression equations. Dillow (1996) also utilized the rainfall-runoff estimates for the small watersheds that were developed by Carpenter (1980). He chose not to use Carpenter's (1980) adjusted design discharges for the small watersheds with observed data for the period 1965-76 but used design discharges based on the observed short-term record.

Moglen and others (2006) evaluated three approaches for regional flood frequency analysis using data for rural and urban ($\geq$ 10% impervious) gaging stations: the Fixed Region approach, the Region of Influence method (Burn, 1990) and regional equations based on L-Moments (Hosking and Wallis, 1997). The Fixed Region approach is analogous to the approach taken by Carpenter (1980) and Dillow (1996) where regression equations are developed for a fixed geographic region and are based on Bulletin 17B estimates at the gaged sites. For the Region of Influence approach, regression equations are based on gaging stations that have the most similar watershed characteristics as the ungaged site of interest. There are no geographic flood regions and the regression equations are different for each ungaged site. For the gaged sites, flood discharges based on Bulletin 17B guidelines were used in the Region of Influence analysis. The L-Moment approach (Hosking and Wallis, 1997) uses linear moments, a linear combination of the untransformed annual peak discharges (not the logarithms), to estimate the parameters of the frequency distribution. Several frequency distributions can be used in the L-Moment approach, but the Generalized Extreme Value distribution was shown to be most appropriate for Maryland streams. For estimation at an ungaged site, the L-Moment approach is analogous to an index flood approach where the mean annual flood is estimated from a regression equation based on watershed characteristics and design discharges such as the 100-yr discharge, are estimated as a ratio to the mean annual flood.

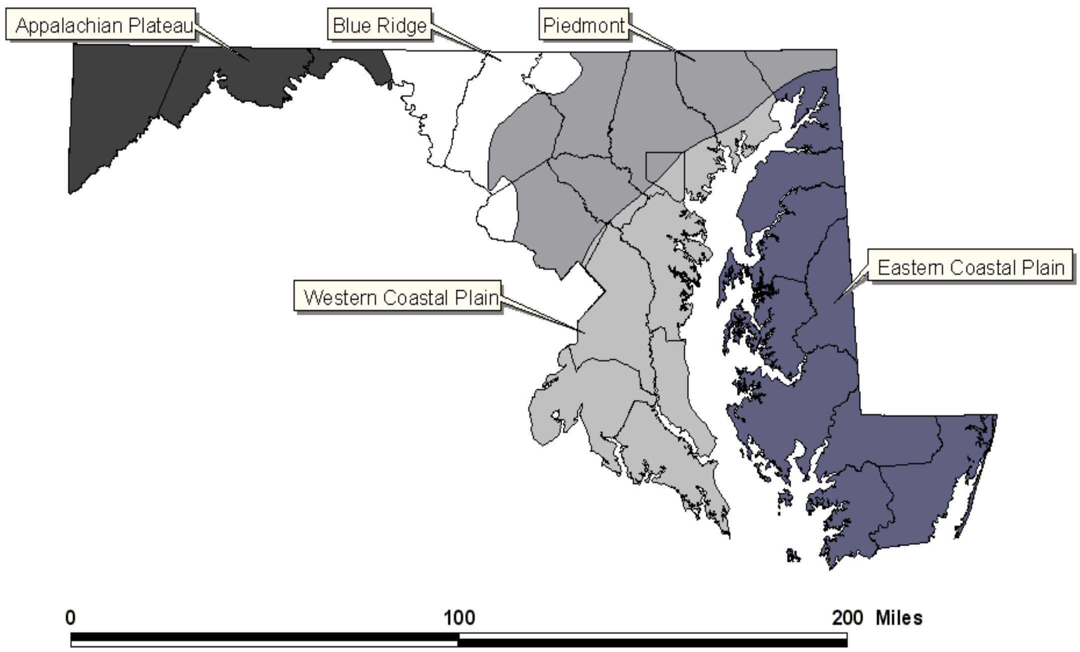


Figure 2.1: Hydrologic Regions Defined by Dillow (1996) and Used by Moglen and others (2006).

Carpenter (1980) and Dillow (1996) used the generalized skew maps in Bulletins 17A and 17B (same map) in developing the weighted skew estimates in defining the design discharges at the gaging stations. Moglen and others (2006) developed new estimates of generalized skew as described later and illustrated that these estimates of generalized skew were more accurate than those from the Bulletin 17B map.

Moglen and others (2006) compared estimates of flood discharges from the Fixed Region, Region of Influence, and L-Moment methods to Bulletin 17B estimates at the gaged sites and determined that the Fixed Region approach was most accurate. The Fixed Region approach uses the five hydrologic regions shown in Figure 2.1 plus there are separate rural and urban equations for the Piedmont Region (a total of six sets of equations). The Fixed Region regression equations developed by Moglen and others

(2006) were included in Appendix 3 of the August 2006 version of the Hydrology Panel report.

For this third revision of the Hydrology Panel report, the Fixed Region regression equations were revised for the Eastern and Western Coastal Plain regions using recently released SSURGO soils data. In addition, the rural gaging stations in the Piedmont and Blue Ridge Regions (see Figure 2.1) were combined to better define the region influenced by karst geology. The regression equations for the urban watersheds in the Piedmont Region and the regression equations for the Appalachian Plateau were not revised. The recommended Fixed Region regression equations are described in more detail in this chapter and in Appendix 3.

The physiographic regions shown in Figure 2.1 appear as crisp lines separating one region from another, and thus one set of regression equations from another. Caution should be exercised by engineers when analyzing watersheds near these physiographic boundaries. For instance, the fall line which separates the Piedmont from the Western Coastal Plain region is more appropriately considered a region of some width, rather than a crisp line. Within this area close to physiographic region boundaries it is possible for a watershed that is strictly located within one region to exhibit flood behavior more consistent with the neighboring physiographic region. In GISHydro2000, the software automatically detects if the watershed comes within 5 km of the physiographic boundary and prints a warning if this is the case. Similarly, in the Blue Ridge physiographic region, underlying limestone geology is a predictor variable. The location of this limestone cannot be known with precision. In GISHydro2000, the software automatically detects if the watershed comes within 1 km of the limestone geology boundary and prints a warning if this is the case.

2.2 FLOOD DISCHARGES AT GAGING STATIONS

Estimates of design discharges, such as the 100-year flood discharge, are made at gaging stations where there is at least 10 years of annual peak discharges by using Bulletin 17B (IACWD, 1982). These guidelines are used by all Federal agencies and several state and local agencies for flood frequency analysis for gaged streams. Bulletin 17B guidelines include fitting the Pearson Type III distribution to the logarithms of the annual peak discharges using the sample moments to estimate the distribution parameters and provide for (1) outlier detection and adjustment, (2) adjustment for historical data, (3) development of generalized skew, and (4) weighting of station and generalized (regional) skew.

Computer programs for implementing Bulletin 17B guidelines are available from the U.S. Army Corps of Engineers (USACE) (HEC-SSP Statistical Software Package, User's Manual, Version 1.1, 2009) and the U.S. Geological Survey (USGS) (Program PEAKFQ User's Manual, Flynn and others, 2006). Annual peak discharges for approximately 200 gaging stations in Maryland are available from the USGS over the World Wide Web at http://water.usgs.gov/md/nwis/sw . The annual peak data and the available computer programs can be used to estimate design discharges for Maryland streams.

If the gaged watershed has undergone significant change during the period of record, the annual peak data may not be homogeneous. The user should ensure that the data are homogeneous, and exhibit no significant trends due to land-use change before performing the frequency analysis. A simple way to check on this is to plot the annual peak discharges versus time and determine if there are any noticeable trends in the data. Statistical procedures for performing a more quantitative evaluation of trends and non-homogeneity in flood data are discussed by Pilon and Harvey (1992), McCuen and Thomas (1991) and McCuen (1993).

Moglen and others (2006) used Bulletin 17B and L-Moment procedures to estimate selected design discharges at gaging stations in Maryland and Delaware in the development of regional regression equations. A generalized skew study was performed for the Bulletin 17B analysis to obtain a new generalized skew (in lieu of the Bulletin 17B skew map) to weight with the station skew. An average generalized skew coefficient of 0.45 with a standard error of 0.41 was determined for stations in the Eastern Coastal Plains region. An average generalized skew coefficient of 0.55 with a standard error of 0.45 was determined for the rest of the state. The nationwide standard error of the Bulletin 17B skew map is 0.55.

For the 2010 update of the regression equations for the Eastern and Western Coastal Plain Regions, new generalized skew analyses were made. For the Eastern Coastal Plain, an analysis of 16 long-term stations indicated a mean skew of 0.43 with standard error of 0.385. Since these revised values were similar to the Moglen and others (2006) analysis, a generalized skew of 0.45 with a standard error of 0.41 was continued in use for the Eastern Coastal Plain. For the Western Coastal Plain, an analysis of 21 long-term stations indicated a mean skew of 0.52 with a standard error of 0.45. Since these revised values were similar to or equal to the Moglen and others (2006) analysis, a generalized skew of 0.55 with standard error of 0.45 was continued in use for the Western Coastal Plain.

Watershed characteristics for 159 gaging stations are given in Appendix 1. Flood discharges for the 1.25-, 1.50-, 2-, 5-, 10-, 25-, 50-, 100-, 200- and 500-year peak discharges at 159 gaging stations in Maryland and Delaware are given in Appendix 2. The flood discharges for the Piedmont, Blue Ridge and Appalachian Plateau are based on annual peak data through the 1999 water year. For the Eastern Coastal Plain, the flood discharges are based on annual peak data though the 2006 water year. For the Western Coastal Plain, the flood discharges are based on annual peak data through the 2008 water year. Estimates of design discharges are available in Appendix 2 to those users who choose not to perform their own Bulletin 17B analysis. The watershed characteristics in Appendix 1 and the flood discharges in Appendix 2 were used to develop the Fixed Region regression equations provided in Appendix 3. **The Fixed Region regression equations given in Appendix 3 are recommended for use in Maryland and supercede the regression equations given in the August 2006 Hydrology Panel report for the Eastern and Western Coastal Plains and for rural watersheds in the Blue Ridge and Piedmont Regions.**

If the watershed characteristics of the gaging station are similar to those used in deriving the regression equations, then the best estimate of design discharges at the gaging station is considered to be weighted estimates based on gaging station data and the Fixed Region regression estimates. The procedures for weighting the gaging station and regression estimates are described below.

In accordance with Appendix 8 of Bulletin 17B guidelines (IACWD, 1982), it is assumed that an estimate at a single gaging station is independent of the regional regression estimate. Assuming independence of estimates, Hardison (1976) has shown that a weighted estimate, obtained by weighting each estimate inversely proportional to its variance, has a variance less than either of the individual estimates. Hardison (1976) further demonstrated that weighting two estimates inversely proportional to their variances was comparable to weighting by the equivalent years of record. The following weighting equation described by Dillow (1996) should be used:

$$LQw = (LQg * Ng + LQr * Nr) / (Ng + Nr) \tag{2.1}$$

where LQw is the logarithm of the weighted peak discharge at the gaging station, LQg is the logarithm of the peak discharge at the gaging station based on observed data, LQr is the logarithm of the peak discharge computed from the appropriate Fixed Region regression equation, Ng is the years of record at the gaging station, and Nr is the equivalent years of record for the Fixed Region regression estimate.

The equivalent years of record of the regression estimate is defined as the number of years of actual streamflow record required at a site to achieve an accuracy equivalent to the standard error of prediction of the regional regression equation. The equivalent years of record (Nr) is computed as follows (Hardison, 1971):

$$Nr = (S/SE)^2 R^2 \tag{2.2}$$

where S is an estimate of the standard deviation of the logarithms of the annual peak discharges at the ungaged site, SE is the standard error of estimate of the Fixed Region regression estimates in logarithmic units, and R^2 is a function of recurrence interval and skewness and is computed as (Stedinger and others, 1993):

$$R^2 = 1 + G*Kx + 0.5 *(1+0.75*G^2)*Kx^2 \tag{2.3}$$

where G is an estimate of the average skewness for a given hydrologic region, and Kx is the Pearson Type III frequency factor for recurrence interval x and skewness G. Average skewness values G were defined using design discharges for each region as follows: 0.489 for the Applachian Region, 0.527 for the rural watersheds in Blue Ridge and Piedment Regions, 0.585 for the urban equations in the Piedmont Region, 0.513 for the Western Coastal Plain Region and 0.484 for the Eastern Coastal Plain Region.

In order to estimate the equivalent years of record at an ungaged site, the standard deviation of the logarithms of the annual peak discharges (S in Equation 2.2) must be estimated. Average values of S were computed for each region and are as follows: 0.241 log units for the Applachian Region, 0.296 log units for the rural stations in the Blue Ridge and Piedmont Regions, 0.324 log units for the urban equations in the Piedmont Region, 0.309 log units for the Western Coastal Plain Region, and 0.295 log units for the Eastern Coastal Plain Region.

A computer program, developed by Gary Tasker, USGS, and modified by Glenn Moglen, Virginia Tech (formerly University of Maryland), can be used to compute the weighted estimate given in equation 2.1 and for determining the equivalent years of record, and standard errors of prediction for these estimates. The equivalent years of record for the weighted estimate is assumed to be Ng+Nr (see Equation 2.1), the sum of the years of gaged record and equivalent years of record for the regression estimate. The Tasker program was updated to use the Fixed Region regression equations shown in Appendix 3.

An example of computing a weighted estimate at a gaging station, Northwest Branch Anacostia River near Colesville (station 01650500), a 21.2-square-mile urban watershed (impervious area = 20.1 percent) in the Piedmont Region is illustrated below. The flood discharges for station 01650500 (Qg in cfs) based on 62 years of record are taken from Appendix 2 and are given in Table 2.1. Also provided in Table 2.1 are the Fixed Region (Piedmont Urban) regression estimates (Qr in cfs) at station 01650500.

Table 2.1: Flood Frequency Estimates for Northwest Branch Anacostia River near Colesville (station 01650500) based on Gaging Station data, Regression Equations and a weighted estimate.

Return period (years)	Station (Qg) (cfs)	Regression (Qr) (cfs)	Weighted (Qw) (cfs)
2	1,250	1,550	1,270
5	2,260	2,920	2,360
10	3,240	4,260	3,500
25	4,960	6,550	5,510
50	6,690	8,860	7,520
100	8,900	11,700	9,980
500	16,600	21,600	18,400

The Fixed Region regression estimates in log units (LQr) are weighted with the station estimates in log units (LQg) using Equation 2.1. The weighting factors are the years of record at station 01650500 (Ng = 62) and the equivalent years of record (Nr) for the regression equations are computed from Equation 2.2 and given in Appendix 3. The weighted estimates are shown in Table 2.1. For example, the 100-yr weighted estimate is computed from Equation 2.1 as follows using the logarithms of the flood discharges

$LQw = (LQg * Ng + LQr * Nr) / (Ng + Nr) = (3.94939*62 + 4.06819*45) / (62+45) =$ 3.999351 log units, where Qw = 9,980 cfs.

The equivalent years of record for the weighted estimate is assumed equal to the sum of the observed record length (62 years) and the equivalent years of record from the regression equation (45 years). Therefore, for the 100-yr weighted estimate, the equivalent years of record are 107 years.

Figure 2.2 illustrates the process of weighting station data with the regional regression estimates.

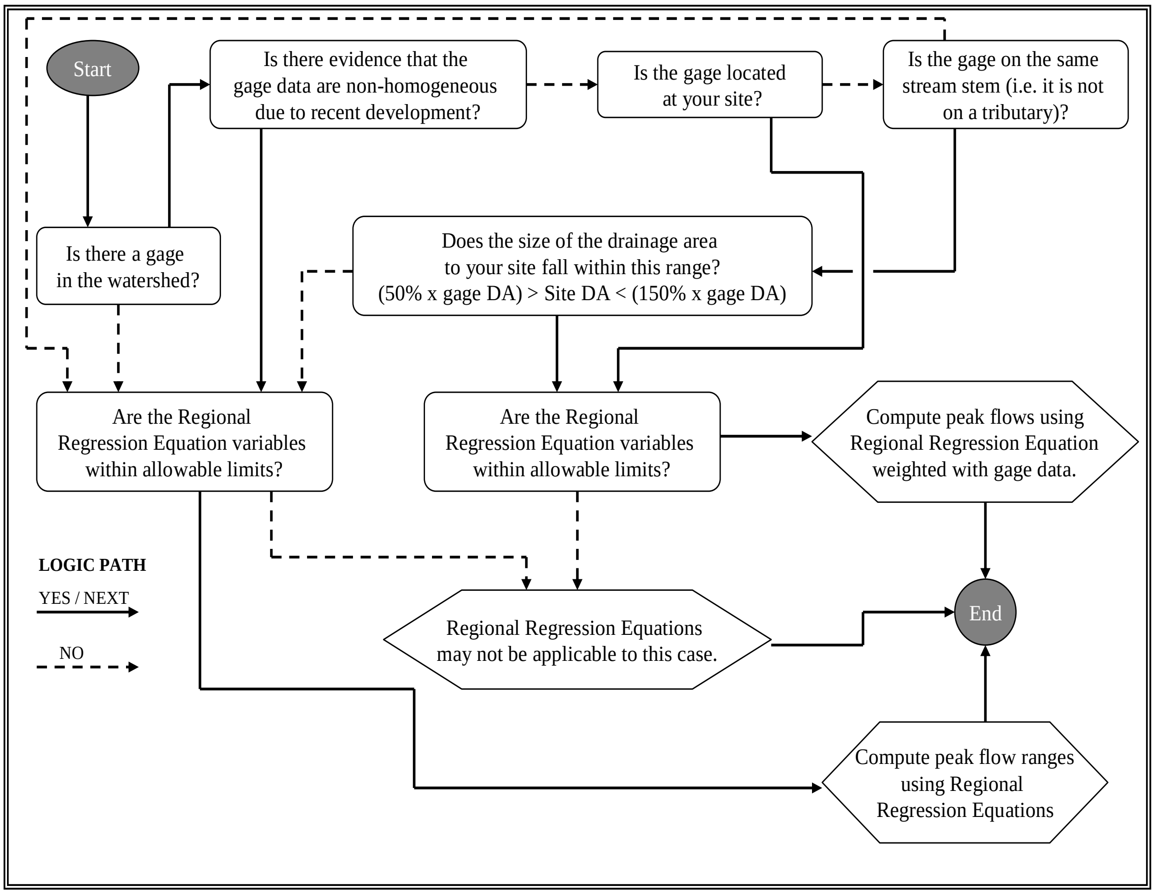


Figure 2.2: Regional Regression Equation Flow Chart

2.3 ESTIMATES FOR UNGAGED SITES NEAR A GAGING STATION

Procedures described by Dillow (1996) are recommended for obtaining estimates of design discharges for ungaged sites that are on the same stream as the gaging station, have similar watershed characteristics as the gaging station and are within 50 percent of the drainage area of a gaging station. Data shown in Appendix 1 can be used to determine if the gaged stream has watershed characteristics similar to those used in developing the regression equations. The procedure involves three steps:

1. Compute the ratio (R) of the weighted estimate to the Fixed Region regression estimate at the gaging station

$$R = Qw/Qr \qquad (2.4)$$

where Qw and Qr are the weighted and regression estimates in cfs.

2. Scale the ratio R based on the difference in drainage area between the ungaged site and the gaging station using the following equation (Sauer, 1974):

$$Rw = R - ((2|Ag-Au|)/Ag) *(R-1) \qquad (2.5)$$

where Rw is the scaled ratio, Ag is the drainage area in square miles at the gaging station and Au is the drainage area in square miles at the ungaged location.

3. Compute the final estimate (Qf) at the ungaged site as

$$Qf = Rw * Qu \qquad (2.6)$$

where Qu is the Fixed Region regression estimate in cfs at the ungaged site.

Equation 2.5 was developed with the limiting assumption that estimates would only be extrapolated upstream and downstream on the same stream to 0.50 or 1.50 times the drainage area of the gaging station. If Equation 2.5 is used beyond these limits, then irrational results may be obtained. If the gaged watershed has undergone significant change during the period of record, then the annual peak data may not be homogeneous and the extrapolation procedure may not be appropriate.

In the case where the ungaged site is between two gaging stations, estimates of Qg should be obtained by interpolating between the two gaging stations on the basis of a logarithmic plot of peak discharge versus drainage area. An estimate of Ng is obtained as an arithmetic average of the record length at the two gaging stations using the differences in drainage area between the ungaged site and the gaging stations as the weighting factor. The values of LQg and Ng so obtained should be used in Equation 2.1 to get a final weighted estimate for the ungaged site.

The weighted estimates at the Northwest Branch of the Anacostia River near Coleville (shown in Table 2.1), where the drainage area is 21.2 square miles, are extrapolated upstream to an ungaged location where the drainage area is 15.1 square miles and the impervious area is 25 percent. For this procedure to be applicable, the watershed characteristics at the ungaged site should be similar to those at the gaged site. For this example, the weighted (Qw) and regression (Qr) 100-yr flood discharge at station 01650500 are 9,980 and 11,700 cfs, respectively, and the regression estimate (Qu) at the ungaged location is 9,940 cfs. The adjusted 100-yr flood discharge at the ungaged location on the Northwest Branch of the Anacostia River is computed to be 9,310 cfs using Equations 2.4 to 2.6 as follows:

$R = Qw/Qr = 9{,}980/11{,}700 = 0.853$

$Rw = R – [((2|Ag-Au|)/Ag) *(R-1)] = 0.853 – [((2|21.2-15.1|)/21.2)*(-0.147)] = 0.937$

$Qf = Rw * Qu = 0.937*9{,}940 = 9{,}310$ cfs.

The equivalent years of record are 71.4 years for the 100-yr flood discharge at the ungaged location. This value is interpolated between 107 years for the weighted station data at 21.2 square miles and 45 years for the Fixed Region regression equation estimate at 0.5 times the gaged drainage area. The computation is 107 – ((107-45)*6.1/10.6) = 71.4 years. The equivalent years of record for the Fixed Region regression equations are given in Appendix 3.

2.4 ESTIMATES AT UNGAGED SITES

Fixed Region regression equations given in Appendix 3 can be used for estimating the 1.25-, 1.50-, 2-, 5-, 10-, 25-, 50-, 100-, 200- and 500-year peak discharges for rural and urban watersheds in Maryland which are not significantly affected by detention storage, urbanization, tidal marshes or changing land-use conditions such as mining, excavation or landfill activities. Equations applicable to urban watersheds are available for just the Western Coastal Plain and Piedmont Regions.

In addition, the watershed characteristics for the site of interest should be within the range of the watershed characteristics of the gaging stations used in the regional analysis. Watershed characteristics used in the development of the Fixed Region regression equations are given in Appendix 1. These data can be used to determine if the ungaged site has similar watershed characteristics as those used in developing the regression equations.

A computer program developed by Gary Tasker, USGS, was modified to facilitate the estimation of flood discharge estimates at ungaged sites using the Fixed Region regression equations documented in Appendix 3. The equivalent years of record, the standard errors of prediction and prediction intervals are also computed for these estimates using the Tasker program.

The standard error of prediction for the ungaged site is computed as the sum of the model and sampling error as described by Hodge and Tasker (1995). Given the standard error of prediction for an ungaged site, the equivalent years of record are computed by Equation 2.2. Prediction intervals are then computed as:

$$\log Qx + t(c/2, n\text{-}p)*(SE^2(1+ho))^{0.5} \qquad \text{upper value} \qquad (2.7a)$$
$$\log Qx - t(c/2, n\text{-}p)*(SE^2(1+ho))^{0.5} \qquad \text{lower value} \qquad (2.7b)$$

where Qx is the flood discharge for recurrence interval x, t is the critical value of Student's t for a 100 (1-c) percent prediction interval with n-p degrees of freedom, n is the number of gaging stations used in the regression analysis, p is the number of explanatory variables in the Fixed Region regression equation, SE is the standard error of estimate in log units, and ho is the leverage of the site. The standard error of prediction (SEp) estimated by the Tasker program is more accurate than using the standard error of estimate given in Appendix 3. The standard error of estimate given in Appendix 3 is a measure of the variability of the station data about the regression equation and is less than the standard error of prediction which is a measure of how well the equations predict flood discharges at an ungaged site. The standard error of prediction includes both the variability about the regression equation and the error in the regression coefficients.

The leverage expresses the distance of the site's explanatory variables from the center of the convex data set (called the Regressor Variable Hull) defined by the explanatory variables in the regression analysis (Montgomery and Peck, 1982). The prediction intervals are directly related to the magnitude of the leverage for a given site. The leverage is computed as (**bold letters** denote a matrix):

$$ho = xo\ (\mathbf{X}^T\mathbf{X})^{-1}\ xo^T \qquad (2.8)$$

where xo is a row vector of the logarithms of the explanatory variables at a given site, $(\mathbf{X}^T\mathbf{X})^{-1}$ is the covariance matrix of the regression parameters (T means transpose), xo^T is a column vector of the logarithms of the explanatory variables at a given site.

Equations 2.7 and 2.8 and the data in Appendix 1 are used to compute the prediction limits in the Tasker program. For plus and minus one standard error of prediction, there is a 68 percent chance that the true discharge is between the upper and lower prediction limits.

The range of watershed characteristics for each hydrologic region is given in Table 2.2. The watershed characteristics were estimated using GIS data from several sources as described in Appendix 1. The Fixed Region regression equations for each hydrologic region are given in Appendix 3 along with the standard error of estimate and the equivalent years of record. The Fixed Region regression equations are based on 28 stations in the Eastern Coastal Plain, 24 rural and urban stations in the Western Coastal Plain, 53 rural stations in the Piedmont and Blue Ridge, 16 urban stations in the Piedmont, and 23 stations in the Appalachian Plateau. A total of 144 stations were used to derive the Fixed Region regression equations in Appendix 3.

In developing the Fixed Region regression equations, forest cover and impervious area for 1985 land use conditions were used because these data tended to be most correlated with the flood discharges. The reason is that the 1985 land use conditions were closer to the midpoint of the period of record of the streamgage data particularly for the urban watersheds in the Western Coastal Plains and Piedmont Regions. In applying the regression equations, the analyst should use the current land use conditions to obtain estimates of the flood discharges for existing conditions.

For streams that cross regional boundaries, the regression equations for each region should be applied as if the total drainage area was in each region. These estimates should then be weighted by the percentage of drainage area in each region. The weighted flood frequency estimates can be obtained using GISHydro2000.

2.5 FUTURE RESEARCH

The Fixed Region regression equations are applicable to both rural and urban watersheds in the Western Coastal Plains and Piedmont Regions. For the urban watersheds, a "relatively constant period of urbanization" was defined as a change in impervious area of less than 50 percent during the period of record. If a watershed had 20 percent impervious area at the beginning of record, it could have no more than 30 percent impervious area at the end of the time period (Sauer and others, 1983). No urban stations were eliminated from the analysis based on these criteria notably because several urban gaging stations were discontinued in the late 1980s. For future analyses, a more detailed approach should be developed for determining a homogeneous period for frequency analysis or for adjusting the annual peak data to existing conditions.

The Maryland Department of Planning (MDP) data were used to estimate land use conditions such as impervious area. The MDP approach is to assign a percentage of impervious area to various land use categories. For example, Institutional Lands are assigned an impervious area of 50 percent but there is considerable variation in impervious area for this land use category. Impervious area as estimated from the MDP data was statistically significant in estimating flood discharges for urban watersheds in the Western Coastal Plains and Piedmont Regions but this variable did not explain as much variability as anticipated. For future regression analyses, more accurate or detailed measures of urbanization (impervious area, percentage of storm sewers, length of improved channels, etc.) should be used for characterizing urbanization and its affect on flood discharges. Improved measures of urbanization would likely provide more accurate regression equations in the future.

Many of the gaging stations on small watersheds (less than about 10 square miles) were discontinued in the late 1970s resulting in generally short periods of record for the small watersheds in Maryland. As described earlier, Carpenter (1980) and Dillow (1996) utilized estimates of flood discharges from a calibrated rainfall-runoff model for eight gaging stations in Maryland. Carpenter (1980) also adjusted flood discharges at 17 other small watersheds based on comparisons to nearby long-term gaging station data. Moglen and others (2006) utilized both of these adjustments in developing the Fixed Region regression equations. There are many other short-record stations in Maryland for which no adjustment was made. For future regression analyses, a more systematic approach for adjusting the short-record stations should be developed. In addition, streamgaging activities should be resumed on several of the small watersheds where there are less than 15 years of record. Improving the data base of small watershed data would provide more accurate regression equations in the future.

Finally, only stations primarily in Maryland were used in developing the Fixed Region regression equations in Appendix 3 because the required land use data were not available in neighboring states. The exception was the inclusion of gaging stations in Delaware. More detailed land use data should be developed for the neighboring states like Pennsylvania, Virginia and West Virginia so that additional gaging stations could be included in the regional regression analyses.

Table 2.2: Range of Watershed Characteristics for Each Hydrologic Region in Maryland.

Variable	Eastern Coastal Plain	Western Coastal Plain	Piedmont and Blue Ridge (Rural)	Piedmont (Urban)	Appal. Plateau
DA	0.91 to 113.7 sm	0.41 to 349.6 sm	0.11 to 820.0 sm	0.49 to 102.05 sm	0.52 to 293.7 sm
S_A	0 to 78.8%	---	---	---	---
IA	---	0 to 36.8 %	---	10.0 to 37.5%	---
S_{CD}	---	13 to 74.7%	---	---	---
FOR	---	---	2.7 to 100%	---	---
LIME	---	---	0.0 to 81.7%	---	---
LSLOPE	0.0025 to 0.0160 ft/ft	---	---	---	0.06632 to 0.22653 ft/ft

DA	Drainage area in square miles measured on horizontal surface.
S_A	Percent of DA that is classified as NRCS Hydrologic Soil Group A based on SSURGO soils data.
IA	Percent of DA that is impervious as defined by the Maryland Department of Planning land use data.
S_{CD}	Percent of DA that is classified as NRCS Hydrologic Soil Group C and D based on SSURGO soils data.
FOR	Percent of DA land cover that is classified as forest cover.
LIME	Percent of DA that is underlain by carbonate rock (limestone and dolomite), from map given in Appendix 3.
LSLOPE	Average land slope of the watershed in feet per feet.

CHAPTER THREE

3 BEHAVIOR OF THE WINTR-20 MODEL IN RESPONSE TO UNCERTAINTIES IN THE INPUT PARAMETERS

3.1 OVERVIEW

The WinTR-20 model is a deterministic hydrologic model that synthesizes a single event runoff hydrograph as a function of a rainfall input and watershed characteristics. The model is designed to operate on a time varying rainfall to produce a hydrograph that simulates the role of the watershed area; land cover; hydrologic soil types; antecedent runoff conditions; topography; characteristics of the overland, shallow confined, and channel flow paths; and, storage attenuation such as that created by flood plains, wetlands, structures, and ponds. A single watershed can be modeled by inputting the drainage area, time of concentration, curve number and a time-intensity rainfall distribution. If the watershed is large or heterogeneous, it can be divided into a number of subwatersheds with their hydrographs attenuated by routing through the stream network that the user defines in terms of length, slope, roughness, cross-section and any storage elements or structures that may be distributed along its length.

Because the WinTR-20 model can simulate watershed conditions and changes in these conditions in terms of relatively simple input parameters, it continues to be the baseline for SHA hydrologic analyses that require hydrographs for both existing and ultimate development conditions. The first step is to select model parameters that are consistent with established hydrologic practice and give a reasonable simulation of existing hydrologic conditions. After the user is satisfied that the model is satisfactory for existing watershed conditions, the curve number and flow network parameters can be changed to simulate the hydrologic response of the watershed under a future, or ultimate development, land cover distribution and drainage hydraulics.

The WinTR-20, like most deterministic hydrologic models, is quite sensitive to the values chosen for the input parameters. These sensitivities and the uncertainties surrounding their selection make it difficult to ensure that the WinTR-20 results are representative of all Maryland conditions. The tendency among SHA and other Maryland designers has been to select parameters that lead to over- prediction in many cases. This Maryland experience is supported by U.S. Water Resources Council (1981) tests on ten procedures for estimating peak discharges for ungaged watersheds. Each procedure was applied by five persons at gaging stations with at least 20 years of observed peak-flow records. Based on 105 applications at 21 gaging stations in the Midwest and Northwest Regions of the country, it was found that the TR-20 model overestimated the 100-yr flood discharge by about 55%, the 10-yr discharge by about 60% and the 2-yr discharge by about 55%.

The Panel recognizes the parameter sensitivities of the WinTR-20 model and its tendency to over predict. However, the Panel has concluded that these problems can be overcome and that the WinTR-20 model can be a sound, dependable model for simulating existing and ultimate conditions for most watersheds provided that it is calibrated for local conditions. Calibration of all deterministic models is strongly recommended by AASHTO (1991, pgs. 7-17, 7-18). The Panel recommends that it become standard practice to require that the WinTR-20 be calibrated for existing watershed conditions against one of the USGS gage-based procedures of Chapter 2, provided that the watershed conditions are consistent with those above the USGS gage or the sample used to derive the approved regional regression equations. The approved regional regression equations are based on statistical analyses of stream gages in Maryland and adjacent states having record lengths between 10 and over 70 years. Thus, a successful calibration following the procedures outlined in Chapter 4 and Appendix 5 can produce reliable WinTR-20 peak discharges that are consistent with Maryland conditions.

In order to gain insight into the sensitivities associated with the TR-20 input parameters under Maryland conditions, the SHA sponsored a study by Ragan and Pfefferkorn (1992). This study entitled, "Analysis of the Role of Storm and Stream Parameters on the performance of SCS-TR-20 and HEC-1 under Maryland Conditions", was conducted on the 21.3 square mile Northwest Branch watershed in Montgomery County. The Northwest Branch was selected because it had been the subject of many studies by various organizations and, therefore, had an excellent data base along with an established GIS that managed the land and stream elements of the watershed. There were 76 surveyed stream cross-sections along 71,000 feet of channel, detailed soil data, high resolution color IR defined land cover and long term stream flow records. All these data were in digital formats and interfaced with a GIS. Most of the examples of hydrograph responses to variations in TR-20 input parameters that follow in Chapter 3 are from the Ragan and Pfefferkorn (1992) experiments.

The remaining sections of Chapter 3 discuss the issues that the Panel examined with respect to defining the input parameters to the WinTR-20 model. Chapter 4 and the appendices discuss procedures that will assist the WinTR-20 user in the selection of input parameters during the calibration process.

3.2 DRAINAGE AREA

The scale of the map can create an error in the estimate of the drainage area. Delineating on a small scale map, such as 1:100,000, probably will not give the same drainage area as one would obtain from a 1:24,000 or 1:4,800 scale map. Normally, watersheds having drainage areas larger than one square mile of interest to the SHA will be delineated on a 1:24,000 scale USGS 7.5 minute quadrangle sheet. Special care must be exercised in flat terrain such as the Eastern Coastal Plain because of the wide spacing of contours and lack of definitive of ridge lines.

Hydrologists and designers working of SHA projects use GISHydro2000. GISHydro 2000 is a geographic information system that generates watershed boundaries and stream networks using USGS digital terrain data. Two issues must be recognized with any region growing method. The first issue is training. The person using region growing techniques must be thoroughly trained. The procedures can give excellent results, but, if the user does not know what he or she is doing, significant errors can result. For example, if one tries to delineate a watershed that is too small - one containing only a few elevation points - the results will be very questionable. Figure 3.1, developed from a study by Fellows (1983), shows the percent difference between watershed areas manually delineated on paper 1:24,000 scale maps and those grown from digital terrain data as a function of the number of elevation points inside the boundary. A_M is the area determined “manually” by visually tracing the ridge lines on 1:24,000 scale maps. A_G is the area “grown” using the digital terrain data. A second issue that must be recognized is resolution -- the spacing of the elevation points in the data base. GISHydro2000 provides 30 meter resolution digital terrain data for all of Maryland. There may be instances where the watershed boundary extends across a state boundary. In such an instance, the user might have to use data from another source that has a 90 meter resolution. The 90-meter data may not give the same level of accuracy as the 30-meter data. If the area of the watershed is incorrect, the peak discharge will be incorrect as well.

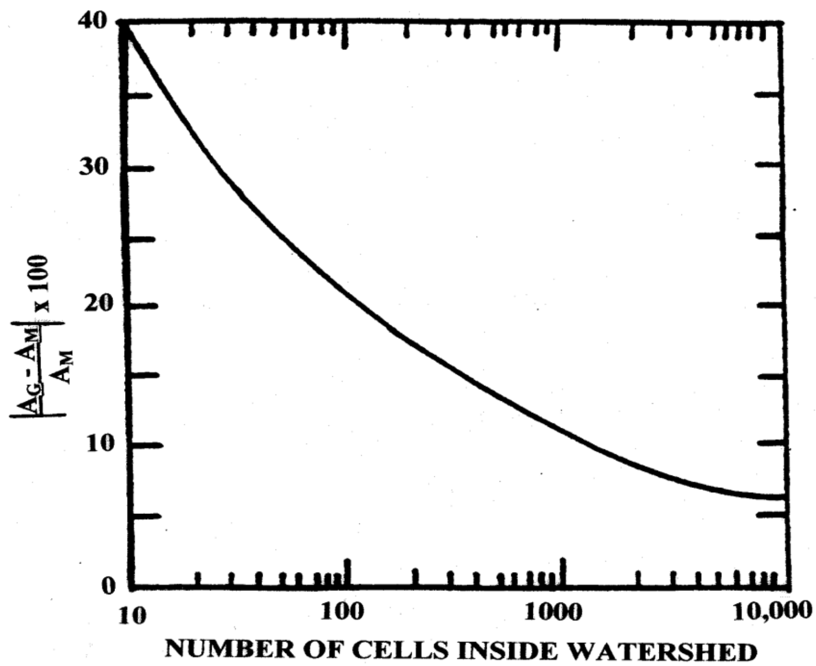


Figure 3.1: 99% Confidence Error Envelope for Difference Between Manually and Automatically Defined Areas

It is emphasized that all watershed and subwatershed boundaries developed with GISHydro2000 must be checked to ensure that there is good agreement with the areas obtained from paper format 1:24,000 USGS quad sheets.

3.3 VOLUME OF RUNOFF

A deterministic model must have a component that estimates the rainfall excess that becomes the volume of the runoff hydrograph. Thus, there must be a means to account for the interception, infiltration and depression storage processes that occur in the watershed. In the NRCS family of models, the rainfall excess is estimated by a Runoff Curve Number (RCN) that is a function of the land cover, the underlying soil type, and antecedent runoff conditions (ARC). Tables 2-2a thru 2-2d from U.S. Department of Agriculture (1986) are recommended for use in SHA hydrologic analyses using the WinTR-20.

The rainfall excess, or volume of runoff under the hydrograph, is given by Equation 3.1

$$Q = (P - .2S)^2 / (P + 0.8S) \tag{3.1}$$

where:

$$S = (1000/RCN) – 10 \tag{3.2}$$

Tables 2a through 2d in TR-55 assign curve numbers in terms of "good," "fair," or "poor" condition in some of the land cover categories. First, it may be difficult for the designer to determine which of the conditions is appropriate for each land parcel in the watershed. Further, the curve numbers were derived using watershed data collected from across the United States. Thus, the specific curve number for a given soil-cover complex may or may not be appropriate for the particular Maryland watershed under investigation. Finally, Equation 3.1 is a simplification of

$$Q = (P - I_a)^2 / ((P - I_a) + S) \tag{3.3}$$

where it is assumed that:

$$I_a = 0.2S \tag{3.4}$$

The data on which the assumption of Equation 3.4 is based, presented as Figure 10-1 in USDA- NRCS-NEH, 630, Chapter 10, (2004), are shown here as Figure 3.2.

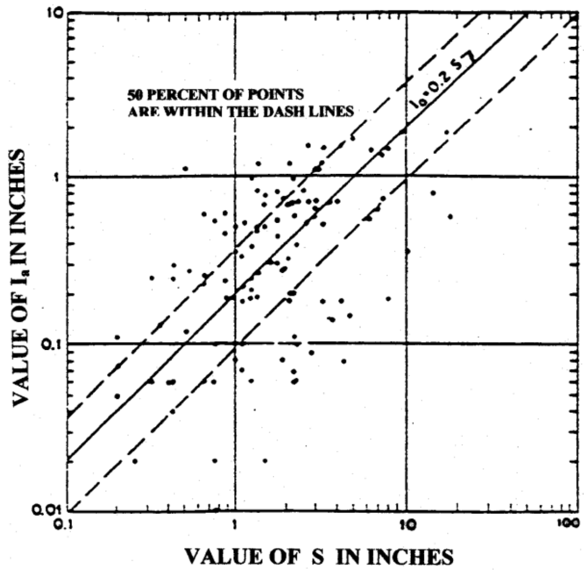


Figure 3.2: Relationship Between I_s and S

(Plotted points are derived from experimental watershed data) Source: Figure 10-1 of USDA-NRCS-NEH Part 630 Hydrology, Chapter 10)

The consequences of making an error in the determination of the weighted curve number for a natural watershed is illustrated by Figure 3.3 from Ragan and Pfefferkorn (1992).

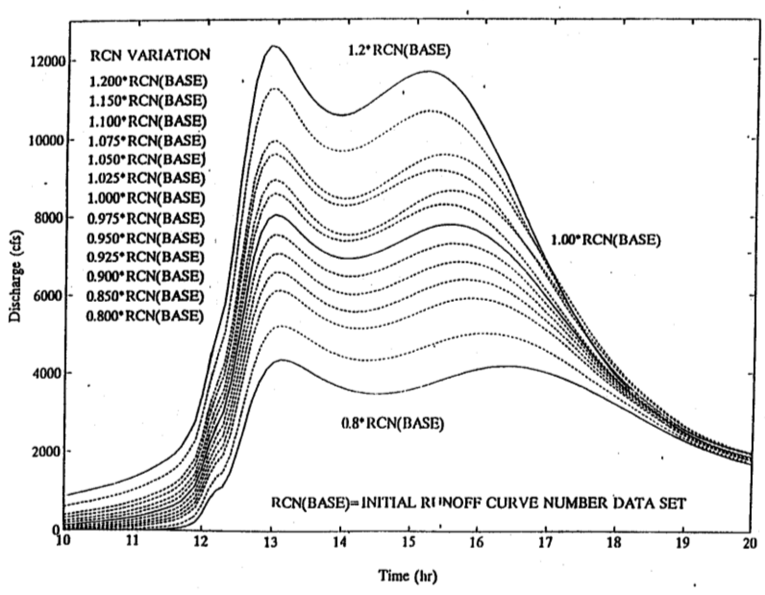


Figure 3.3: Hydrograph Response to Changing RCN

The purpose of this Section 3.3, Volume of Runoff, is to encourage users of the WinTR-20 to recognize that estimating the volume of surface runoff using the curve number approach is an imperfect process. Thus, as described in Chapter 4, the Panel recommends that the user exercise a degree of flexibility in the selection of curve numbers to represent specific land/soil complexes provided that the basis for the decision is explained.

3.4 PEAK DISCHARGE AND SHAPE OF THE RUNOFF HYDROGRAPH

3.4.1 The Dimensionless Unit Hydrograph

A storm occurring on a low relief watershed with wide, flat streams will produce a long duration hydrograph with a low peak discharge in comparison with that generated by a high relief mountain basin having steep narrow channels. Many deterministic models, including the WinTR-20, simulate the interrelationships among the runoff processes through a unit hydrograph (UHG). If stream flow records are available for the subject watershed, the WinTR-20 allows a site specific UHG to be input. If possible, the derived site specific UHG should be used. However, the usual circumstance is to use the default dimensionless UHG built into the WinTR-20. While the NRCS dimensionless UHG is thoroughly discussed in Chapter 16 of NRCS-NEH Part 630, Hydrology, several issues are presented here for completeness.

The dimensionless UHG controls the shape and peak discharge of the runoff hydrograph using the drainage area, the volume of runoff, and the time of concentration as input parameters. NRCS-NEH Part 630, Hydrology gives the peak discharge of the unit hydrograph that the WinTR-20 convolutes with the time-distribution of rainfall excess as

$$q_p = 484AQ / T_p \tag{3.5}$$

$$T_p = \Delta D/2 + 0.6T_c \tag{3.5a}$$

where T_p is the time to peak. In Equation 3.5, Q is 1.0 inches because it is a unit hydrograph. Time to peak is a function of the duration of the unit excess rainfall, ΔD, and the time of concentration T_c as shown in equation 3.5a.

The constant value of 484 is the “peak rate factor.” NRCS-NEH Part 630, Hydrology points out that “this factor has been known to vary from about 600 in steep terrain to 300 in very flat swampy country.” A UHG with a peak rate factor of 284 has been used for some time on the flat watersheds of the Maryland Eastern Coastal Plain.

In the case of the Maryland Eastern Coastal Plain UHG, the lower peaking factor accounts for the greater storage and longer travel times of the flat wetlands often found on streams in that area. However, one must be aware that a peak flow rate can sometimes be changed by subdividing the watershed into sub-basins and then routing the sub-basin hydrographs through the storage provided by the network of connecting streams. In general, models that have larger (more than one square mile) sub-basins should use the regional dimensionless unit hydrograph. In Maryland, these regional dimensionless unit hydrographs are currently being updated by the NRCS. Until other values are published, the designer may use the new peaking factor values for the Maryland Dimensionless Unit Hydrographs, shown in Table 3.1. The dimensionless unit hydrograph to be used when the peak factor is 284 is presented as Table 3.2

Table 3.1: Unit Hydrograph Peak Factors

REGION	PEAK FACTOR
Eastern Coastal Plain	284
Western Coastal Plain	284
Piedmont	484
Blue Ridge	484
Appalachian	484

Table 3.2: Dimensionless Unit Hydrograph
for Use When Peak Factor is 284

```
TITLE     DELMARVA UNIT HYD PRF NEAR 284
 4 DIMHYD             .02
 8         0.0        .111        .356        .655        .896
 8         1.0        .929        .828        .737        .656
 8         .584       .521        .465        .415        .371
 8         .331       .296        .265        .237        .212
 8         .190       .170        .153        .138        .123
 8         .109       .097        .086        .076        .066
 8         .057       .049        .041        .033        .027
 8         .024       .021        .018        .015        .013
 8         .012       .011        .009        .008        .008
 8         .006       .006        .005        .005        0.0
 9 ENDTBL
```

If a watershed falls within more than one region boundary, the WinTR-20 model can be split into appropriate parts with corresponding regional dimensionless unit hydrographs (DUH). If the WinTR-20 flood discharges agree with the regional estimates without use of two DUH, then no additional action is needed. If the WinTR-20 flood discharges are not within the calibration Window, subdivide watershed at the Fall Line and use the two DUH as appropriate. If a significant portion (75% or more) of the watershed falls within one region, then use that region's dimensionless unit hydrograph.

In addition to the probable variation of the peak rate factor as a function of the watershed topography, it can also be seen from Equation 3.5 that the peak discharge of the UHG is a function of the time of concentration, T_c. As described later in this chapter, the time of concentration is difficult to define. Thus, the NRCS dimensionless or any other "nationally-derived" synthetic UHG defined in terms of a few parameters can create errors in the runoff estimate. In the future there may be approaches that allow the use of more site specific UHG's, even when no stream flow records are available. Because of the availability of the USGS digital terrain data, the "geomorphic" UHG using a time-area-curve concept that tracks the flow path of each grid cell in the watershed should be a practical approach in the near future.

3.4.2 Time of Concentration and Lag

Definitions

Travel time is the time it takes for runoff to travel from one location in a watershed to another location downstream. Estimating travel time is complicated by the fact that it may occur on the surface of the ground or below it or a combination of the two. The *Time of Concentration* is the time required for runoff to travel from the hydraulically most distant part of the watershed to the outlet of the watershed. Recall that it is the time of concentration that is input to the WinTR-20 to define the peak discharge of the unit hydrograph from the dimensionless UHG. The *Lag* can be thought of as a weighted time of travel. If the watershed is divided into increments, and the travel times from the centers of the increments to the watershed outlet are determined, then the lag is calculated as:

$$L = \frac{\Sigma\,(a_i\,Q_i\,T_{ti})}{\Sigma\,(a_i\,Q_i)} \qquad (3.6)$$

where:

- L is the lag time, in hours;
- a_i is the the ith increment of the watershed area, in square miles;
- Q_i is the the runoff from area a_i, in inches;
- T_{ti} is the the travel time from the center of a_i to the point of reference, in hours.

NRCS-NEH Part 630, Hydrology provides the empirical relation

$$L = 0.6\,T_c \qquad (3.7)$$

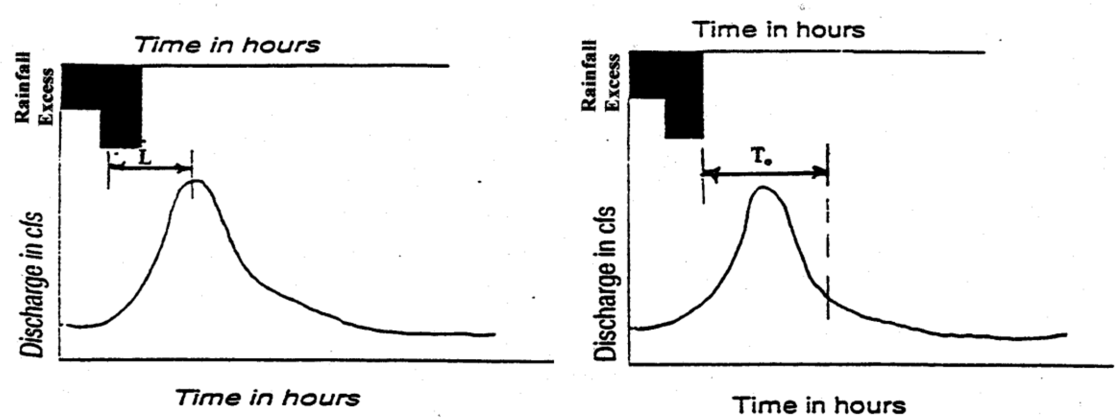


Figure 3.4: Graphical definitions of lag time and time of concentration.

Lag, as defined by NRCS, is the time from the center of mass of the rainfall excess to the peak rate of runoff as shown by Figure 3.4 (left). Similarly, the time of concentration is the time from the end of the rainfall excess to the point on the falling end of the hydrograph where the recession curve begins, as shown in Figure 3.4 (right). It is quite difficult to determine the time that the rainfall excess begins and ends. Where sufficient rainfall and runoff data are not available, the usual procedures for determining L and T_c are outlined in the following sections.

NRCS-NEH Part 630, Hydrology discussed two methods for estimating time of concentration and lag when hydrograph data are not available. These methods, the curve number method and the flow path hydraulics method, are discussed in the following sections.

3.4.3 Watershed Lag Method to Estimate Time of Concentration

One parameter that is needed for input to the WinTR-20 is the time of concentration. The designer may use Watershed Lag Equations or graphs instead of calculating the individual overland/sheet flow and shallow concentrated flow separately. The time-of-concentration is calculated as:

$$Tc = 1.67\ L \qquad (3.8)$$

where both Tc and L are in either hours or minutes.

The NRCS Watershed Lag Equation is:

$$L = \frac{L_h^{\ 0.8}\ (S+1)^{\ 0.7}}{1900\ Y^{\ 0.5}} \qquad (3.9)$$

where: L is the Lag, in hours

L_h is the hydraulic length of watershed, in feet

$$S \text{ is } \frac{1000}{RCN} - 10 \qquad (3.10)$$

Y is the average watershed land slope (perpendicular to flow), in Percent

<u>The NRCS Watershed Lag Equation may not be used when the drainage area is greater than five square miles. The minimum length used in the Lag Equation shall be 800 ft.</u> Shorter lengths will result in artificially low lag times.

There are several ways to estimate the watershed slope, Y, and they may not agree with each other. The original version of the SHA GISHydro2000 used the average slope categories assigned to the soil types. This is probably the weakest approach. The optimal approach is to use the 30-meter resolution digital terrain data that are available for Maryland in GISHydro2000. Slopes estimated with 90-meter data will not agree with the 30-meter data. Another approach is to digitize the areas between “heavy line” contours, assign average elevations to these enclosed areas and then weight them for the watershed. The "heavy line" contours are those such as 100 feet, 200 feet, etc. Finally, the lengths of the heavy line contours can be measured and the watershed slope estimated as:

$$\text{Watershed Slope} = MN/A_{sf} \qquad (3.11)$$

where:

M is the total length of heavy line contours, in feet
N is the contour interval, in feet
A_{sf} is the drainage area in, square feet

The hydraulic L_h length in feet can be estimated from a map or the following relation can be used:

$$L_h = 209(A)^{0.6} \qquad (3.12)$$

where A is in acres.

In summary, there are several issues in the use of the empirical lag equation approach that impact the time of concentration and, thereby, the peak discharge of the storm hydrograph. The uncertainties in the value of the curve number discussed in Section 3.3 represent one problem. Estimating the hydraulic length is another. And the value assigned to the slope depends on the estimation approach adopted.

The reader will note that the lag equation is not included as a procedure in WinTR-55, Hydrology for Small Watersheds. Thus, the Panel cautions against the use of the lag equation in urban ($\geq$ 10% impervious) watersheds until additional research becomes available.

3.4.4 Estimating the Time of Concentration from Flow Path Hydraulics

The time of concentration is the cumulative flow time required for a particle of water to travel overland from the hydraulically most remote point overland, through the shallow concentrated flow channels, and through the main stream network to the watershed outlet. The time may increase as a consequence of flow through natural storage such as lakes or wetlands or ponding behind culverts or other man-made structures. Estimating the time of concentration by simulating the hydraulics of each flow path component is treated in this section. Because the quantity of flow and, therefore, the hydraulics are different for each storm frequency, it is logical to expect that the time of concentration will be different for a 2-yr storm than for a 100-yr storm. Recognizing this, the Panel recommends that bankfull conditions that many consider to approximate the 2-yr storm conditions be used to estimate the time of concentration.

3.4.5 Overland Flow

At the upper reaches of a watershed, runoff does not concentrate into well-defined flow paths, such as rills, gullies, or swales. Instead it probably flows over the surface at reasonably uniform, shallow depths as sheet flow. Sheet flow is evident on long, sloping streets during rainstorms. After some distance, sheet flow begins to converge into concentrated flow paths that have depths noticeably greater than that of the shallow sheet flow. The distance from the upper end of the watershed or flow surface to the point where significant concentrated flow begins is termed the overland flow length. For impervious surfaces the overland flow length can be several hundred feet. For pervious erodable surfaces and surfaces with vegetation, concentrated flow will begin after relatively short overland flow lengths.

In the upper reaches of a watershed, overland flow runoff during the intense part of the storm will flow as a shallow layer with a reasonably constant depth. An equation, referred to as the kinematic wave equation for the equilibrium time, can be developed using Manning's equation with the assumption that the hydraulic radius equals the product of the rainfall intensity and the travel time, i.e., $R_h = i\,T_o$, which is the uniform flow depth for a wide open channel. Using the velocity equation with the travel time (minutes) equal to the time of concentration, Manning's equation becomes:

$$V = \frac{L}{T_t(60)} = \frac{1.49}{n} R_h^{2/3} S^{1/2} = \frac{1.49}{n} \left(\frac{i\,T_t}{60(12)} \right)^{2/3} S^{1/2} \tag{3.13}$$

in which i = in./hr, T_t = min, S = ft/ft, and L = ft. Solving for the travel time yields:

$$T_t = \frac{0.938}{i^{-0.4}}\left(\frac{nL}{\sqrt{S}}\right)^{0.6} \tag{3.14}$$

Equation 3.14 requires the rainfall intensity i for the time of concentration. Since T_t is not initially known, it is necessary to assume a value of T_t to obtain i from a rainfall IDF curve and then compute T_t. If the initial assumption for T_t is incorrect, then a new estimate of i is obtained from the IDF curve using the computed value of T_t. The iterative process should be repeated until the value of T_t does not change. Generally, only one or two iterations are required.

To bypass the need to solve Equation 3.14 iteratively, Welle and Woodward (1986) assumed a power-model relationship between rainfall intensity and rainfall duration. Using a return period of two years, they substituted the 2-yr, 24-hour rainfall depth for the rainfall intensity i and derived the following alternative model for Equation 3.14:

$$T_t = \frac{0.42}{P_2^{0.5}}\left(\frac{nL}{S^{0.5}}\right)^{0.8} \tag{3.15}$$

in which L is the flow length (ft), S is the average slope (ft/ft), P_2 is the 2-yr. 24-hr rainfall depth (in.), and T_t = min. Equation 3.15, which is presented in USDA-NRCS-NEH Part 630 Chapter 15 (2010), has the important advantage that an iterative solution is not required.

In addition to the previously mentioned assumptions, these two kinematic wave equations make the following assumptions: (1) constant rainfall intensity, i; (2) no backwater effects; (3) no storage effects; (4) the discharge is only a function of depth, for example $q = ay^b$, and (5) planar, non-converging flow. These assumptions become less realistic as the slope decreases, the surface roughness increases, or the length of the flow path increases.

The overland or “sheet flow” Manning n values for use with Equations 3.14 and 3.15 are given in Table 3.3 and are for very shallow flow depths. These values reflect the effects of rain drop impact; drag over plane surfaces; obstacles such as litter, crop ridges, and rocks; and, erosion and transportation of sediment. The 24-hour rainfall depth P_2 for Equation 3.15 can be computed as the product of 24 and a 24-hour intensity obtained from an IDF curve for the 2-yr return period.

Table 3.3: Manning's Roughness Coefficients "n" for Sheet Flow

Surface Description	N
Concrete, Asphalt, bare smooth ground	0.011
Gravel, rough ground	0.02
Fallow (no residue)	0.05
<u>Cultivated Soils:</u>	0.06
Residue cover > 20%	0.17
Residue cover < 20%	0.40
No-till Cultivated (corn–mature growth)	0.30
Cultivated (corn-mature growth)	0.50
Cultivated – fallow (no residue)	0.60
Soybeans (full growth)	0.15
<u>Grass:</u>	
Short and sparse	0.24
Dense turf (residential lots & lawns)	0.41
Very dense, tall, rough surface, uncut	0.20
Short Pasture grasses	0.073
<u>Woods:</u>	
Light undergrowth	0.40
Dense undergrowth	0.80

(The values in Table 3.3 are a composite of information compiled by Engman, 1986)

3.4.6 Shallow Concentrated Flow

The shallow concentrated flow segment of the time of concentration is generally derived using Figure 15-4 of the NEH Part 630 chapter 15 or similar graphs. The flow velocities of Figure 15-4 are computed using the Manning's equation; and the information in Table 15-3 of NEH 630 Chapter 15. The selected values of the Manning n are those normally expected for channel flow.

Use of the NEH Part 630 Chapter 15 graph (and the values of n and R listed above) may underestimate the travel time by overestimating the flow velocity for upper reaches of the shallow concentrated flow path. In shallow depths the hydraulic radius approaches the depth of flow. In this shallow flow range the n value should represent a higher resistance than that which would be used for channel flow. For example, a wide grass swale with flow depths of less than 0.5 feet and grass 6-inches high or more, the n value may fall between the 0.24 value for sheet flow and the 0.05 value for channel flow. In this case the designer might select an n value of 0.10 which better represents this shallow concentrated flow.

For more insight on the behavior of the Manning n in grassed channels, the reader should examine pages 179-188 in Chow (1959) which discuss the extensive experimental work of W.O. Ree (1949). Ree's experiments showed that Manning roughness coefficients varied with the type, density and height of grass and the product of the velocity and hydraulic radius. Shallow depths with low velocities produced roughness coefficients as high as 0.5.

3.4.7 Open Channel Flow

Estimating the travel time through the main stream requires the user to model the length, slope, roughness and the typical bankfull cross section. While a good map is assumed to provide a reasonable estimate of the length and slope of the stream, it is very difficult to select the Manning roughness coefficient and the "typical" cross section. Even if one uses stream gaging to determine a roughness coefficient at a point, the coefficient is likely to be different at another discharge or at another point along the stream. The cross section varies significantly along the stream, so it is difficult to determine which is the "typical" section. Errors in the cross selections can lead to incorrect estimates of the time of concentration and storage conditions and, therefore, lead to peak predictions that are too high or too low.

3.4.8 Length and Slope of Streams

The Panel recommends that the USGS 1:24,000 quadrangle sheets be the standard for determining the length and slope of streams used to estimate part of the time of concentration. It is recognized that the 1:24,000 scale cannot adequately represent the meanders of many streams. Thus, the estimated length may be too short and the slope too steep. When field investigations indicate that this may be a problem, the user should seek a larger scale map or support changes through additional field investigations or aerial photography.

3.4.9 Open Channel Manning Roughness Coefficient

There are two major uses of Manning roughness coefficient in WinTR-20. One is estimating the Manning n for the channel flow segment for the calculation of travel time and time of concentration. The other is estimating the Manning n for representative cross sections used for routing reaches.

The channel flow segment for the calculation of travel time and time of concentration is concerned primarily with the Manning n for the bankfull cross section, whereas the Manning n for the representative cross section for a routing reach applies to the complete cross section including channel and flood plain. Estimating Manning n for representative cross sections for reach routing is discussed in Section 3.5.3.

The Manning roughness coefficient is a very difficult parameter to estimate and can cause significant changes in the estimates of peak discharge. Even if estimates are based on carefully measured field data, the "n" would probably change if the measurements are made at a different discharge or at another cross section.

A study conducted by the US Army Corps of Engineers Hydrologic Engineering Center (USACE-HEC, 1986) explored the question of uncertainty in roughness coefficient estimates by asking their staff and training course participants to estimate roughness coefficients for several natural streams given photographs and descriptions of the streams. This effort found that the estimates by the participants were approximately log normally distributed with a standard deviation given by the equation

$$SD = n(e^{(0.582+.10\ \ln(n))2} - 1)^{\ 0.5} \tag{3.16}$$

The equation indicates that an average estimate of n = 0.04 has a standard deviation of 0.011. Thus, if the average estimate of a group of experienced designers is n = 0.04, we can anticipate that their estimates will scatter, with approximately 68% of their predictions being between n = 0.029 and n = 0.051.

A number of tables list Manning roughness coefficients for different types of man-made and natural channels. The table presented by Chow (1959) in his Chapter 5 is an excellent source. Chow points out that these values should be adjusted to reflect local conditions such as channel irregularity, alignment, silting and scouring, obstructions, meandering, suspended material and bed load. These and other corrections are discussed in considerable detail in Chow's Chapter 5. Supplement B of NRCS National Engineering Handbook Section 5 "Hydraulics" (1956) provides a manual procedure to estimate Manning's n value for stream cross section. Other references include Arcement and Schneider (1984), Fasken (1963) and Barnes (1967).

Still another problem arises when field investigations indicate that the roughness varies significantly from one section of the stream to another. In these instances it may be necessary to break the stream into segments and compute the flow time for each. In the absence of field investigations, an initial Manning n value of 0.05 should be used for the bankfull cross sections for estimating the time of concentration.

3.4.10 Bankfull Cross Section

Another factor contributing to changes in the peak flow prediction is the "typical" bankfull cross section selected to determine the velocity and, therefore, one part of the time of concentration. For example, selection of a cross section near the outlet of the watershed may result in a channel velocity that is significantly different from that predicted by the use of a cross section chosen from a point about half-way up the stream. Increasing the hydraulic radius will result in a higher velocity and corresponding shorter the time of concentration. Because the cross section varies from point to point along the channel, it is quite difficult to decide which is <u>the</u> representative cross section. Thus, the user must recognize the importance of the representative cross section when calibrating against the Regional Regression Equations based methods of Chapter 2.

If it is not practical to survey bankfull cross sections, an alternative is to use regional regression equations that relate the bankfull depth, width and cross sectional area to the area of the upstream drainage basin. Figure 3.5 shows an example of channel cross-section regional regression equations developed for SHA by McCandless, Tamara and

Everett (2002), McCandless and Tamara (2003) and McCandless and Tamara (2003). Appendix 4 presents the equations that are accepted by Maryland's SHA and WMA. Dunne and Leopold (1978) present a similar set of relations and Rosgen (1996) includes several examples of findings similar to Figure 3.5.

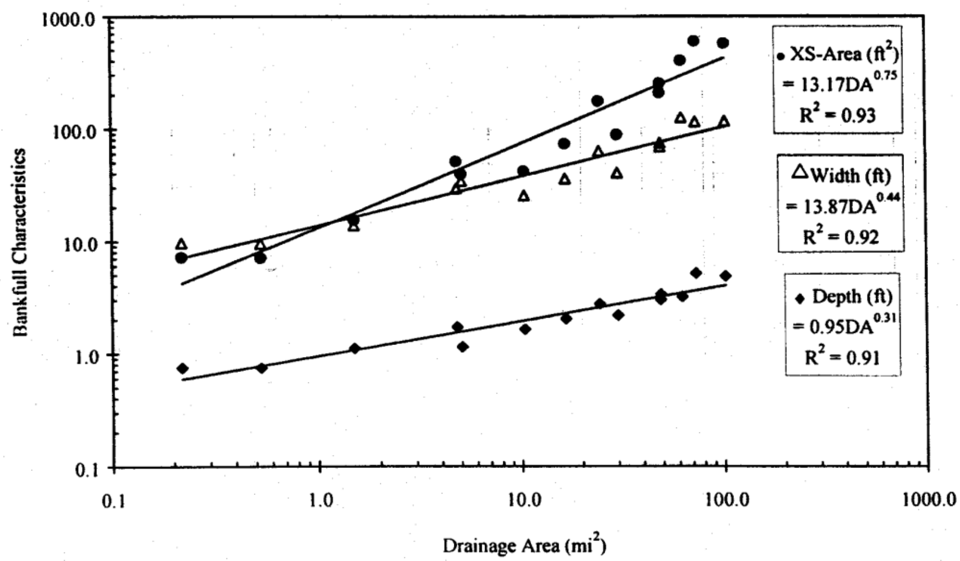


Figure 3.5: Bankfull Characteristics for Selected USGS Sites in the Maryland Piedmont

In Figure 3.6 and Figure 3.7 indicate that time of concentration differences associated with cross-sections defined through the use of regional regression equations, as opposed to surveyed cross sections, may be less than the differences associated with different roughness coefficients. In Figure 3.6, the Siebach (1987) S-curve (time-area curve) defining time of concentration used travel times computed with surveyed, bankfull cross sections. The Dunne and Leopold curve used cross sections that were defined with their regional regression equations that estimated bankfull width, area and depth as a function of the watershed area. The S-curves used to estimate the time for concentration in Figure 3.7 used surveyed cross sections with the Manning roughness coefficient being varied.

The two figures indicate that errors in the Manning roughness coefficient can cause larger errors in the time of concentration than the changes associated with differences between surveyed and regression defined bankfull cross sections. This is to be expected because the channel velocity varies linearly with the roughness coefficient and with the 0.667 power of the hydraulic radius.

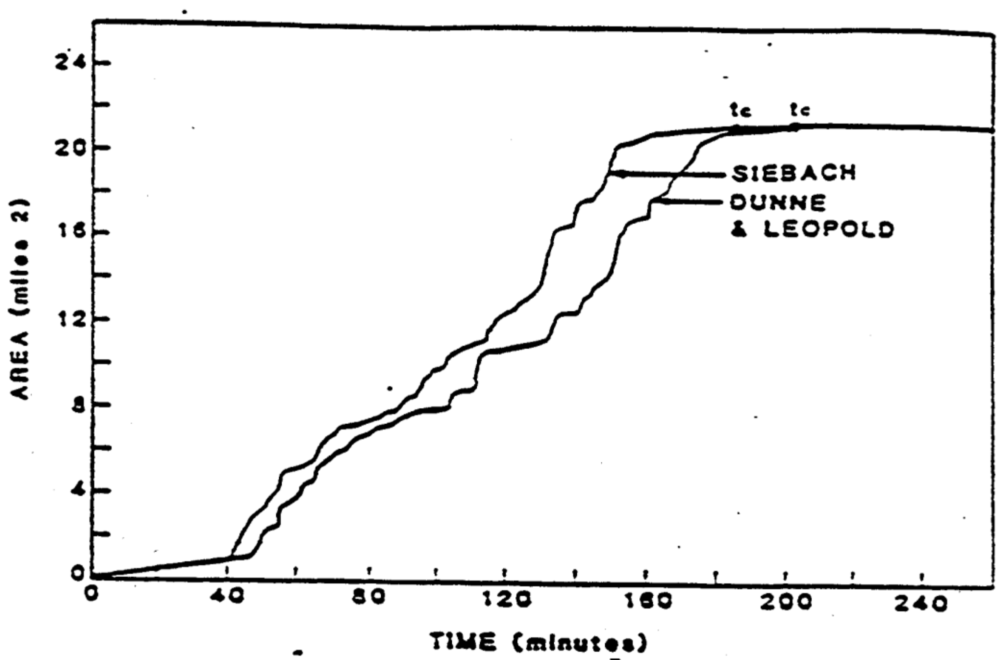


Figure 3.6: Time-Area Curves Using Surveyed and Regression Equation Defined In-Bank Cross Sections (n= 0.04)

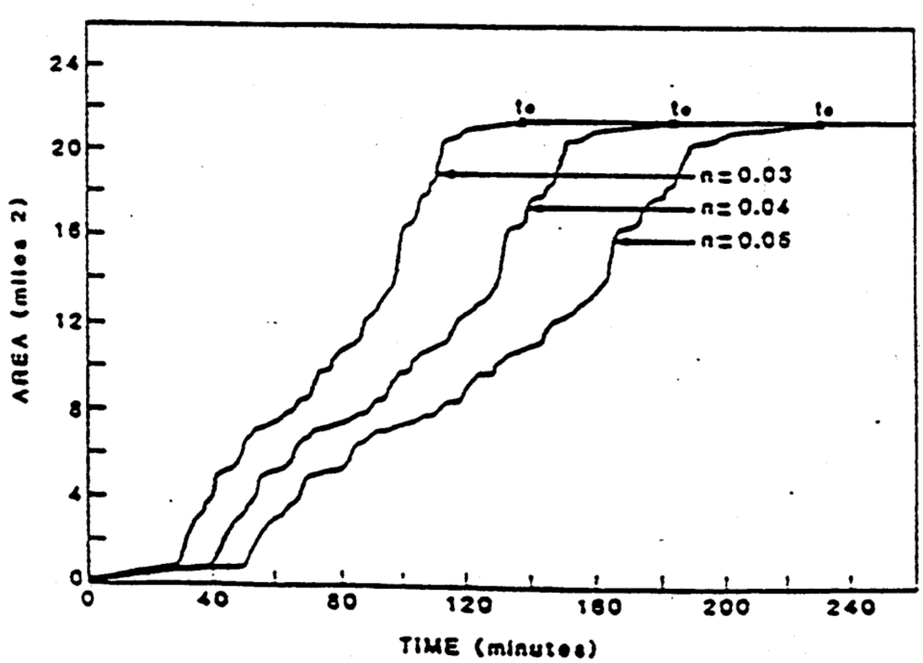


Figure 3.7: Time-Area Curves Using Surveyed In-Bank Cross Sections and Indicated Manning Roughness Coefficients

As can be seen from the above discussion, accurate estimates of the time of concentration are difficult to obtain because of the large uncertainty in the parameters used to compute the time of concentration. Thus, there needs to be an alternative approach that can serve to define upper and lower bounds for time of concentration. Regression models that estimate time of concentration based on watershed characteristics provide an attractive approach. Limited tests with a model developed by W.O. Thomas, Jr. and described in Appendix 6 have been very encouraging. The Panel recommends that designers be encouraged to apply the Thomas model in their studies to check realistic bounds for the time of concentration. The Panel also recommends that a regional regression research project described in Chapter 5 be given one of the highest priorities.

3.5 SUBDIVIDING INTO SUB-WATERSHEDS AND ROUTING

If the watershed is large or has tributary drainage areas that have land/soil complexes that differ from each other, the watershed may be divided into sub-watersheds. In this approach, the dimensionless UHG uses the area, curve number and time of concentration for each sub-watershed to develop storm hydrographs. These hydrographs for each subwatershed are then routed through the stream network to the outlet of the overall watershed. Even if the watershed is not especially large or heterogeneous, calibrating to the USGS methods may require subdivision in order to model the attenuation provided by the flood plain.

No “magic number” exists to define a small versus a large watershed. A watershed might be considered small if the land phase processes - overland and shallow confined flow - dominate the peak discharge and the shape of the runoff hydrograph. A watershed might be large if the translation and storage provided by the stream network provides significant attenuation or modification to the storm hydrograph. A large watershed by this definition could require subdividing and flood routing.

3.5.1 How Many Sub-watersheds

Part of the decision controlling the subdivision of the watershed is tied to the heterogeneous nature of the watershed. A watershed should be subidivided if peak discharges or hydrographs are needed at points within the watershed in addition to the peak or hydrograph at the watershed outlet. In the past NRCS has used the criteria if the drainage exceeds 20 square miles subdivision should be considered.

There does not appear to be a “rule” that one can apply to confirm that there is an optimal number of subdivisions for a watershed of a given size or set of topographic characteristics. Designers must calibrate against the Regional Regression Equations to ensure that their subdividing approach is appropriate.

3.5.2 The Representative Routing Cross Section

Bankfull and over-bank cross sections often show tremendous variations along a stream reach. Selecting the representative cross section for use in developing the required stage-area-discharge relation for the routing reach is a very difficult task. If the flood plain is too narrow, the peak will be too high and if it is too wide, the peak will be subject to too much attenuation.

An alternative to the use of field surveys to define typical cross sections is to digitize along transects drawn on maps, perpendicular to the stream. In many areas, 1:2400 or similar scale maps are available. Transects on these maps can provide an excellent base for routing sections. The bankfull portion of the section is generated by the regression equations discussed in Section 3.4.8. As shown by Figure 3.8, even a 1:24,000 scale map can be used in areas where there is good topographic definition.

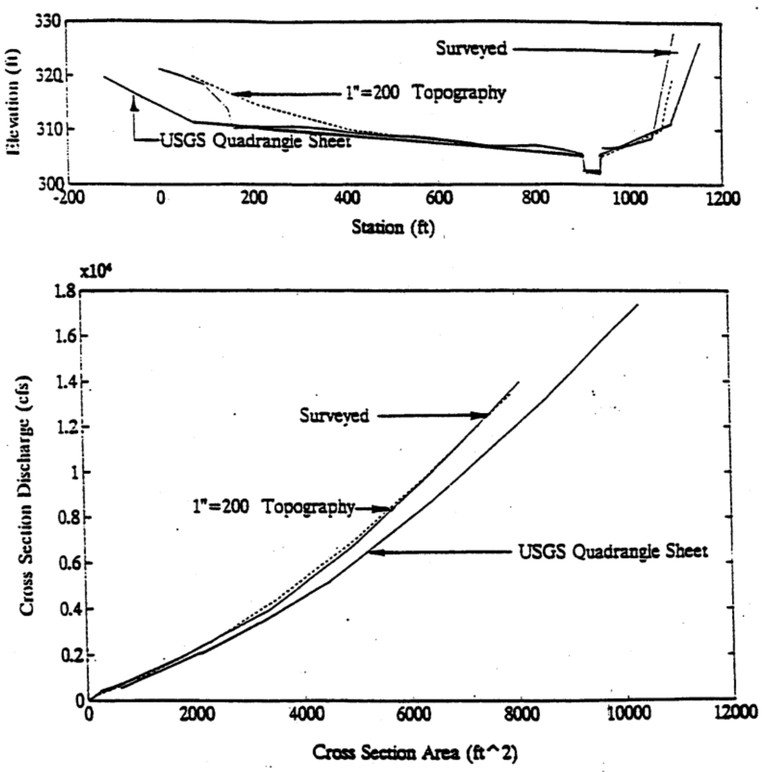


Figure 3.8: Discharge-Area Curves for Surveyed and Contour Defined Synthetic Cross Sections

Assume that we are confident that the "correct" representative cross sections for the flood routing component of the WinTR-20 have been chosen. We are now faced with the problem of selecting the Manning roughness coefficients required for the stage-area-discharge relationship. Section 3.4.9 discussed the difficulties associated with the definition of the in- bank roughness and illustrated the impact of the roughness on the time of concentration.

3.5.3 Manning n for the Representative Routing Cross Section

Estimating the over-bank roughness involves more uncertainty than the bankfull coefficient because of the extremely limited amount of data collected for flow in a flood plain. Chow's (1959) table suggests flood plain Manning roughness coefficients that range from 0.02 to 0.20.

For the representative cross section for reach routing, different Manning n values are estimated for the channel and overbank areas to the left and right of the channel. Arcement and Schneider (1984) include photographs of flood plains with Manning n estimates from 0.10 to 0.20.

3.5.4 Channel Routing Techniques

The WinTR-20 replaces the Modified Att-Kin routing module with a Muskingum-Cunge (M-C) approach. The M-C method is a spin-off of the Muskingum method that has been used for many years in river forecast operations by the National Weather Service, U.S. Army Corps of Engineers and similar organizations. Both the M-C and Muskingum methods use a series of routing coefficients that are defined by the routing period, Δt, a travel time constant for the routing reach, K, and a weighting factor, X. In the traditional river forecast environment, there are usually recorded inflow and outflow hydrographs that can be used to define K and X and earlier experiences on the river can evolve the optimal value of Δt. Concise summaries of the two routing methods can be found in Bedient and Huber (1992).

In the SHA environment, there will be no records of inflow and outflow hydrographs at the point of interest that can be used to determine K and X. Without historic records of inflow and outflow hydrographs, K is estimated by the length of the routing reach and the celerity of a small gravity wave moving through the reach. The length of the routing reach is a decision made by the user. The celerity of the small gravity wave requires an estimate of the average velocity, width and depth of flow through the routing reach. The major difference between the Muskingum and M-C procedures is that the M-C procedure includes an equation to estimate X from cross section hydraulic properties and reach length. The value of X is defined from the routing reach length, average width, average slope, celerity of a gravity wave, and the peak discharge entering the reach. The second major difference between the Muskingum and M-C is that with the M-C there is a possibility of breaking the reach into a number of routing steps.

The M-C method was selected by NRCS because it was concluded that it would overcome some of the problems associated with the Modified Att-Kin module. A paper by Merkel (2002) outlines the studies that NRCS made before selecting the M-C procedure. The M-C procedure was compared to the dynamic wave routing for a large number of cross section shapes, reach lengths, and slopes. Note that all the parameters in the previous paragraph have feedbacks involving many of the same issues that impact the performance of the current Modified Att-Kin method. For example, to get the coefficients K and X, the user must have decided on the length of the routing reach and must still make judgment decisions on the Manning n and "average cross section" so that the celerity can be computed. The values for each of these elements are difficult to determine.

3.6 THE DESIGN STORM

The WinTR-20 requires that the user define the total depth of rainfall, the duration of the storm, and time distribution of cumulative rainfall depth within the storm. Before NOAA Atlas 14 was published, the usual approach was to accept one of the "standard" design storms such as the NRCS Type II, 24-hour storm.

A major assumption used in the development of the design storm is that the 5-minute through 24-hour rainfall values have the same return period. In other words, the 5-minute 100-year rainfall, 10-minute 100-year rainfall, etc, up to the 24-hour 100-year rainfall occur within the same storm. A second assumption is that the durations "nest" with the most intense rainfall at the storm center (12 hours) and the intensity gradually reducing symmetrically from the storm center to the starting and ending times (zero and 24 hours), (Merkel, et.al., 2006). Details on the procedure and an example based on Howard County, Maryland are included in Appendix 7. This procedure has been incorporated into the WinTR-20 so the user does not need to do significant amounts of hand or spread sheet calculations.

The watershed area and time of concentration are used to convert the dimensionless UHG to a UHG. Then the cumulative rainfall distribution and runoff curve number are used to generate a series of cumulative runoff values. The cumulative runoff values for the design storm are then convoluted with the UHG to produce a storm hydrograph. If the 100-yr, 24-hour depth of rainfall is used to define the intensities in the design storm distribution, the "design expedient" typically accepts the peak discharge generated by the WinTR-20 as an estimate of the 100-year frequency peak discharge to be used in design. **It must be emphasized that the WinTR-20 computes an estimate of the peak discharge caused by a synthetic 100-yr storm that is based on rainfall records and not an estimate of the peak discharge based on stream flow records. The two discharges may differ significantly. The Panel's recommended calibration against one of the methods described in Chapter 2 of this report is intended to reconcile some of the disagreement.**

Decisions that define the storm input are very important because the performance of the WinTR-20 is very sensitive to the structure of the rainfall input.

Segments of the NRCS 24-hour design storm should be used to develop synthetic storms having different durations. When developing a synthetic storm having a duration that is shorter than 24 hours, one should use the period that is distributed equally on each side of the steepest portion of the mass curve. For example, a six-hour storm would be based on the dimensionless intensities between T = 9.0 and T= 15.0 hours on the NRCS 24-hour storm distribution. A 12-hour storm would be based on the dimensionless intensities between T = 6.0 and T= 18.0 hours on the NRCS 24-hour storm distribution. Figure 3.10 illustrates the NRCS 24-hour storm used to generate the storm distributions having durations of 6 and 12 hours for a location in Howard County, Maryland (longitude -76.9862 and latitude 39.2922). An example of development of a 6-hour and 12-hour storm distribution based on a location in Howard County, Maryland is included in Appendix 7.

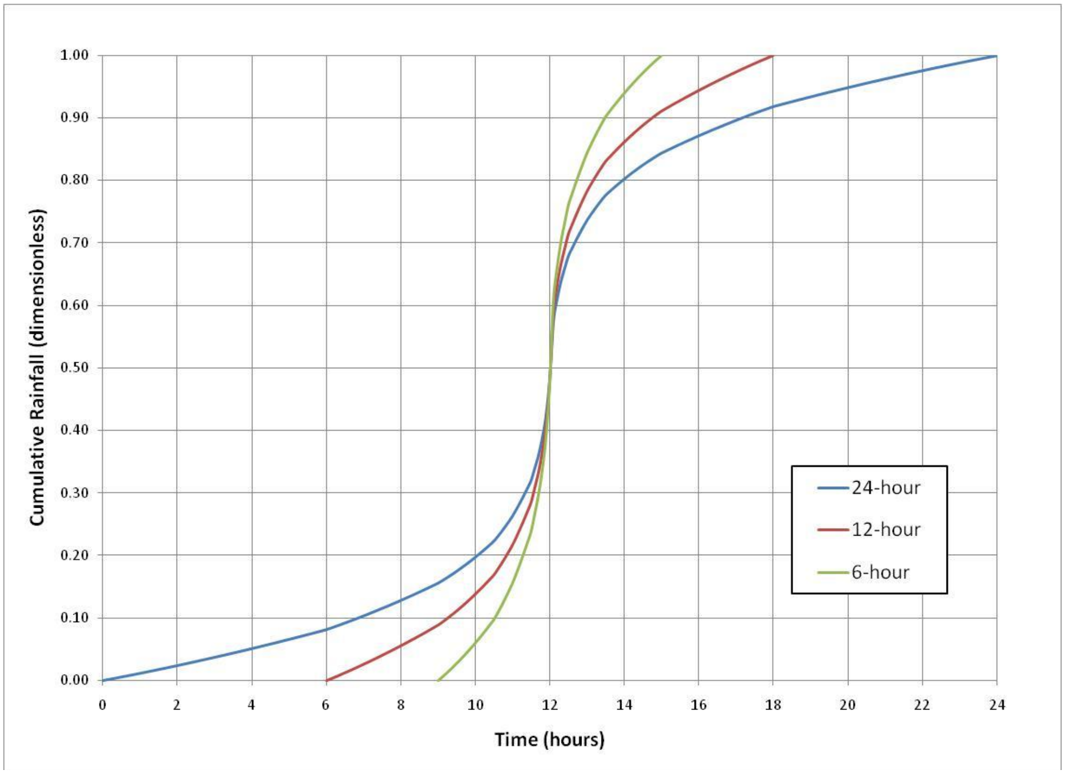


Figure 3.9: 6, 12, and 24 Hour Storm Distributions Howard County MD

Design storms having similar structures, but different durations, produce significantly different hydrographs and peak discharges when input to the WinTR-20. As a consequence, there is uncertainty as to what storm duration should be used. The traditional practice in Maryland in the past has been to use the 24-hour Type II storm in all cases. However, the Type II storm distribution does not fit the data from NOAA Atlas 14 for the entire state of Maryland nor does it fit the NOAA Atlas 14 data for the 1-year to 500-year return periods. If ratios of shorter duration to 24-hour rainfall are computed at a point, there can be significant differences when compared to the ratios within the Type II storm distribution. For example, at a point in Howard County (longitude -76.9862 and latitude 39.2922) rainfall ratios are included in Table 3.5. The rainfall data used to develop this table are based on the partial duration series.

Table 3.4: Rainfall ratios based on NOAA 14 and Type II for a point in Howard County

Duration	Type II Ratio	1-year NOAA ratio	10-year NOAA ratio	100-year NOAA ratio
5 min	0.114	0.129	0.110	0.085
10 min	0.201	0.208	0.177	0.135
15 min	0.270	0.261	0.224	0.170
30 min	0.380	0.356	0.324	0.261
60 min	0.454	0.443	0.422	0.359
2 hour	0.538	0.530	0.511	0.456
3 hour	0.595	0.568	0.548	0.496
6 hour	0.707	0.708	0.682	0.636
12 hour	0.841	0.867	0.849	0.826
24 hour	1.000	1.000	1.000	1.000

Table 3.4 shows that the 100-year rainfall intensity is much less for the distribution based on NOAA 14 data when compared to the Type II. The rainfall intensity for the 1-year storm is relatively close to the intensity of the Type II.

Table 3.5: Comparison of peak discharges between NOAA 14 and Type II storm distributions.

	Peak Discharge cfs	**Peak Discharge cfs**	**Peak Discharge cfs**	**Peak Discharge cfs**	**Peak Discharge cfs**	**Peak Discharge cfs**
	NOAA 14	Type II	NOAA 14	Type II	NOAA 14	Type II
Time of Con. hours	1-year	1-year	10-year	10-year	100-year	100-year
0.75	825	845	2715	3065	5166	7151
1.25	585	582	1984	2123	3933	4970
2.0	420	408	1450	1487	2968	3488
3.0	314	300	1090	1083	2299	2549

Table 3.5 was developed at the same location in Howard County, Maryland. It is based on a drainage area of 3.0 square miles and curve number 75. Short to long times of concentration were used to show the sensitivity of storm distribution to changes in time of concentration. As expected, the 1-year peak discharges are not significantly different between the two storm distributions. However, the NOAA 14 distribution produces 100-year discharges significantly lower. These results may not be generalized for the entire state of Maryland because a storm distribution based on NOAA 14 data depends on the relationship of 5-minute through 24-hour rainfall data at each location and return period.

Experiments conducted by the Panel demonstrate that the 25-, 50-, and 100-yr flood peaks predicted by the WinTR-20 model, using the 24-hour design storm duration and appropriate estimates of watershed parameters, agree reasonably well with the flood peaks predicted by the USGS – based equations. However, such is not the case for more frequent storm events. The Panel's experiments indicate that the 2-, 5-, and 10-yr flood peaks generated by the WinTR-20 model using the 24-hour design storm duration are often significantly higher than those predicted by the USGS - based equations. When shorter duration design storms, based upon center-peaking period of the NRCS Type II storm and meeting all of the conditions imposed by the Maryland IDF curve, are used for the 2-, 5-, and 10- year flood peaks, the WinTR-20 and USGS estimates may be brought into close agreement. Obviously, more research using NOAA Atlas 14 data is warranted. In the interim, the 10-, 5-, and 2-yr storm events should be derived using either the 6-hour or 12-hour design storm duration if needed during the calibration process.

The depths of precipitation (partial duration) of a given frequency and duration vary considerably across Maryland. The depth of precipitation in a 100-yr 24-hour storm varies from 5.4 inches in western Garrett County to 9.3 inches in Calvert, St Mary's, Wicomico, and Worcester counties.

There appears to be a problem in applying WinTR-20 models in western Maryland. Peak flood flows predicted by WinTR-20 are often significantly higher than the estimates provided the USGS based regression equations. Many of the USGS stream gages have operated in that region for more than 70 years. These gages simply have not measured peak flows as high as those measured in the central portion of the State. Analysis of eleven USGS gages in the Maryland Appalachian Plateau and Valley and Ridge provinces demonstrates that the observed maximum flows range between 83 and 300 cfs per square mile, with an average of 167 cfs per square mile. The minimum length of record is 17 years and the maximum length is 50 years. The average watershed area is 23 square miles. The same analysis conducted on six gages in the Maryland Piedmont indicates that the maximum flows vary from 319 to 780 cfs per square mile, with an average of 452 cfs per square mile. The minimum length of record is 12 years and the maximum length is 60 years. The average watershed area is 22.3 square miles. Based upon watershed characteristics alone, one would expect the steep mountain areas in western Maryland would yield higher peak flows than the Piedmont. However, indications are that flood producing rainfalls in western Maryland may be shorter in duration than those farther east. More specific research using NOAA 14 data is warranted in this regard. Therefore, if the flood estimates using the 24-hour storm do not lie between the regression estimate and the upper 68% limit, the analyst should use the 12-hour storm for the 25-, 50- and 100-yr events and the 6-hour storm for the 2-, 5- and 10-yr events**.**

Partial duration precipitation values from NOAA Atlas 14 are recommended for design purposes. Precipitation values available from NOAA Atlas 14 are point estimates. The typical storm is spatially distributed with a center area having a maximum rainfall and a gradual reduction of intensity and depth away from the storm center. The spatial distribution of rainfall within a storm generally produces an average depth over an area that is a function of watershed area and storm duration. Figure 3.11 is based on the areal reduction curves from USWB-TP-40. The Panel recommends that the hydrologist adjust the design storm rainfall to reflect spatial distribution.

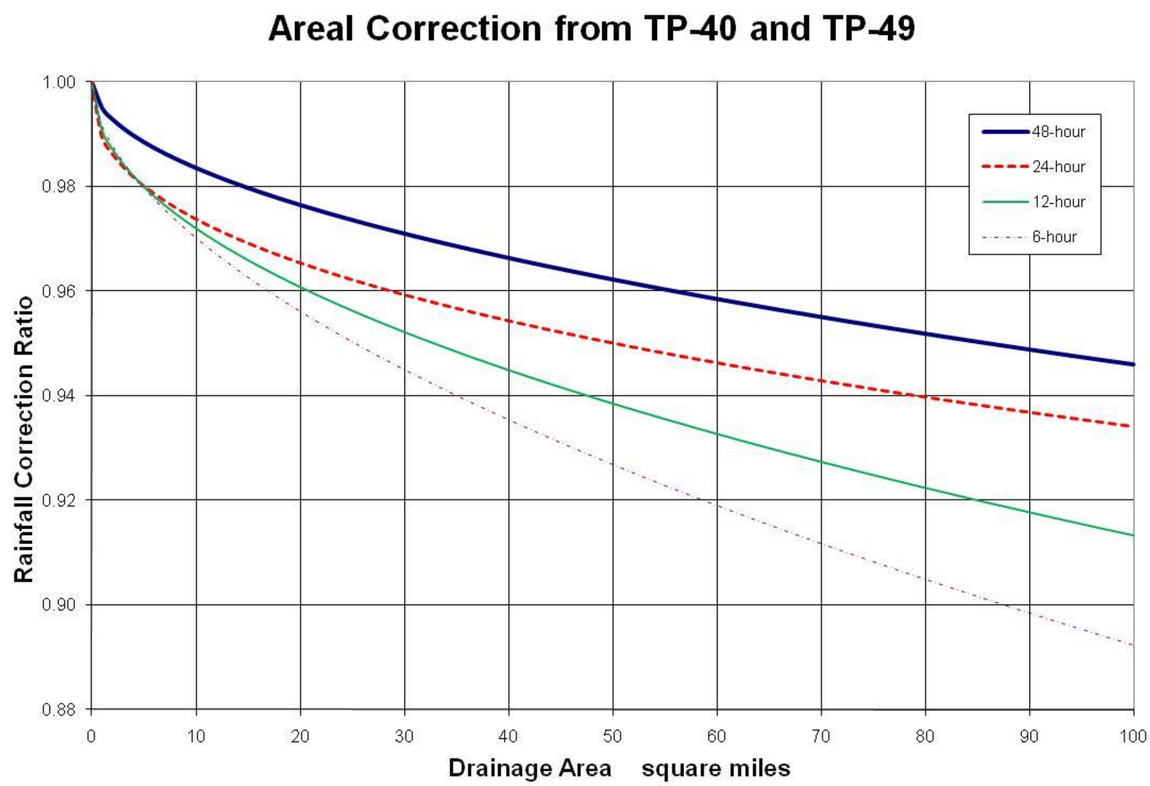


Figure 3.10: Areal Reduction curves based on TP-40

If the hydrologist is using GISHydro2000 the adjustment is an option presented as a screen prompt and should be implemented for all watershed studies. If the hydrologist is conducting a study outside the GISHydro2000 environment, the adjustment for spatial distribution should be made using equations 3.17 – 3.20.

$$RF = 1 - \alpha A^{\beta} \quad \text{(6 hour)} \tag{3.17}$$

$$RF = 1 - (\alpha/2)A^{\beta} - (\phi/2)A^{\rho} \quad \text{(12 hour)} \tag{3.18}$$

$$RF = 1 - \phi A^{\rho} \quad \text{(24 hour)} \tag{3.19}$$

$$RF = 1 - \gamma A^{\kappa} \quad \text{(48 hour)} \tag{3.20}$$

where the area, A, is square miles, $\alpha = 0.008245$, $\beta = 0.558$, $\phi = 0.01044$, $\rho = 0.4$, $\gamma=0.005$, and $\kappa=0.5169$.

CHAPTER FOUR

4 CALIBRATION OF WINTR-20 WITH STATISTICAL METHODS

4.1 OVERVIEW

The hydrologic analysis of SHA bridges and culverts must examine the behavior of the structure and local stream conditions under both existing and ultimate development watershed conditions. Because two land cover and flow path conditions are involved, the basis for these hydrologic analyses must be a deterministic model that can simulate the major runoff processes for both existing and future conditions. The recommended approach is to first select field and map defined parameters that describe the runoff processes for existing watershed conditions. After the designer is satisfied that the model provides a realistic representation of the existing watershed conditions, the impact of ultimate conditions can be simulated by adjusting the input parameters to reflect future land cover and flow path modifications.

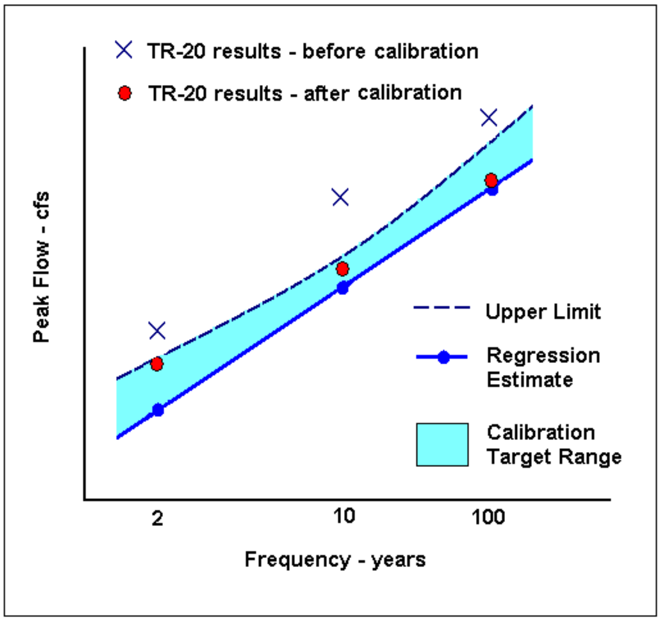


Figure 4.1: Over-prediction behavior of WinTR-20 for all return periods.

The NRCS-WinTR-20 computer program is a well established deterministic model that has an extensive history of use in Maryland. However, the WinTR-20, as with all deterministic models, is sensitive to the values of the input parameters. In most instances, the input parameters are difficult to determine. As discussed earlier, the WinTR-20 model has a tendency to over predict peak flows at all return periods. This behavior is illustrated by Figure 4.1. The Panel has concluded that this tendency to over predict can be overcome through calibration. Thus, in order to provide the designer with confidence that the input parameters selected are representative of the existing watershed conditions, the Panel recommends that the WinTR-20 peak discharges for existing watershed conditions be calibrated against one of the methods described in Chapter 2. The WinTR-20 will be accepted as calibrated if the peak discharges for the design frequency event are in the window between the statistical best estimate and an upper limit of plus one error of prediction as defined in Chapter 2. If the watershed conditions are such that a calibration cannot be achieved in accordance with the procedures defined below, the designer will explain why the calibration cannot be accomplished and what approach will be followed to generate the required flows.

In many cases, the designer will not be able to choose one calibration adjustment for the WinTR-20 to bring the peak flow rates within the regression equation target range for all storm frequencies. For example, a calibration adjustments needed to bring the 100-year storm within the target range may not be sufficient to bring the 50, 10, or 2-year storms within their respective target ranges. In these cases, it will be necessary to use a progression of calibration adjustments in a logical sequence. Table 4.1 suggests a logical progression of calibration steps for multiple storm frequencies. It can be used as a guide for the designer with the understanding that there may be other logical calibration progressions that are more suitable for a particular watershed.

Table 4.1: Logical Progression of Calibration for Multiple Storm Frequency Models

Calibration Variable/ Input Element	Application
T_c (Time-of-Concentration variables)	Same for all storms
RCN conditions (good-fair-poor)	Same for all storms
Reach Length	May increase for greater return periods but not reverse.
Dimensionless Unit Hydrograph	Same for all storms
Rainfall Table – 24-hr duration	Use for 25-year to 500-year storms
Rainfall Table – 12-hr duration	May use for the 2 through 10-year storms if the time-of-concentration is greater than 6 hours. May use for Appalachian Plateau for 25-year through 100-year storms
Rainfall Table – 6-hr duration	May use for 2, 5 and 10-year storms if time-of-concentration is less than 6 hours or for Appalachian Plateau.
ARC (Antecedent Runoff Condition)	Use 2 for 25-year and greater return period storms. May use <2 for the 2-year to 10-year storms provided that it does not decrease for greater return period storms. ARC of >2 may be considered for storms of 200+-years providing that it does not decrease with greater return period storms.

The Panel emphasizes that all input parameters to the WinTR-20 must be consistent with accepted hydrologic practice. Thus, all WinTR-20 computations will be supported by documentation that lists the values of (1) category curve numbers; (2) the quantities used to define the time of concentration, and (3) the watershed segmentation and stage-area-discharge relations if routing is involved. This documentation will explain the decision making process behind the selection of each input quantity.

The following sections examine the types of errors that may occur in the definition of inputs to the WinTR-20 and the procedures to follow in making adjustments to achieve calibration. Because so few watersheds of concern to the SHA are located at a USGS gage or at a point that will allow gage transposition, the emphasis of this chapter is on calibration against Maryland Regional Regression Equations. Figure 4.1 illustrates the situation that often occurs where the WinTR-20 model estimates are higher than the USGS regression estimates. The WinTR-20 estimates in Figure 4.1 are actually greater than the regional regression estimates plus one standard error of prediction. The objective of the calibration of the WinTR-20 model is to modify the model input parameters to produce estimates of the flood discharges that are between the regression line and the upper limit represented by plus one standard error of prediction. This chapter provides guidance on modifying the model input parameters.

4.2 SIZE AND CHARACTERISTICS OF THE WATERSHED

For watersheds greater than about 300 square miles in size, WinTR-20 models are not recommended. The NRCS developed the dimensionless UHG from data collected on relatively small watersheds. On most large watersheds, significant peak flow attenuation caused by the channel network may not be incorporated into the NRCS dimensionless UHG. Also, the assumption of homogeneous rainfall over the watershed becomes less likely for very large areas. Thus, the validity of WinTR-20 applications on large watersheds is questionable. Moreover, the effects of ultimate land use conditions on peak flows generally are muted on very large watersheds.

For large watersheds with large sub-basins (over 5 square miles), each sub-basin may be calibrated as an individual unit. Thereafter, the calibrated sub-basins may be incorporated into a WinTR-20 model of the entire watershed. After this the WinTR-20 model of the entire watershed would be used as the basis for any further iterations needed to adjust the input parameters.

Before any calibration of the WinTR-20 is attempted, care should be exercised to ensure that the characteristics of the watershed are within the limits of the statistical data set used to develop the regression equations. Calibration will not be valid if there are other factors that are not accounted for in the Fixed Region Regression Equations such as ponds, wetlands storage, or structures that significantly change the natural flow characteristics of the watershed. For some regions, the regression equations are not valid if existing impervious area exceeds 10%. This is because these regions contain insufficient gage data for urban ($\geq$ 10% impervious) watersheds. For urbanized watersheds in regions where the urban regression equations are not available, the Panel recommends a modified calibration procedure that can be found in Section **Error! Reference source not found.**.

4.3 UNDERSTANDING ERRORS

The construction of any deterministic model involves the selection of certain input values. The selection estimate or measurement of any value includes the possibility of several types of errors. These can be labeled: Random (sometimes more and sometimes less), Systematic (always more or always less), and Cumulative (small systematic errors that add up to large systematic errors). Each variable entered in the WinTR-20 model can have one or more of these errors. As with the regional equations, the selected value for any WinTR-20 input variable represents the "best educated guess." Unfortunately, unlike the standard error of the regional equation, the standard errors of WinTR-20 input variables are unknown. However, with experience and the guidelines of standard practice, designers can estimate the range of reasonable WinTR-20 input values and confine their choices to those within this range. For example, a Manning's roughness coefficient for a natural stream channel might be 0.05. Estimates that are 0.07 and 0.03 still appear to be within a reasonable range while 0.3 and 0.002 are not. In general, the designer should select the variables with large potential systematic errors as the most likely values to calibrate or adjust.

The WinTR-20 input variables and a description of the types of errors that are inherent in their estimate follows, along with recommendations regarding adjustments for calibration to more closely simulate the results of the Fixed Region Regression Equations. Table 4.2 is a summary of these variables and their inherent errors. It also shows the limits of calibration adjustments of the input variables. They are guidelines only and not intended as absolute limits.

4.3.1 Drainage Area

Assuming that both the map used to delineate the drainage area and the measuring device are accurate, the estimation of the drainage area includes a random error. When digitizing areas, the designer should check for random errors by ensuring that the sum of all sub-areas equals the digitized total area. Adjusting the size of a drainage area is seldom justified unless the watershed includes Karst topography or non-contributing drainage areas. In some unusual cases such as for extractive land use (mining), depression areas will not contribute to watershed runoff at the 2-year event but may contribute at the 50- or 100-year event.

4.3.2 Runoff Curve Number

The error in selection of an RCN value is random. The NRCS handbook (NEH Part 630, Chapter 15 Hydrology) shows the acceptable range of values for each land cover. Those for croplands and natural ground cover are based on hydrologic conditions such as fair, poor, or good. In cases where one land cover is predominate, a potential for a systematic error exists because of the impact of the selection of one significant value rather than the distribution of small random errors in a varied land cover model.

RCN value(s) can be adjusted to match a measured runoff volume provided that the resulting RCN falls within the logical limits of their respective ARC (Antecedent Runoff Conditions) limits. Consideration should be given to the use of ARC $\leq$ 2 for the frequent events (1- up to 10-year storms). The reasoning is that these small storms are usually the result of short duration summer thunderstorms without the preceding ground wetting light rain. Greater storms (10-year and larger) are generally related to cyclonic storms of 12- to 48-hour duration where several hours of rain precedes that of the flood producing rain intensities. In this case, the ARC value is set at 2.

4.3.3 Land Use Categories and RCN Values

Land Use categories such as those used in GISHydro2000, are defined by the Maryland State Department of Planning. They are intended to be used for planning studies that extend beyond hydrologic modeling. The term land use is intended to describe a function rather than a hydrologic response. Because of this, there are several categories of land use that are not sufficiently descriptive of their corresponding hydrologic response and, if other than an insignificant part of the watershed, may require a more detailed evaluation and sub-classification. The follog are a list of those land use categories that have these characteristics.

1. *Low Density Residential.* Residential lots of 2 acres and greater may produce a hydrologic response that is characteristic of other predominate land cover such as forest (or woods), meadow, grass, cropland, etc. If this land use is a significant portion of the watershed, an examination of aerial photographs may help better define the ground cover conditions.

2. *Institutional.* Institutional land use incorporates a wide range of uses including governmental offices, educational facilities, health facilities, etc. that exhibit land cover that ranges from parking lots to woods. It is important to examine available mapping and aerial photographs to subdivide this category to better simulate the hydrologic response.

3. *Extractive.* Extractive land use is defined by mining operations. There is a potential of a wide range of hydrologic responses depending on the nature of the type of mining. In particular, strip mining may respond as bare ground while a limestone quarry may act as a reservoir without an outlet. If this land use is a significant part of the watershed, the analyst should determine the particular type of mining. Many large mining operations include areas of active disturbance, areas of reclaimed land, and undisturbed areas of future excavations. More significantly, the hydrologic response of a mining operation is often determined by the way runoff is handled at the site. This could include peak storage, pumping, diversion swales and berms. To conform to the environmental regulations, each active mining operation must have a stormwater, sediment control, and drainage plan that will define these elements. These plans are filed with the Maryland Department of the Environment, Bureau of Mines.

4. *Transportation.* Transportation includes major highways, interchanges, storage and maintenance yards for government highway agencies, Metro facilities, rail yards, and similar uses. Large interstate highway interchanges may include higher proportions of grass than pavement as compared to the highway right-of-way alone. Storage yards may be predominantly impervious surface while rail yards may be compacted gravel. Aerial photos and site inspections will enable the analyst to subdivide this category to better define the hydrologic response.

The default values of RCN for the above land uses in GISHydro2000 have been derived using assumed percent imperviousness. These default values may not affect the runoff hydrograph if the corresponding areas are insignificant relative to the total watershed area. However, the engineer must decide if this is the case or provide more appropriate RCN values as described above.

4.3.4 Time-of-Concentration (overland/sheet flow component)

The application of several methods to calculate the overland component to the time-of-concentration can contain both random and systematic errors. This overland flow variable, by experience, has shown to be the most difficult to quantify of any of the input variables. The potential for a systematic error is high, which may be related to the experience or application techniques of the designer. This is one of the variables that should be examined for adjustment, especially if the sub-basins are small and the times-of-concentration are short.

4.3.5 Time-of-Concentration (shallow concentrated flow component)

Calculation of this portion of the T_c often will generate a systematic error that will result in underestimation of the flow time. The shallow concentrated flow portion of the time-of concentration is generally derived using Figure 3.1 of the TR-55 manual or similar graphs. The flow velocities for Figure 15-4 of NEH Part 630 were developed from the information in Table 15-3.

Use of the Figure 15-4 (and the values of n and R listed in Table 15-3) may underestimate the travel time by overestimating the flow velocity for upper reaches of the shallow concentrated flow path. For shallow depth, the hydraulic radius approaches the depth of flow. In this shallow flow range the n value should represent a higher resistance than that which would be used for channel flow. Consider, for example, for a wide grass swale with flow depths of less than 0.5 feet and grass 6-inches high or more. The n value may fall between the 0.2 value for sheet flow and the 0.05 value for channel flow. In this case the designer might select an n value of 0.10 which better represents this shallow concentrated flow. For specific shallow concentrated flow conditions, the designer can develop a new relationship of velocity to slope for more appropriate values of n and the hydraulic radius.

4.3.6 Time-of Concentration (channel flow component)

The selection of the channel component of the time-of-concentration can produce a systematic error that will shorten the travel time. This can be attributed to three factors: incorrect estimates of the channel length, the Manning roughness coefficient and the bankfull cross-section.

Measuring the length of channel flow generally involves a scale error. Larger scale maps such as the USGS quad maps at 1:24,000 do not account for all the bends or meanders of a natural stream channel. Using a smaller scale map (1 inch = 200 feet) will help reduce this error, but it will always be systematic. **Adjustments in channel lengths up to 25% when measuring from a USGS 1:24,000 map can be reasonable providing the designer documents the decision.**

A single Manning n value selection to represent full cross sectional flow should be higher than an n value used for just the channel in a hydraulics model like HEC-RAS. This single n value must account for all hydraulic losses including high resistance overbanks, expansion and contraction losses, gradient changes, debris in flow, and local obstructions such as culverts. An increase of up to 50% in the n value is appropriate when using a simple trapezoidal cross section and single n value as is most often done when calculating the channel flow portion of the travel time.

The NRCS recommends that the velocity defined by the bankfull, cross section be used to estimate the channel component of the time of concentration. The channel velocity is a function of the two-thirds power of the hydraulic radius. Because the cross section and, therefore, the hydraulic radius changes from point to point along the channel, it may be difficult to determine the “typical” bankfull section. Care must be taken in the definition of the “typical” section because an error can lead to a significant overestimate or underestimate of the time of concentration in a large watershed that has a relatively long channel component.

4.3.6 Representative Reach Cross Section for Reach Routing

The selection of a representative cross section for reach routing can produce large systematic errors. WinTR-20 models with many reaches may exhibit cumulative systematic errors that will significantly affect the peak flow estimation. Since the WinTR-20 model is sensitive to the timing of hydrographs routed through long reaches, the typical routing cross section is a likely choice for adjustment.

Systematic errors in the selection of a “representative cross section” often produce reach routing that underestimates the hydrograph travel and underestimates the attenuation. The n value selection and length of reach are again suspect as in the time-of-concentration channel flow component described earlier.

Generally, representative cross sections are derived from contour maps supplemented by estimates of the channel geometry from field reconnaissance. In most cases surveyed cross sections are not available. GISHydro2000 uses the digital terrain data supplemented with empirical equations for the channel geometry.

The effect of stream storage is often underestimated. A good method to derive a representative cross section, if the data is available from prior studies of from FEMA, is to use the results of multiple HEC-2 and HEC-RAS runs. For each flow rate the cumulative volume in the reach is divided by the total reach length. This results in a representative cross sectional area for each flowrate. However, cross sections for a hydraulic model such as HEC-RAS are usually taken so as to eliminate ineffective flow areas. These ineffective flow areas, while not contributing to the stream conveyance in the hydraulic model, do affect the attenuation of the hydrograph in the reach routing computation. This is most common in reaches that are characterized by wide, flat flood plains and wetlands. If stream storage is expected to be underestimated, the designer may be justified in increasing the area for each flowrate value on the WinTR-20 cross section table.

4.3.7 Reach Length

Reach lengths measured on large-scale maps (USGS Quad, 1:24,000) commonly underestimate the true length of a stream. Topographic maps of a scale of (1:2400) and smaller will show more meanders and yield longer measurements. The effective stream length may not be the same for minor and severe events (2-year vs. 100-year). This is due to the fact that the more extreme events are conveyed over floodplains rather than in the channel, resulting in shorter flow paths. For minor events, such as 5-year and less events, a longer reach length is appropriate due to the longer flow path in the meandering channel.

Figure 4.2 shows the relationship of total time-of-concentration to drainage area for gaged watersheds in Maryland. It can be used as a guide reference for comparison to calculated T_c values.

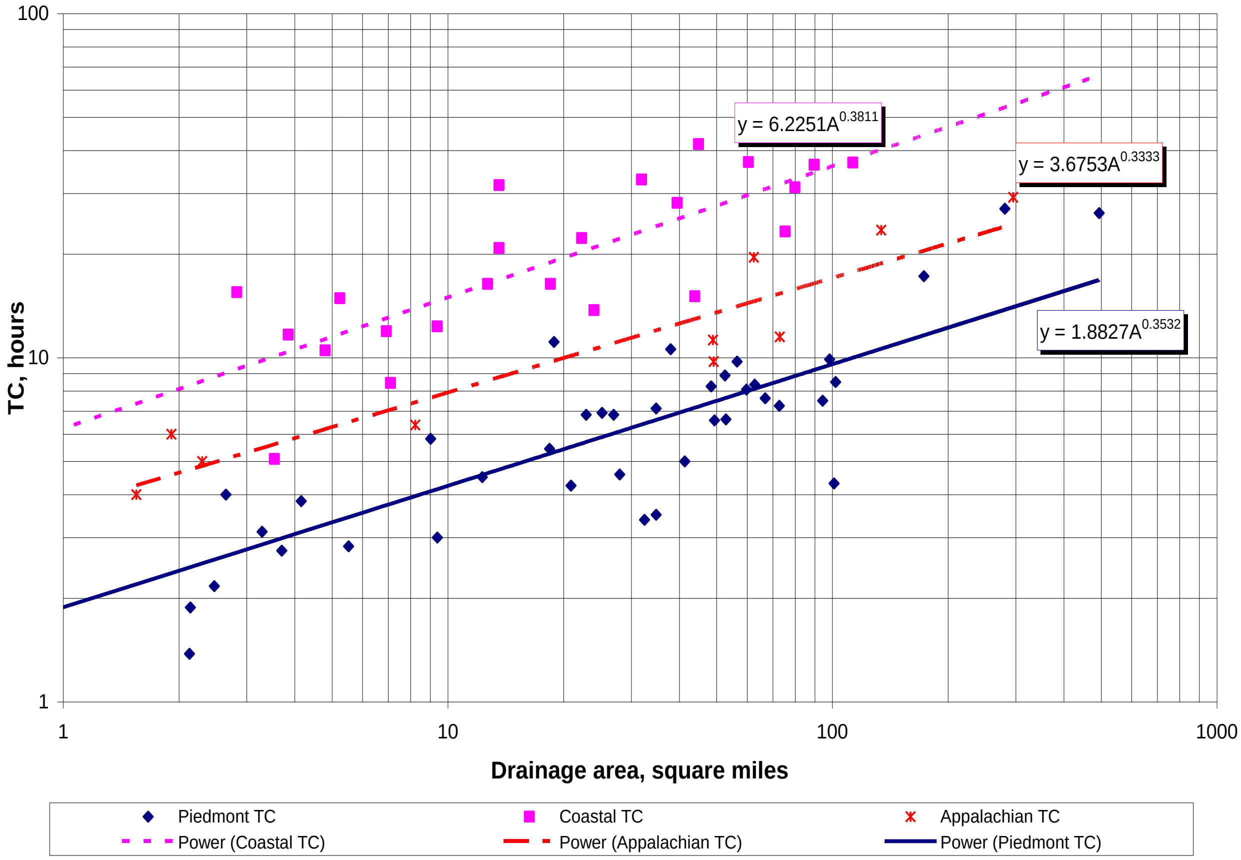


Figure 4.2: Time of concentration versus drainage area in Maryland.

4.3.8 Storage at Culverts

Experience shows that if the storage behind a culvert is less than 10% of the volume of runoff of the contributing drainage area, storage routing may be ignored without significant impact in the peak flow rate prediction. However, an accumulation of several culverts, each having storage potential near 10%, could affect the peak flow prediction and should be examined.

The measurement of storage behind a culvert is sometimes subject to systematic error, which tends to underestimate storage, especially for low flows. Topographic maps with large contours (10 or 20 feet) will not show small depressions and ditches that may contain storage that can affect the peak flow prediction of small storms.

4.3.9 Antecedent Runoff Condition (ARC)

Most applications will use the recommended value of ARC=2 to represent the preliminary wetting of the ground surface and filling of small depressions. The ARC = 2, which represents the average watershed conditions when flooding occurs, is appropriate for severe storms such as the 10-, 25-, 50-, and 100-yr events because they are generally related to the longer duration cyclonic events such as hurricanes and tropical storms with a longer duration**.** ARC = 1, which is the dry soil condition, may be more applicable to short duration summer thunderstorms in dry weather for the more frequent 1 to 10-year rainfall events.

One calibration procedure that may be employed for the more frequent storms of 10-year frequency and less is the global change in RCN values for fractional ARC conditions. While the WinTR-20 program only accepts integer values of 1, 2 or 3 for ARC, an equivalent RCN value for fractional ARC values between 1 and 3 can be produced using the folloWing relationships:

4.3.10 Dimensionless Unit Hydrograph

The dimensionless unit hydrograph varies by region. Refer to Table 3.1. The peak factor K determines the generalized shape of the runoff hydrograph. In a subdivided watershed, the subarea runoff hydrographs are routed downstream and added to other runoff branches at various intervals that influence its shape. Therefore, the influence of the unit hydrograph selection diminishes as the watershed is subdivided. Conversely, the total stream hydrograph shape for single area watersheds or those with a few large subareas are more influenced by the selection of the unit hydrograph.

4.3.11 Rainfall Tables

The 24-hour rainfall distribution used in the WinTR-20 model has been shown to approximate closely most of the Maryland statistical rainfall data for large cyclonic storms. However, there is justification for selecting storm durations of less than 24 hours in certain circumstances. Until new research on storm structure is complete, the 25-, 50-, and 100-year storm events should be derived using the 24-hour design storm duration. The 2-, 5-, and 10-year storm events may be derived using either the 6-hour or 12-hour design storm duration. For watersheds having a total time of concentration of less than six hours, the 6-hour design storm duration may be more appropriate. For watersheds having a total time of concentration greater than six hours, the 12-hour design storm duration may be more appropriate. In western Maryland (Appalachian Plateau as defined in Dillow (1996)), there are indications that flood producing rainfalls may be shorter duration than those further to the east. Therefore, if the flood estimates using the 24-hour storm do not lie between the regression estimate and the upper prediction limit, the analyst should use the 12-hour storm for the 25-, 50-, and 100-year events and the 6-hour storm for the 2-, 5- and 10-year events provided that the T_c to the design point is not greater than 6 hours.

Rainfall total depths for various frequency storms can be found in NOAA Atlas 14, Volume 2, dated 2006. This information is also available on the Web at: http://dipper.nws.noaa.gov/hdsc/pfds/.

Table 4.2: Table of WinTR-20 Variable Adjustment Limits for Calibration

Variable	Error Type	Error Source Variable	Common Error Trend	Effect On Peak Q	Note	Adjustment Limits of variable in column 3
Area	Random	Area	High or Low	Increase or Decrease		Not Recommended, check for non-contributing areas
RCN	Random	Table Selection	High or Low	Increase or Decrease	4	± 10% for each category and within the limits of the NRCS guidelines.
T_c (Overland)	Systematic	n_o, L	Low	Increase	3	n_o up to 25%, L max = 100’
T_c (shallow conc.)	Systematic	Length, n	Low	Increase	3	Increase L up to 25%, n to ± 50%
T_c (channel)	Systematic	Length, n	Low	Increase	3	Increase L up to 25%, n to ± 50%
Representative X-section	Systematic	Area, n	Low	Increase	3	Area to ± 25%, n to ± 50%
Reach Routing Length	Systematic	Length	Low	Increase	3	Up to 30% for 1;24,000 maps, up to 19% for 1:2,400 maps
Storage at culverts	Systematic	Volume	Low	Increase	1	Up to 15%
ARC	Random	N/A	N/A	N/A	2	ARC= 2 is base value. See note below.
Dimensionless Unit Hydrogr.	Systematic	Peak Factor K	High or Low	Increase or Decrease		Regional values of K in Maryland
Rainfall Tables	Systematic	Increment, intensity, & duration	High or Low	Increase or Decrease		48, 24, 12 and 6 hr. distributions

Definitions:
Random (errors) = either high or low from an expected mean value.

Systematic (errors) = always higher or always lower than the calculated value.

Low = calculated value lower than probable “actual” value.

High = calculated value higher than probable “actual”

Notes:
1. If the total volume of “reservoir” storage in the watershed is less than 10% of the total runoff volume, the effects of storage may be ignored.
2. ARC < 2 may be more appropriate for estimating the 10-year or more frequent storms. ARC > 2 may be appropriate for severe storms of 200 year and above.
3. Primary calibration variable.
4. Do not adjust the weighted RCN.

Table 4.2 *is presented as a guide to assist the designer in the reevaluation of WinTR-20 input parameters that might be causing the peak discharges to fall outside the recommended regional regression equation bounds. The table is a guide suggesting that, because of the difficulties in the estimation process, the parameters of column 3 could be in error by as much as the value listed in the last column. The selected values of all parameters in column 3 must be supported by field and map investigations, be consistent with standard hydrologic practice and documented.*

4.4 SENSITIVITY OF WINTR-20 RESULTS TO VARIATION IN INPUT VARIABLES

Experience has shown that the variables that affect hydrograph timing contain the greatest potential error of estimation and are, therefore, those that should be calibrated first. The hydrograph timing variables include each of the time-of-concentration components, the Representative Reach Cross Section, and the reach length.

If further calibration is necessary, re-evaluate the watershed storage by adding storage routing at culverts and other structures that create backwater. In particular, railroad culverts and embankments frequently cause backwater and reservoir storage. In very flat areas only a small rise in backwater may generate substantial amounts of storage that should be included as reservoirs in the WinTR-20 model. Occasionally, urban watersheds may experience a cumulative effect of storage from multiple road culverts. It may be practical to combine a series of small culverts with backwater into one reservoir to simplify modeling if accurate flows between these culverts are not needed.

Calibration of RCN values involves selecting values within the range recommended by NRCS for each land cover and soil type. Generally, the designer will be changing the RCN value for woods, meadows, or croplands from average to good or poor condition to adjust the peak discharge**. However, these changes must be documented.** In limestone regions, there may be some justification for a further reduction in RCN values.

The designer must compare the appropriate Fixed Region Regression Equation with the peak flow rates computed by the WinTR-20 model. In some circumstances, a decision may be made to adjust the WinTR-20 model input variables to yield peak flows that are closer to the results of the regional equation. In most instances, the adjustment of the WinTR-20 input variables should fall within the ranges shown in Table 4.2. However, the folloWing factors should be evaluated before adjusting the WinTR-20 input:

Does the WinTR-20, using map and field study defined input parameters that are within the bounds of sound hydrologic practice, estimate peak discharges that fall between the best estimate plus one standard error of prediction? If it does, adjustment of the WinTR-20 may not be necessary.

1. Are the values of the input variables used for the Regional Regression Equation within the limits prescribed? Do the study watershed conditions lie within the bounds of the data from which the regional regression derived? If the answer to either of these equations is no, then the regional equation results may not be valid.

2. If part of the study watershed lies within different regions, has the proportional regional equation been computed using the recommended USGS procedures?

3. Have the Fixed Region Regression Equation input variables been measured from the same scale maps used in the derivation of the regional equations (i.e., USGS 1:24,000 Quadrangle maps)? If not, the designer should determine if there is a possible bias by calibrating the map used with the USGS map for the same area.

For example, a 200 scale map may show many small clusters of trees that are not shown as green shaded areas on the USGS quadrangle maps from which the forest cover percentage was derived. Use of the 200 scale map to measure forest cover may result in a higher area of forest or a bias toward this variable that will affect the peak flow estimate of the regional equation.

4. Are there reservoir storage, wetlands, quarries, or other features that may invalidate the regional equations? If these areas have been accounted for in the WinTR-20 model, there would be no benefit in a comparison to regional equation estimates.

5. Is the study area more than 10% impervious? If so, then the regional equation may not be valid. The percent impervious can be estimated using the TR-55 values for each land use type.

If it is determined that the regional equation has been applied correctly and is valid for the study watershed, these results then may be used to adjust the input parameters of the WinTR-20 program. However, these WinTR-20 input parameter adjustments must be map and/or field justified and within the range of sound hydrologic practice. The designer will provide documentation that explains the selection and adjustment of each input parameter.

4.5 SPECIAL PROBLEMS WITH SMALL URBAN WATERSHEDS

Recent SHA experience has shown that the calibration of the WinTR-20 models to the Regional Regression Equations for some small urban watersheds having drainage areas of less than two square miles may be problematic. In particular, small urban watersheds with predominant Type A or B soils may generate WinTR-20 peak discharges that are well below the target range calculated by the Fixed Region Regression Equations. In these cases, the Panel suspects that the standard RCN table values may not satisfactorily describe this urban condition and recommends one or more of the folloWing additional calibration adjustments:

1. Use RCN values for urban land that are derived using "fair" or "poor" hydrologic conditions rather than "good". (The urban RCN values in TR-55 were derived using proportions of impervious RCN = 98 and open space RCN based on soil type and "good" hydrologic condition.) See Table 4.3 below.

2. Subdivide generalized land use categories. Predominant land use in particular categories may result in a false hydrologic response. Refer to Section 4.3.3 for further discussion.

3. Some small urban watersheds may respond in more complicated ways than that accounted for in standard hydrologic applications. For instance, a watershed model that is highly urban may produce higher peak discharges when the shorter "dominant" time-of-concentration from large impervious areas is applied rather than the longest T_c that is computed from non-impervious upland areas.

Similarly, using the "paved" rather than the "non-paved" option for computation of the shallow concentrated flow segment of the T_c may be more appropriate where a significant proportion of non-stream channel flow is carried in pipes and street gutters.

Table 4.3: Urban Curve Numbers

good conditions

Type	Impervious %	A soil	B Soil	C Soil	D Soil
1/8 acre	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	85
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acre	12	46	65	77	82
Commercial	85 *	89	92	94	95
Industrial	72 *	81	88	91	93

fair conditions

Type	Impervious %	A soil	B Soil	C Soil	D Soil
1/8 acre	65	81	88	91	93
1/4 acre	38	68	80	86	89
1/3 acre	30	64	78	85	88
1/2 acre	25	61	76	84	88
1 acre	20	59	75	83	87
2 acre	12	55	72	81	86
Commercial	85 *	91	94	95	96
Industrial	72 *	84	90	93	94

poor conditions

Type	Impervious %	A soil	B Soil	C Soil	D Soil
1/8 acre	65	88	91	94	95
1/4 acre	38	79	86	91	92
1/3 acre	30	77	85	90	92
1/2 acre	25	76	84	89	91
1 acre	20	74	83	88	91
2 acre	12	72	81	87	90
Commercial	85 *	94	95	96	97
Industrial	72 *	90	93	95	95

***** Impervious values are based on buildings, parking lots, driveways, and related landscaped edges. Open space and woods are not included.

4.6 DERIVING ULTIMATE DEVELOPMENT PEAK FLOW RATES USING THE ADJUSTED WINTR-20 MODEL

In most cases, the designer will derive the "Ultimate Development" peak flow rates by only changing the RCN values in the calibrated Existing Land Cover model. The new RCN values for each sub-basin are computed to reflect the future conditions using zoning maps or comprehensive planning maps. The other existing Land Cover model parameters usually remain unchanged. Preserving the hydrograph timing parameters can usually be justified in watersheds over one square mile since it is unlikely that a significant length of existing stream channels will be hydraulically improved under current regulations. However, there may be instances where there is ultimate development channelization or enclosure that will result in velocities that are significantly different from those under existing conditions. In that situation the changed time of concentration would have to be incorporated. The focus on stream water quality, stormwater management, wetland and habitat preservation in Maryland and the relatively few large river flood prone areas has inhibited the construction of major channel improvements, long large diameter pipe systems, and flood conveyance channel-levee systems. Of course, there may be exceptions to this assumption that should be examined on a case-by-case basis. If justified, the hydrograph timing parameter can be also modified to reflect expected significant changes to stream channel hydraulic characteristics. Figure 4.3 below describes this procedure.

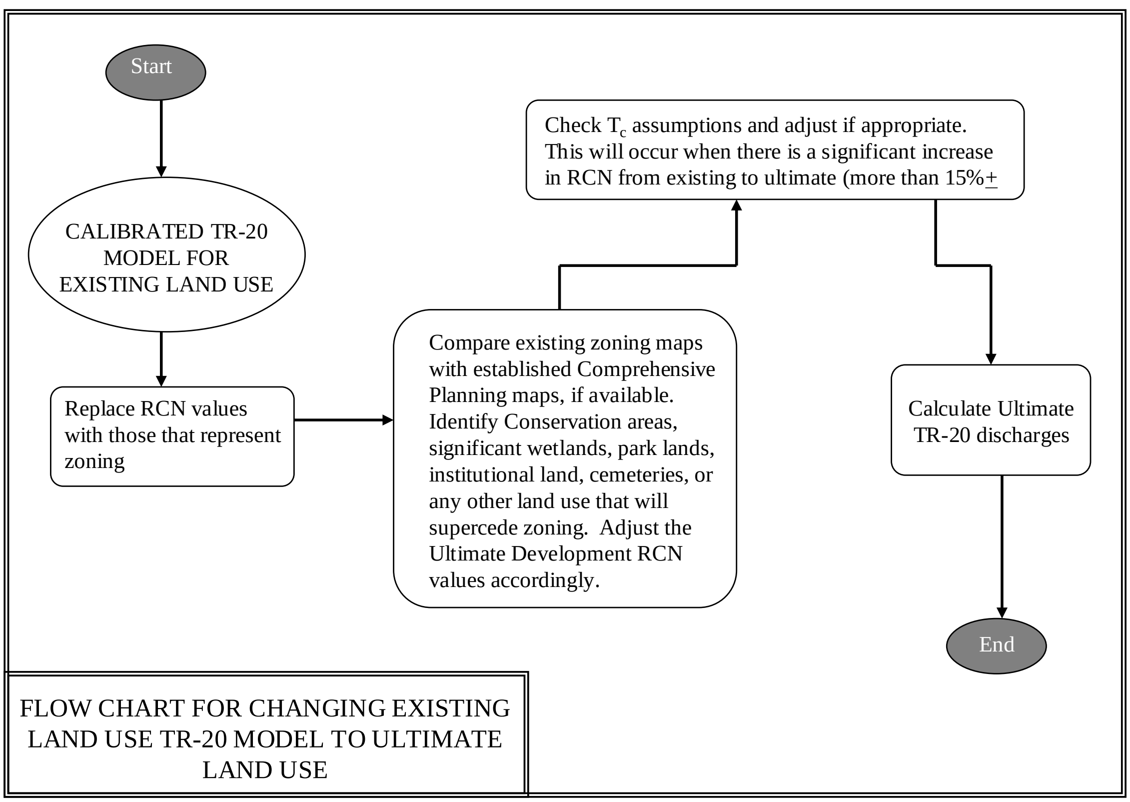


Figure 4.3: Flow chart for changing existing land use

4.6.1 Ultimate Development as Defined Under COMAR Title 08, Subtitle 05

This paragraph in "Chapter 03, Construction on Non-Tidal Waters and Floodplains" states:

"*F. Unless waived by the Administration, hydrologic calculations shall be based on the ultimate development of the watershed assuming existing zoning.*"

In the creation of a WinTR-20 hydrologic model for ultimate conditions, it is common practice for the designer to derive RCN values for each zoning type for the jurisdiction of the watershed. These "ultimate development" RCN values are substituted for the "existing" RCN values and an "ultimate development" model is constructed. This model, when the regulatory 2-, 10-, and 100-yr rainfall is applied, results in "ultimate development" peak flow rates. These peak flow rates then are used for structure design or floodplain delineation and become the benchmark for regulatory evaluation. However, there are several pitfalls that both the practitioner and regulator should consider in its application. They are:

1. Many zoning districts cover a wide range of permitted uses that have significant variability in hydrologic characteristics. There are two methods of accounting for the wide variation: (1) use more subdivision of the zoning divisions into more homogeneous areas; (2) use weighted RCN for the zoning district based on the actual land use and hydrologic soils.

2. Existing agricultural areas that are zoned for large multi-acre lots may yield lower RCN values under "ultimate development" than under the existing conditions of active croplands. Common practice has been to select the higher of the two RCN values. In some cases this situation may be realistic if the hydrologic condition of the area was poor. However, this case is often unidentified or ignored in large, variable land use models.

3. Many modern zoning types do not lend themselves to simple conversion to an RCN value. Several of these zoning types are related to ecological and historic preservation or recreation that have a wide range of possible future RCN values.

4. Many jurisdictions permit clustered or planned unit development that typically creates high density mixed development interspersed with natural preservation areas. The resulting land cover then bears no resemblance to the originally described zone type; hence, the ultimate RCN value derived from it is unreliable.

5. The creation and editing of zoning maps is a political process and is not intended to represent future hydrologic conditions. A jurisdiction wishing to promote industrial development, for example, may designate large areas for that zoning classification to attract industry, yet have no realistic expectation that all such zoned land will be developed. Similarly, rural jurisdictions may find it politically preferable to label vast areas as "agricultural" or "conservation" but expect to re-

zone specific sites if a non-conforming, intensive use is deemed desirable. In all such cases the direct conversion from zoning type to RCN is invalid as a prediction of future peak flow rates.

6. Current environmental regulations inhibit full build out of many residential and other intensive use zoning districts. For example, a district that may permit 16 units per acre seldom achieves full density. This is due to restrictions such as wetlands, road systems, forest conservation, and recreational or open space reservations.

While these pitfalls are known to many in the hydrologic profession, the common rationalization of the use of zoning is that it is the best, or simplest, way to derive a future development model that will ensure that newly designed hydraulic structures are not under-designed. In other words, the regulation requiring the use of “ultimate development” peak flow rates for design is simply a hydrologic safety factor. Unfortunately, because of the unreliable nature of the future land use – zoning relationship, the use of existing zoning to derive “ultimate” peak flow rates will result in undefined and highly variable factors of safety for different watersheds. This is not a correct application of factors of safety in a hydrologic analysis.

The selection of a factor of safety to apply to a calculated peak flow rate should be based on the folloWing considerations:

1. The potential for land use changes

2. The timing of land use change

3. The potential risk of failure of the hydraulic structure

4. The economic life and useful life of the hydraulic structure

5. The reliability of the computational method

Item number 5 is usually addressed in the selection of input values for each method and is discussed in other chapters of this report. Items 3 and 4 are often considered by selecting the flow or storm frequency. In general, large expensive structures or ones that could endanger the public are designed for flows of lesser frequency such as the 100-year (1% annual change of exceedance) for major interstate highways. Minor drainage systems are designed using the 10-year (10% annual chance of exceedance) event.

Item numbers 1 and 2, as discussed above, are not reliably estimated by zoning district. A better estimate of Items 1 and 2 can be derived from comprehensive planning maps. Comprehensive planning maps are prepared for most major jurisdictions in the state. Most plans include a 20-year projection and are available in both map and digital GIS form.

4.6.2 Using Comprehensive Planning Maps for Future Hydrologic Conditions

Comprehensive planning maps, if available, offer a better tool for the designer to predict the future land use of a watershed than the zoning map. They incorporate the key elements of time and spatial distribution that are not apparent in zoning maps. The designer can compare these maps to the zoning maps to determine the folloWing:

1. Does the 20-year comprehensive plan approach complete build-out as defined by the zoning maps? If not, it may be better to use the comprehensive plan as the more realistic future projection.

2. Does the comprehensive plan define specific land use within a general zoning type? Comprehensive plans will show areas of likely growth based on existing and planned transportation networks, proximity to growth centers, and water and sewer service areas. They will also account for special environmental or historic areas and buffers, critical areas, unfavorable terrain, proximity to uninviting land use such as landfills and airports, and similar conditions that are likely to inhibit growth.

3. Will the intensively urbanized areas induce in-fill type development according to zoning or will the general character of the urban area change? Comprehensive plans may account for the trends for more urban green space or the conversion from heavy industrial to office parks, recreation/tourism, or mixed residential/commercial use.

The current regulation permits the Administration (now Maryland Department of the Environment) to waive the requirement of current zoning to define ultimate development. This requirement should be waived in favor of the Comprehensive Planning Maps, wherever appropriate

CHAPTER FIVE

5 RECOMMENDATIONS FOR RESEARCH

5.1 INTRODUCTION

In spite of the volume of research reported in professional literature, knowledge of many aspects of applied engineering hydrology is lacking. In this section, some aspects of design hydrology that require additional research are identified along with the potential benefits that could result from better knowledge about these topics. Research on the topics below would possibly enable better decisions to be made with respect to the use of hydrologic methods in hydrologic design.

5.2 TIME OF CONCENTRATION

The time of concentration is a principal input to most hydrologic design methods. The velocity method generally uses Manning's equation to compute the velocity. The NRCS WinTR-55 kinematic wave equation is frequently applied for computing travel time for shallow sheet flow.

When the velocity is computed using Manning's equation, estimates of the roughness coefficient, the hydraulic radius, and the slope are required. Each of these inputs is important, and error or uncertainty in the inputs reduces the accuracy of estimates of the time of concentration. Roughness varies considerably with river stage. Since the river stage for a design discharge is related to the return period of the flow, it is likely that the roughness used to compute a velocity should depend on the cross section that reflects the discharge rate for the design return period. Research on the effects of depth dependent Manning roughness coefficients on time of concentration is needed. If only the roughness of bankfull flow is used when the design return period would suggest out-of bank flow conditions, the estimated velocity and, therefore, the computed T_c could be significantly different than the most appropriate value.

An estimated velocity is sensitive to the hydraulic radius. The hydraulic radius is a function of the stage of flow, which as indicated above depends on the return period. The hydraulic radius also depends on the shape of the cross section, which can vary considerably along a channel. Therefore, it is necessary to understand the sensitivity of computed velocities when using a single supposedly representative hydraulic radius for a stream in which the cross section changes noticeably over the channel length. Research on the effects of variation in both the return period and cross-section characteristics as they relate to the hydraulic radius could improve the estimation of T_c.

If a representative cross section is difficult to select because of excessive variation in cross section characteristics throughout a channel reach, the Fish and Wildlife Service (FWS) (2002) equations can be used to compute the cross-section characteristics. While preliminary analyses suggest that these equations provide reasonable estimates in Maryland. More analyses of these equations using data from Maryland are needed.

The slope of a channel section is computed using the elevation drop and the reach length. Generally, the variation in reach length for different scale maps is considerably greater than variation in the elevation drop. Where the reach length is estimated from a map, the accuracy of the length will influence the accuracy of the computed slope. If a large map scale is used and the scale of the map prevents accurate depiction of the meanders, then the overall length could be underestimated, which leads to an overestimate of the slope and velocity and an underestimate of the T_c. The significance of this factor needs investigation.

Empirical models are possible alternatives to the velocity method. While a number of studies indicate that some empirical models provide reasonable estimates of T_c, the accuracy of empirical models for use in Maryland has not been evaluated. Useful research could result from using times of concentration obtained from rainfall-runoff data to assess the accuracy of empirical equations. As additional research, T_c values estimated from rainfall-runoff data could be used with measured physiographic data to calibrate empirical equations for different regions of Maryland and develop a synthetic hydrograph in conjunction with these times.

Another alternative to the velocity method is to define the time of concentration from observed rainfall hyetographs and discharge hydrographs. Using this approach, the time of concentration is defined as the time from the ending of rainfall excess to the first inflection point on the recession of the discharge hydrograph. Regression analysis can be used to relate the computed time of concentration to watershed and climatic characteristics for the gaged watershed. Estimates of the time of concentration can be made at ungaged locations by simply determining the watershed and climatic characteristics and applying the regression equation.

An alternative procedure to determine T_c from rainfall-runoff data is first to determine the event runoff curve number based on rainfall and runoff volumes. The next step is to set up a WinTR-20 data set with the watershed drainage area, curve number, and event rainfall table and try different T_c's until the simulated hydrographs as close as possible the actual hydrographs. The dimensionless unit hydrograph may also be adjusted, if needed, to provide a better match of simulated and actual hydrographs.

A regression equation for estimating time of concentration for Maryland streams is described in Appendix 6. The regression approach is easy to use and provides reproducible estimates, but the time of concentration is generally in excess of that determined by the velocity method. Several questions have been raised as to whether it is appropriate to use estimates of the time of concentration determined from observed rainfall-runoff data in conjunction with the NRCS unit hydrograph. Furthermore, the computed times of concentration given in Appendix 6 were generally based on runoff events less than the 2-year flood. Research is needed to determine if the time of concentration from observed rainfall-runoff data should be used with NRCS hydrograph theory and to determine if the time of concentration varies significantly with the magnitude and frequency of peak discharge**.**

5.3 UNIT HYDROGRAPH PEAK RATE FACTORS

While some research on the peak rate factor for the NRCS unit hydrograph has been completed, additional work is still needed. Most importantly, peak rate factors need to be estimated from hydrograph data, not just peak discharge data. It is important to estimate the peak rate factor from unit hydrographs computed from measured hyetographs and hydrographs. This research could show the geographic variation of peak rate factors, as well as the extent of their uncertainty. Additionally, peak rate factors computed from unit hydrographs obtained from rainfall-runoff data could be compared to the peak rate factors computed using geomorphic unit hydrographs derived from time-area curves. This would enable geomorphic unit hydrographs to be combined with hyetograph – hydrograph generated unit hydrographs in selecting regional peak rate factors. Improving estimates of the peak rate factor for Maryland watersheds will improve design accuracy.

5.4 PEAK DISCHARGE TRANSPOSITION

While various forms of peak discharge transposition are widely used, surprisingly little understanding of their accuracy exists. The results provided by McCuen and Levy (1999) for Pennsylvania, Virginia, and Maryland appear to be the only empirical assessment of the transposition procedure. The PA/VA/MD data base is sparse; therefore, these results need to be verified for other data sets. Additionally, the variation of the weighting functions, both of the area-ratio and USGS methods, needs to be assessed over a broader range of data. The structures of the weighting functions need to be specifically evaluated.

Research on the alternative transposition methods should be performed to assess the accuracy of the methods. The results would increase the confidence that could be placed in their use. Without this additional research, transposition methods should be used with caution.

5.5 TRANSFORMATION OF ZONING-MAP INFORMATION INTO HYDROLOGIC MODEL INPUT

Some designs require assessment for ultimate-development watershed conditions. The input to hydrologic models for ultimate-development conditions often requires obtaining information from zoning maps. Zoning maps delineate areas assigned to different land use categories. However, these categories are not consistent across political boundaries and, more importantly, a systematic method for transforming the land use categories into inputs for hydrologic models is lacking. For example, different jurisdictions use different notations for the various densities of residential development, and measures of the corresponding impervious area, which is important input to hydrologic design methods, are not provided or are ambiguously assessed.

While it would be useful to have standard zoning classifications for all jurisdictions in Maryland, this is unlikely to happen. Even this would not eliminate the need for a procedure for transforming zoning map classifications into input parameters for hydrologic design methods. Research could provide a procedure for estimating model inputs such as impervious areas and curve numbers from zoning classifications. This would improve the reproducibility of designs.

5.6 ADJUSTING WINTR-20 USING REGRESSION EQUATION ESTIMATES

When applying the WinTR-20 adjustment procedure using the confidence limit on the regression equation, the best estimate plus one standard error of prediction window is recommended herein. This value is based on the judgment and hydrologic experience of the Panel members.

Research needs to be undertaken on the most accurate and appropriate confidence level, which will probably vary with geographic region, return period, drainage area and project. A systematic research effort should provide confidence levels that can make WinTR-20 adjustments more accurate.

5.7 THE DESIGN STORM

Before NOAA Atlas 14 was published, the traditional approach followed in Maryland was to use the NRCS Type II 24-hour duration storm as the input to the WinTR-20. The depth of precipitation was selected from the appropriate precipitation duration frequency maps. The access of precipitation data and use of the data to develop site-specific rainfall distributions has changed with the release of WinTR-20 version 1.11. NOAA Atlas 14 precipitation data may be downloaded and saved as a text file from the NOAA web site for a location selected by the user. This text file may then be imported to WinTR-20. Rainfall distributions are developed for each return period based on the ratio of rainfall at durations of 5 minutes to 12 hours to the 24 hour rainfall. As an alternative, NRCS has developed a set of text files representing the average 100-year 24-hour rainfall in each of the Maryland counties. Washington and Frederick counties are divided into two parts because the rainfall varied significantly from one side of the county to the other. Depending on which county the watershed is located, one of these text files may be imported to WinTR-20.

After application of WinTR-20, if the WinTR-20 over-predicts peak discharge, a major portion of the problem may originate from the severity of this design storm input. Twenty-four hours may be too long and the storm distribution may not be appropriate for all parts of Maryland. The 24-hour duration coupled with the NRCS storm distribution may be especially inappropriate for Western Maryland where gaged discharges tend to be much lower than those estimated by the WinTR-20 model. More research is needed to finalize a synthetic storm structure and duration to be used for specific frequencies and locations.

A flood hydrograph study for the State of Maryland by the U.S. Geological Survey (Dillow, 1997) identified 278 rainfall-runoff events at 81 gaging stations throughout Maryland. These rainfall-runoff events were used to develop dimensionless hydrographs for three hydrologic regions in Maryland and to estimate the average basin lag time for each of the 81 gaging stations.

These rainfall-runoff data were used to investigate the duration of rainfall to provide insight into whether the 24-hour duration storm used with the WinTR-20 model was reasonable. Rainfall events were analyzed for 10 gaging stations where one of the runoff events exceeded a 10-year event. The time from the beginning of rainfall to the ending of rainfall, including intermittent periods of rainfall, was tabulated. The longest duration storms tended to be tropical depressions such as the November 1985 Hurricane Juan that caused severe flooding in Western Maryland or the June 1972 Hurricane Agnes that caused extensive flooding across central Maryland and Delaware. The duration of these tropical depressions ranged from 14 to 24 hours.

Spring and summer rainfall events were generally less than 10 hours in duration. A few spring or summer rainfall events in Western Maryland exceeded 10 hours in duration but the rainfall was intermittent with long periods of no rainfall. Based on a limited sample of events, it appears that rainfall events in Western Maryland are less intense than in Central and Eastern Maryland and this may contribute to the lower peak discharges per square mile that have been observed in this region.

Additional research is needed to determine the most appropriate storm duration and structure for use with WinTR-20.

5.8 GEOMORPHIC UNIT HYDROGRAPHS

Standard unit hydrograph shapes are used in hydrologic design. For Maryland, the NRCS 484-UHG and 284-UHG are accepted. Research suggests that the most appropriate unit hydrograph for a watershed is one that is based on the geomorphic characteristics of the watershed. Recent research in the professional literature suggests that time-area based unit hydrographs accurately regenerate observed storm runoffs. With the capability of GIS to generate watershed boundaries and internal drainage structures from digital terrain data, it is feasible to use GIS to develop a unit hydrograph that is unique to a watershed, thus improving the accuracy of design hydrographs.

A study of Maryland watersheds should be undertaken to evaluate the accuracy of geomorphic unit hydrographs. Predictions of storm runoff based on these should be compared with predictions based on the 484-UHG and 284-UHG. Both the NRCS and geomorphic unit hydrographs could be compared with measured runoff events in Maryland to assess their accuracy.

5.9 STATISTICAL ALTERNATIVES

The Fixed Region regression equations are applicable to both rural and urban ($\geq$ 10% impervious) watersheds in the Western Coastal Plains and Piedmont Regions. For the urban watersheds, a "relatively constant period of urbanization" was defined as a change in impervious area of less than 50 percent during the period of record. If a watershed had 20 percent impervious area at the beginning of record, it could have no more than 30 percent impervious area at the end of the time period (Sauer and others, 1983). No urban stations were eliminated from the analysis based on these criteria notably because several urban gaging stations were discontinued in the late 1980s. For future analyses, a more detailed approach should be developed for determining a homogeneous period for frequency analysis or for adjusting the annual peak data to existing conditions.

The Maryland Department of Planning (MDP) data were used to estimate land use conditions such as impervious area. The MDP approach is to assign a percentage of impervious area to various land use categories. For example, Institutional Lands are assigned an impervious area of 50 percent but there is considerable variation in impervious area for this land use category. Impervious area as estimated from the MDP data was statistically significant in estimating flood discharges for urban watersheds in the Western Coastal Plains and Piedmont Regions but this variable did not explain as much variability as anticipated For future analyses, a more detailed approach should be developed for determining a homogeneous period for frequency analysis or for adjusting the annual peak data to existing conditions Improved measures of urbanization would likely provide more accurate regression equations in the future.

Many of the gaging stations on small watersheds (less than about 10 square miles) were discontinued in the late 1970s resulting in generally short periods of record for the small watersheds in Maryland. As described earlier, Carpenter (1980) and Dillow (1996) utilized estimates of flood discharges from a calibrated rainfall-runoff model for eight gaging stations in Maryland. Carpenter (1980) also adjusted flood discharges at 17 other small watersheds based on comparisons to nearby long-term gaging station data. Moglen and others (2006) utilized both of these adjustments in developing the Fixed Region regression equations in Appendix 3. There are many other short-record stations in Maryland for which no adjustment was made. or future analyses, a more detailed approach should be developed for determining a homogeneous period for frequency analysis or for adjusting the annual peak data to existing conditions. Improving the data base of small watershed data would provide more accurate regression equations in the future.

Finally, only stations primarily in Maryland were used in developing the Fixed Region regression equations in Appendix 3 because the required land use data were not available in neighboring states. The exception was the inclusion of nine gaging stations in Delaware. For future analyses, a more detailed approach should be developed for determining a homogeneous period for frequency analysis or for adjusting the annual peak data to existing conditions.

5.10 DEVELOPMENT OF A MODEL FOR USE ON MIXED URBAN- RURAL WATERSHEDS

An increasing number of watersheds of concern to the SHA are going to have some portions that are highly urbanized and other areas that are in agricultural or forest land cover. The WinTR-20 can adjust the structure of the runoff flow paths to reflect man-made drainage, and urban curve number categories can define the land covers. However, the WinTR-20 was not designed for this type of watershed. The dimensionless UHG, as one example, was derived from rural watershed data.

The SHA needs a deterministic model that can handle a rational partitioning of the watershed into urban and rural segments. Such a model would not have to be a totally original system. It could be a combination of two models, one of which would be implemented on the urbanized portions and the other on the rural portions. The urban component might draw on the EPA Storm Water Management Model as a base and the rural component could be a revision of the WinTR-20. The mechanics of this approach could be done today. However, a significant level of research would have to be conducted to put the components into a package that would give consistent results and would be relatively easy to run.

A research project similar to that of Ragan and Pfefferkorn (1992) is needed to indicate the changes in the routed hydrograph caused by different decisions on the input parameters to the Muskingum-Cunge method. The project will need to provide more guidance to the user on the selection of the input parameters than is currently available. The project should be based on actual stream gage data. More research is needed in selecting a representative cross section location and developing a representative cross section based on a number of cross sections within a routing reach.

5.11 MUKSINGUM-CUNGE CHANNEL ROUTING PROCEDURE

A research project similar to that of Ragan and Pfefferkorn (1992) is needed to indicate the changes in the routed hydrograph caused by different decisions on the input parameters to the Muskingum-Cunge method. The project will need to provide more guidance to the user on the selection of the input parameters than is currently available. The project should be based on actual stream gage data. More research is needed in selecting a representative cross section location and developing a representative cross section based on a number of cross sections within a routing reach.

5.12 RELATIONSHIP OF PERCENT IMPERVIOUS AND COVER TYPE

The current guidelines for percent impervious and cover type used by SHA are taken from WinTR-55. There are many other sources for this relationship and many are related to the technique used to determine the cover type. Aerial photograph analysis has provided additional sources for this relationship. A research effort is needed to provide additional guideline for determining percent impervious for various land uses. This would provide the SHA a better idea of the curve number that should be used with the range of normal cover types.

5.13 RECOMMENDATIONS FOR UPDATING THE HYDROLOGY PANEL REPORT

The recommendations provided in this report are based on a combination of hydrologic judgment, existing reports and methodologies, and limited testing and evaluations of new concepts. The centerpiece of the recommendations is to quasi-calibrate the WinTR-20 deterministic watershed model using the regional regression equations where these equations are applicable. This approach has not been tested extensively but appears to be a logical approach for improving estimates of flood discharges for Maryland and for combining the strengths of WinTR-20 modeling and regional regression equations. As more experience is gained with this approach and as technology changes, this approach may need to be revised. Similarly, as new research is completed, new technology should be incorporated into this report.

This report should be considered a dynamic report with updates as needed. MSHA and MDE should jointly pursue the recommended research to improve the estimation of flood discharges for Maryland streams. To date three editions of the Panel report have been developed in 2001, 2006 and 2010 to incorporate new data and research.

5.14 SUMMARY OF THE MAJOR RESEARCH ITEMS

In summary, there are many areas of hydrology that require additional research if we are to improve our confidence in the modeling process. It is imperative that a continuing, well-conceived and adequately funded research program be implemented to address a number of problems, especially:

Improving the structure and duration of the design storms,

Determining if T_c from observed rainfall-runoff data should be used with NRCS hydrograph theory,

Determining if the T_c varies significantly with the magnitude and frequency of peak discharge,

Using the time-area curve available from the digital terrain data to generate geomorphic unit hydrographs that are unique for the watershed being modeled,

Continuing research on the regionalized peak factors to be used with the NRCS dimensionless unit hydrograph,

Continuing analysis of the FWS equations for cross section characteristics,

Continuing analysis of the impact of the method of estimating channel length on the computation of slope, Improving methods for estimating travel times through rural and urban watersheds,

Determining the relationship of the peak rate factor with the NRCS unit hydrograph,

Refining the transposition procedures of peak discharges from of gaging station,

Estimating confidence levels that are appropriate for WinTR-20 adjustments,

Providing improved statistical alternatives to develop estimates of the 2- to 500-year peak discharges for rural and urban streams in Maryland,

Defining guidelines for the application of the Muskingum-Cunge routing module in the NRCS WinTR-20,

Developing guidelines for estimating NRCS runoff curve numbers from information on planning and zoning maps,

Improving the effects of depth dependent Manning roughness coefficients on the Time of Concentration,

Investigation of the procedure for estimating the model inputs such as impervious and curve number from zoning classifications,

Investigating the most accurate and appropriate confidence level and its variance with geographic region, return period, drainage area and project,

Developing a more detailed approach for determining a homogeneous period for frequency analysis or for adjusting the annual peak data to existing conditions, and

Developing a more systematic approach for adjusting the short record stations.

REFERENCES

Arcement, G.J., and Schneider, V.R., 1984, Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains, US Department of Transportation, Federal Highway Administration, Report No. FHWA-TS-84-204, April 1984

AASHTO, 1991, *Model Drainage Manual*: American Association of State Highway and Transportation Officials, Washington, DC.

Bedient, P.B. and Huber, W.C., 1992, *Hydrology and Floodplain Analysis*: Addison-Wesley, 2nd Edition, Reading, MA, 672 p.

Bonnin, G,. Martin, D., Lin, B., Parzybok, T., Yekta, M, and Riley, D., 2006, *Precipitation-Frequency Atlas of the United States, Volume 2, Version 3.0*: NOAA Atlas 14, National Oceanic and Atmosperic Administration, National Weather Service, Silver Spring, Maryland, http://hdsc.nws.noaa.gov/

Burn, D.H., 1990, *Evaluation of regional flood frequency analysis with a region of influence approach*: Water Resources Research, 26(10), pp. 2257-2265.

Carpenter, D.H., 1980, *Technique for estimating magnitude and frequency of floods in Maryland*: U.S. Geological Survey Water-Resources Investigations Open-File Report 80-1016, 79 p.

Chow, V.T., 1959, *Open-channel hydraulics*: McGraw-Hill Book Co., New York, 680 p.

Dillow, J.J.A., 1996, *Technique for estimating magnitude and frequency of peak flows in Maryland*: U.S. Geological Survey Water-Resources Investigations Report 95-4154, 55 p

Dillow, J.J.A., 1997, *Technique for simulating peak-flow hydrographs in Maryland*: U.S. Geological Survey Water-Resources Investigations Report 97-4279, 39 p.

Dunne, T. and Leopold, L.B., 1978, *Water in environmental planning*: W.H. Freeman and Co., San Francisco, California, 818 p.

Fasken, G.B., 1963, *Guide to Selecting Roughness Coefficient n Values for Channels*: Soil Conservation Service, USDA, 45 p.

Flynn, K.M., Kirby, W.H., and Hummel, P.R., 2006, *User's Manual for Program PeakFQ Annual Flood –Frequency Analysis Using Bulletin 17B Guidelines*: U.S. Geological Survey, Techniques and Methods Book 4, Chapter B4, 42 pp.

Fellows, J.D., 1983, *A geographic Information System for Hydrologic Modeling*, PHD Dissertation, University of Maryland, Department of Civil Hydrologic, College Park, Hardison, C.H., 1971, *Prediction error of regression estimates of streamflow characteristics at ungaged sites*: U.S. Geological Survey Professional Paper 750-C, pp. C228-C236.

Hardison, C.H., 1976, *Estimates of 100-yr floods and the need for appraising their accuracy*: Presented at the Second Annual Meeting of the American Geophysical Union Midwestern Region.

Hodge, S.A., and Tasker, G.D., 1995, *Magnitude and frequency of floods in Arkansas*: U.S. Geological Survey Water-Resources Investigations Report 95-4224.

Hosking, J.R.M., and Wallis, J.R., 1997, *Regional frequency analysis, an approach based on L-moments*: Cambridge University Press, Cambridge, United Kingdom.

Interagency Advisory Committee on Water Data, 1982, *Guidelines for determining flood flow frequency*: Bulletin 17B of the Hydrology Subcommittee, U.S. Geological Survey, Office of Water Data Coordination, Reston, Virginia, 183 p.

Maryland State Highway Administration, and Maryland Department of the Environment, 2001, *Application of Hydrologic Methods in Maryland*: A report prepared by the Hydrology Panel, February 1, 2001.

Maryland State Highway Administration, and Maryland Department of the Environment, 2006, *Application of Hydrologic Methods in Maryland*: A report prepared by the Hydrology Panel, August 2006.

McCandless, T.L., and Everett, R.A., 2002, *Maryland stream survey: Bankfull discharge and channel characteristics of streams in the Piedmont Hydrologic Region*: U.S. Fish and Wildlife Service, Chesapeake Bay Field Office, CBFO-S02-01.

McCandless, T.L., 2003a, *Maryland stream survey: Bankfull discharge and channel characteristics of streams in the Allegheny Plateau and Valley and Ridge Hydrologic Regions*: U.S. Fish and Wildlife Service, Chesapeake Bay Field Office, CBFO-S03-01.

McCandless, T.L., 2003b, *Maryland stream survey: Bankfull discharge and channel characteristics of streams in the Coastal Plain Hydrologic Region*: U.S. Fish and Wildlife Service, Chesapeake Bay Field Office, CBFO-S03-02.

McCuen, R.H., 1993, *Microcomputer applications in statistical hydrology*: Prentice Hall, Englewood Cliffs, New Jersey, 306 p.

McCuen, R.H., and Thomas, W.O., Jr., 1991, *Flood frequency analysis techniques for urbanizing watersheds*: Proceedings of the Urban Hydrology Symposium at the AWRA annual meeting in Denver, Colorado, November 4-8, 1990, pp. 35-46.

McCuen, R.H., and Levy, B.S., 2000, *Evaluation of peak discharge transposition*: ASCE Journal of Hydrologic Engineering, Vol. 5, No. 3, pp. 278-289.

Merkel, W. H., July, 2000, “Muskingum-Cunge Flood Routing in NRCS Hydrologic Models”, Second Interagency Hydrologic Modeling Conference, Las Vegas, NV

Merkel, W. H, et. al, 2006, Design Rainfall Distributions Based on NOAA 14 Volumes 1 and 2 Data, Proceedings of the Third Federal Interagency Hydrologic Modeling Conference, Reno, Nevada, April, 2006.

Moglen, G.E., Thomas, W.O., Jr., and Cuneo, Carlos, 2006, *Evaluation of alternative statistical methods for estimating frequency of peak flows in Maryland*: Final report (SP907C4B), Maryland State Highway Administration, Baltimore, Maryland.

Montgomery, D.C., and Peck, E.A., 1982, *Introduction to linear regression analysis*: John Wiley & Sons, 504 p.

Pilon, P.J. and Harvey, K.D., 1992, *Consolidated Frequency Analysis (CFA), Version 3.1 Reference Manual*, Environment Canada, Ottawa, Ontario, 130 p.

Ragan, R.M., and Pfefferkorn, R.L., 1992, *Analysis of the role of storm and stream parameters on the performance of the SCS-TR-20 and HEC-1 under Maryland conditions:* Maryland State Highway Administration AW092-351-046, Final Report, Baltimore, Maryland, 93 p.

Ree, W.O., 1949, *Hydraulic Characteristics of Vegetation for Vegetated Waterways*: Agricultural Engineering, vol. 30, no 4, April, 1949.

Rosgen, D.L., 1996, *Applied river morphology*: Wildland Hydrology, Pagosa Springs, Colorado.

Sauer, V.B., 1974, *Flood characteristics of Oklahoma Streams*: U.S. Geological Survey Water-Resources Investigations Report 52-73, 301 p.

Sauer, V.B., Thomas, W.O., Jr., Stricker, V.A., and Wilson, K.V., 1983, *Flood characteristics of urban watersheds in the United States*: U.S. Geological Survey Water-Supply Paper 2207, 63 p.

Siebach, P.R., 1987, *Integration of Desktop Image Processing Geographic Information Systems for the Operation of HEC-1*, Master of Science Thesis, University of Maryland, Department of Civil Engineering, College Park, MD

Stedinger, J.R., Vogel, R.M., and Foufoula-Georgiou, E., 1993, Chapter 18 *Frequency analysis of extreme events: in* Handbook of Hydrology, David Maidment, Editor in Chief, McGraw-Hill, Inc.

Tasker, G.D. and Stedinger, J.R., 1989, *An operational GLS model for hydrologic regression*: Journal of Hydrology, vol. 111, pp. 361-375.

Thomas, W.O., Jr., Monde, M.C., and Davis, S.R., 2000, *Estimation of time of concentration for Maryland streams*: Transportation Research Record No. 1720, Transportation Research Board, National Research Council, National Academy Press, Washington, DC, pp. 95-99.

U.S. Army Corps of Engineers, 2009, *HEC-SSP Statistical Software Package:* User's Manual, Version 1.1, Hydrologic Engineering Center, Davis, California, 214 p.

U.S. Army Corps of Engineers, 1986, *Accuracy of computed water surface profiles*: Hydrologic Engineering Center, RD-26, Davis, California, 177 p.

U.S. Department of Agriculture, 1956, *Supplement B of the National Hydrologic Handbook, Section 5, Hydraulics*: Soil Conservation Service, Washington, DC.

U.S. Department of Agriculture, 2004, *National Engineering Handbook, Part 630, Hydrology*: Natural Resources Conservation Service, Washington, DC.

U.S. Department of Agriculture, 2002, *Hydrology for small watersheds WinTR-55User Manual*: Natural Resources Conservation Service, Washington, DC.

U.S. Department of Agriculture, 2004, Draft WinTR-20 User Guide, Natural Resources Conservation Service, Washington, D. C.

U.S. Water Resources Council, 1977, *Guidelines for determining flood flow frequency*: Bulletin 17A of Subcommittee on Hydrology, U.S. Water Resources Council, Washington, DC.

U.S. Water Resources Council, 1981, *Estimating peak flow frequencies for natural ungaged watersheds – A proposed nationwide test*: Hydrology Committee, U.S. Water Resources Council, Washington, DC, 346 p.

Viessman, W. Jr., Lewis, G.L., and Knapp, J.W., 1989, *Introduction to hydrology*: Harper Collins Publishers, New York, New York, 780 p.

Welle, P.I., and Woodward, D.E., 1989, *Dimensionless unit hydrograph for the Delmarva Peninsula*: Transportation Research Record 1224, Transportation Research Board, National Research Council, Washington, DC, pp. 79-80.

APPENDIX 1
WATERSHED PROPERTIES
FOR USGS STREAM GAGES
IN MARYLAND AND DELAWARE

Watershed Propoerties

- Station Number: the station identification number as reported by the USGS. The leading zero of each gage is omitted.

- Station Name: the station name as reported by the USGS.

- Years of Record: the number of years of gage record, excluding those years of regulated gage record (range: 10 – 76 years)

- Area: probably the single most important watershed characteristic for hydrologic design. It reflects the volume of water that can be generated from rainfall. GIS calculated variable equal to the number of pixels composing the watershed times the pixel's area or cell size (mi^2). (range: 0.1 – 820 mi^2)

- Perimeter: GIS calculated variable equal to the length of the boundary of the watershed (mi). (range: 2.0 – 249.7 mi)

- Length: GIS calculated variable equal to the distance measured along the main channel from the watershed outlet to the basin divide (mi). (range: 0.8 – 72.4 mi)

- Channel Slope: the change of elevation with respect to distance along the principal flow path. The channel slope was calculated using GIS as the difference in elevation between two points located 10 and 85% of the distance along the main channel from the outlet divided by the distance between the two points (ft/mile). (range: 2.2 – 250.6 ft/mile)

- Watershed Slope: the average basin slope is the average of all neighborhood slopes determined along the steepest direction of flow. These are the local slopes determined from the upstream to downstream pixel for each pixel within the watershed (ft/ft). This quantity is represented by the symbol "LSLOPE" in the Fixed Region Method text. (range: 0.00378 – 0.22673 ft/ft)

- Basin Relief: the average elevation of all points within the watershed minus the elevation at the outlet of the watershed (ft). (range: 16.2 – 1,363.4 ft)

- Lime: the percentage of limestone within the watershed (%). (range: 0 – 100 percent)

- High Elev.: the percentage of area within the watershed with elevation in excess of 2000 feet. (range: 0 – 100 percent)

- Hypso: hypsometric area ratio, a single-valued index of the hypsometric curve, equal to the ratio of the area under the normalized hypsometric curve. (range: 0.18 – 0.74)

- # First Order Streams: the number of first order streams in the watershed as defined by the 1:250,000 mapping in the digitized National Hydrography Dataset. (range: 0 – 405)

- Total Stream Length: total length of streams in the watershed as defined by the 1:250,000 mapping in the digitized National Hydrography Dataset. (range: 0 – 1,546.9 mi)

- Area in MD: the fraction of the watershed that is within Maryland boundaries. (range: 0.005 – 1.0)

- 2-yr Prec: the 2-yr, 24-hour precipitation depth in hundredths of an inch (range: 2.243 – 3.760 inches)

- 100-yr Prec: the 100-yr, 24-hour precipitation depth in hundredths of an inch (range: 5.247 – 9.436 inches)

- Res70: the percentage of the basin defined as residential by the USGS 1970's land use (%). (range: 0 – 82.6 percent)

- Com70: the percentage of the basin defined as commercial by the USGS 1970's land use (%). (range: 0 – 33.9 percent)

- Ag70: the percentage of the basin defined as agricultural by the USGS 1970's land use (%). (range: 0 – 100 percent)

- For70: the percentage of the basin defined as forest by the USGS 1970's land use (%). (range: 0 – 100 percent)

- St70: the percentage of the basin defined as storage by the USGS 1970's land use (%). (range: 0 – 16.9 percent)

- IA70: the percentage of the basin defined as impervious area by the USGS 1970's land use (%). Impervious area includes the following land use classifications: residential, commercial, industrial, transportation, industrial/commercial complexes, mixed urban or built-up land, dry salt flats, and bare exposed rock. (range: 0 – 49.3 percent)

- Res85: the percentage of the basin defined as residential by the Ragan 1985 land use (%). (range: 0 – 68.7 percent)

- Com85: the percentage of the basin defined as commercial by the Ragan 1985 land use (%). (range: 0 – 27.2 percent)

- Ag85: the percentage of the basin defined as agricultural by the Ragan 1985 land use (%). (range: not available)

- For85: the percentage of the basin defined as forest by the Ragan 1985 land use (%). (range: 2.7 – 100 percent)

- St85: the percentage of the basin defined as storage by the Ragan 1985 land use (%). (range: 0 – 15.9 percent)

- IA85: the percentage of the basin defined as impervious area by the Ragan 1985 land use (%). Impervious area includes the following land use classifications: low density residential, medium density residential, high density residential, commercial, industrial, institutional, extractive, open urban land, bare exposed rock, and bare ground. (range: 0 – 41.1 percent)

- Res90: the percentage of the basin defined as residential by the (Maryland Office of Planning (MOP) 1990 land use (%). (range: 0 – 69.2 percent)

- Com90: the percentage of the basin defined as commercial by the MOP 1990 land use (%). (range: 0 – 26.1 percent)

- Ag90: the percentage of the basin defined as agricultural by the MOP 1990 land use (%). (range: 0 – 97.8 percent)

- For90: the percentage of the basin defined as forest by the MOP 1990 land use (%). (range: 0 – 98.8 percent)

- St90: the percentage of the basin defined as storage by the MOP 1990 land use (%). (range: 0 – 16.0 percent)

- IA90: the percentage of the basin defined as impervious area by the MOP 1990 land use (%). Impervious area includes the following land use classifications: low density residential, medium density residential, high density residential, commercial, industrial, institutional, extractive, open urban land, bare exposed rock, and bare ground. (range: 0 – 43.8 percent)

- Res97: the percentage of the basin defined as residential by the MOP 1997 land use (%). (range: 0 – 65.0 percent)

- Com97: the percentage of the basin defined as commercial by the MOP 1997 land use (%). (range: 0 – 33.9 percent)

- Ag97: the percentage of the basin defined as agricultural by the MOP 1997 land use (%). (range: 0 – 96.3 percent)

- For97: the percentage of the basin defined as forest by the MOP 1997 land use (%). (range: 0 – 98.0 percent)

- St97: the percentage of the basin defined as storage by the MOP 1997 land use (%). (range: 0 – 14.4 percent)

- IA97: the percentage of the basin defined as impervious area by the MOP 1997 land use (%). (range: 0 – 45.0 percent)

- CN70: the average runoff curve number for the basin as defined by the USGS 1970's land use. Soils data are from the NRCS STATSGO dataset. (range: 57 – 84.1)

- CN97: the average runoff curve number for the basin as defined by the MOP 1997 land use. Impervious area includes the following land use classifications: low density residential, medium density residential, high density residential, commercial, industrial, institutional, extractive, open urban land, bare exposed rock, bare ground, transportation, large lot agriculture, large lot forest, feeding operations, and agricultural buildings. (range: 57.1 – 84.6)

- Hyd._A: the percentage of the basin defined as hydrologic soil A, computed as the number of pixels of hydrologic soil A divided by the number of pixels in the basin (%). This is computed from SSURGO soils data data in Eastern and Western Coastal Plain regions and from STATSGO soils data in the other regions. (range: 0 – 84.5 percent)

- Hyd._B: the percentage of the basin defined as hydrologic soil B, computed as the number of pixels of hydrologic soil B divided by the number of pixels in the basin (%). This is computed from SSURGO soils data data in Eastern and Western Coastal Plain regions and from STATSGO soils data in the other regions. (range: 0 – 100 percent)

- Hyd._C: the percentage of the basin defined as hydrologic soil C, computed as the number of pixels of hydrologic soil C divided by the number of pixels in the basin (%). This is computed from SSURGO soils data data in Eastern and Western Coastal Plain regions and from STATSGO soils data in the other regions. (range: 0 – 95.7 percent)

- Hyd._D: the percentage of the basin defined as hydrologic soil D, computed as the number of pixels of hydrologic soil D divided by the number of pixels in the basin (%). This is computed from SSURGO soils data data in Eastern and Western Coastal Plain regions and from STATSGO soils data in the other regions. (range: 0 – 85.7 percent)

- Province: the physiographic province in which the watershed is located (A = Appalachian, B = Blue Ridge, E = Eastern Coastal Plain, P = Piedmont, W = Western Coastal Plain).

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware

Station Number	Station Name	Years of Record	Area (mi^2)	Perimeter (mi)	Length (mi)	Channel Slope (ft/mi)	Watershed Slope (ft/ft)	Basin Relief (ft)	Lime (%)	High Elev. (%)	Hypso
1483200	Blackbird Creek at Blackbird, DE	54	4.10			14.80	0.016000	41.90			
1483500	Leipsic River near Cheswold, DE	33	9.6			8.51	0.012964	39.05			
1483720	*Puncheon Branch at Dover, DE	10	2.55			14.08	0.009333	18.31			
1484000	Murderkill River near Felton, DE	31	13.24			6.98	0.006163	27.28			
1484002	*Murderkill River Tributary near Felton, DE	10	0.91			14.14	0.009338	24.59			
1484050	*Pratt Branch near Felton, DE	10	3.08			11.96	0.010631	28.59			
1484100	Beaverdam Branch at Houston, DE	49	3.55			5.93	0.003982	14.64			
1484300	*Sowbridge Branch near Milton, DE	22	7.17			8.63	0.007492	28.45			
1484500	Stockley Branch at Stockly, DE	62	5.27			4.92	0.005009	17.49			
1485000	Pocomoke River near Willards, MD	57	56.09	82.5	15.9	1.99	0.004265	20.08	0.0	0.0	0.42
1485500	Nassawango Creek near Snow Hill, MD	57	45.02	64.6	15.7	2.81	0.004200	30.31	0.0	0.0	0.39
1486000	Manokin Branch near Princess Anne, MD	53	5.02	23.4	7.1	5.68	0.003493	18.93	0.0	0.0	0.59
1486100	Andrews Branch near Delmar, MD	10	3.27			7.76	0.006420	17.82	0.0		
1486980	*Toms Dam Branch near Greenwood, DE	10	6.44			1.99	0.003013	7.42			
1487000	Nanticoke River near Bridgeville, DE	64	72.94			2.74	0.004762	29.48			
1487900	Meadow Branch near Delmar, DE	9	4.11			3.07	0.002498	6.73			
1488500	Marshyhope Creek near Adamsville, DE	60	47.4			2.90	0.004460	21.41			
1489000	Faulkner Branch near Federalsburg, MD	42	7.69	25.3	6.7	5.91	0.010423	25.76	0.0	0.0	0.60
1490000	Chicamacomico River near Salem, MD	34	16.35	31.6	8.4	5.93	0.006270	26.39	0.0	0.0	0.54
1490600	Meredith Branch Near Sandtown, DE	10	9.17			5.82	0.004407	20.70			
1490800	Oldtown Branch at Goldsboro, MD	10	4.06	20.2	4.7	7.87	0.005156	17.19	0.0	0.0	0.62
1491000	Choptank River near Greensboro, MD	59	113.71	94.9	21.7	3.35	0.006099	42.07	0.0	0.0	0.44
1491010	*Sangston Prong near Whiteleysburg, DE	10	2.04			4.20	0.004419	11.27			
1491050	Spring Branch near Greensboro, MD	10	3.34	17.3	4.9	4.92	0.003465	17.56	0.0	0.0	0.61
1492000	Beaverdam Branch at Matthews, MD	32	5.49	20.0	5.7	11.28	0.006900	34.82	0.0	0.0	0.74
1492050	Gravel Run at Beulah, MD	11	8.90	22.5	5.0	9.56	0.011444	34.63	0.0	0.0	0.67
1492500	Sallie Harris Creek near Carmicheal, MD	36	7.60	23.7	7.4	9.53	0.008995	36.71	0.0	0.0	0.62
1492550	Mill Creek near Skipton, MD	11	4.61	16.3	4.9	14.35	0.006818	33.11	0.0	0.0	0.62
1493000	*Unicorn Branch near Millington, MD	56	20.19			5.91	0.008739	47.20			
1493500	Morgan Creek near Kennedyville, MD	55	11.97	28.1	7.6	9.11	0.009899	39.25	0.0	0.0	0.62
1494000	Southeast Creek at Church Hill, DE	14	12.46	25.4	7.3	6.57	0.008415	44.28	0.0	0.0	0.69
1495000	Big Elk Creek at Elk Mills, MD	68	53.49	64.4	23.9	17.6	0.08607	329.9	0.0	0.0	0.57
1495500	Little Elk Creek at Childs, MD	10	26.46	42.7	16.8	24.2	0.06752	294.1	0.0	0.0	0.58
1496000	Northeast River at Leslie, MD	37	24.87	42.5	14.3	24.5	0.04863	288.5	0.0	0.0	0.57
1496200	Principio Creek near Principio Furnace, MD	27	9.00	22.1	6.7	33.2	0.06388	165.6	0.0	0.0	0.58
1577940	Broad Creek tributary at Whiteford, MD	15	0.67	5.8	1.7	175.7	0.07430	107.7	0.0	0.0	0.35
1578500	Octoraro Creek near Rising Sun, MD	19	191.66	99.7	43.6	10.8	0.08256	422.8	0.0	0.0	0.50

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	# First Order Streams	Total Stream Length	Area in MD	2-yr Prec. (in x 100)	100-yr Prec. (in x100)	Res70 (%)	Com70 (%)	Ag70 (%)	For70 (%)	St70 (%)	IA70 (%)	Res85 (%)
1483200	Blackbird Creek at Blackbird, DE												
1483500	Leipsic River near Cheswold, DE												
1483720	*Puncheon Branch at Dover, DE												
1484000	Murderkill River near Felton, DE												
1484002	*Murderkill River Tributary near Felton, DE												
1484050	*Pratt Branch near Felton, DE												
1484100	Beaverdam Branch at Houston, DE												
1484300	*Sowbridge Branch near Milton, DE												
1484500	Stockley Branch at Stockly, DE												
1485000	Pocomoke River near Willards, MD	27	99.8	0.334	333.9	858.8	0.6	0.0	53.1	29.4	16.9	0.2	0.2
1485500	Nassawango Creek near Snow Hill, MD	9	54.5	1.000	355.6	914.4	0.8	0.5	18.1	79.4	1.2	0.8	1.2
1486000	Manokin Branch near Princess Anne, MD	2	7.9	1.000	338.0	869.0	0.1	0.0	24.1	75.7	0.0	0.0	0.6
1486100	Andrews Branch near Delmar, MD												
1486980	*Toms Dam Branch near Greenwood, DE												
1487000	*Nanticoke River near Bridgeville, DE												
1487900	Meadow Branch near Delmar, DE												
1488500	Marshyhope Creek near Adamsville, DE												
1489000	Faulkner Branch near Federalsburg, MD	5	14.6	1.000	359.0	921.0	1.7	0.0	75.4	22.9	0.0	0.6	1.5
1490000	Chicamacomico River near Salem, MD	9	26.7	1.000	334.1	859.7	0.4	0.1	51.1	48.1	0.3	0.2	0.2
1490600	Meredith Branch Near Sandtown, DE												
1490800	Oldtown Branch at Goldsboro, MD	3	8.0	1.000	337.0	865.0	1.1	0.0	65.4	29.8	3.6	0.4	1.1
1491000	Choptank River near Greensboro, MD	68	232.7	0.316	330.5	848.1	2.6	0.1	52.7	37.1	7.1	1.1	2.5
1491010	*Sangston Prong near Whiteleysburg, DE												
1491050	Spring Branch near Greensboro, MD	2	6.3	0.998	337.0	865.0	1.9	0.0	76.7	21.4	0.0	0.7	0.0
1492000	Beaverdam Branch at Matthews, MD	3	10.9	1.000	317.0	814.0	1.2	0.0	67.9	31.0	0.0	0.4	0.0
1492050	Gravel Run at Beulah, MD	7	13.7	1.000	359.0	921.0	1.0	0.0	87.3	11.0	0.0	0.4	0.2
1492500	Sallie Harris Creek near Carmicheal, MD	3	11.9	1.000	345.0	887.0	4.7	0.0	64.5	30.8	0.0	1.8	0.5
1492550	Mill Creek near Skipton, MD	2	7.0	0.995	345.0	887.0	0.0	0.0	91.7	8.3	0.0	0.0	0.0

1493000	*Unicorn Branch near Millington, MD													
1493500	Morgan Creek near Kennedyville, MD	7	17.0	1.000	315.8	810.4	1.2	0.0	93.3	5.4	0.2	0.4	1.0	
1494000	Southeast Creek at Church Hill, DE	6	20.4	1.000	340.0	874.1	0.5	0.0	77.9	17.4	4.2	0.2	0.4	
1495000	Big Elk Creek at Elk Mills, MD	22	85.6	0.201	318.9	802.7	2.4	3.0	80.2	14.2	0.0	3.7	5.4	
1495500	Little Elk Creek at Childs, MD	12	42.1	0.533	328.4	834.2	6.1	2.0	75.7	15.9	0.1	4.0	6.3	
1496000	Northeast River at Leslie, MD	9	34.8	0.693	325.6	824.7	2.0	2.4	78.8	15.3	0.0	3.0	4.4	
1496200	Principio Creek near Principio Furnace, MD	4	13.4	1.000	315.8	799.9	0.0	0.0	95.7	4.2	0.0	0.0	2.9	
1577940	Broad Creek tributary at Whiteford, MD	1	0.9	1.000	348.0	872.0	2.0	0.8	42.9	54.3	0.0	1.3	5.4	
1578500	Octoraro Creek near Rising Sun, MD	88	345.8	0.083	317.1	794.5	1.5	0.7	79.3	17.6	0.5	1.3	5.2	

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware(continued)

Station Number	Station Name	Com85 (%)	Ag85 (%)	For85 (%)	St85 (%)	IA85 (%)	Res90 (%)	Com90 (%)	Ag90 (%)	For90 (%)	St90 (%)	IA90 (%)	Res97 (%)
1483200	Blackbird Creek at Blackbird, DE												
1483500	Leipsic River near Cheswold, DE												
1483720	*Puncheon Branch at Dover, DE												
1484000	Murderkill River near Felton, DE												
1484002	*Murderkill River Tributary near Felton, DE												
1484050	*Pratt Branch near Felton, DE												
1484100	Beaverdam Branch at Houston, DE												
1484300	*Sowbridge Branch near Milton, DE												
1484500	Stockley Branch at Stockly, DE												
1485000	Pocomoke River near Willards, MD	1.8	0.0	34.2	0.0	1.5	0.3	0.1	57.8	34.7	0.0	0.5	1.5
1485500	Nassawango Creek near Snow Hill, MD	1.6	0.0	65.6	0.3	1.7	1.5	0.9	20.4	64.5	0.3	1.3	3.1
1486000	Manokin Branch near Princess Anne, MD	1.6	0.0	57.4	0.0	1.5	1.4	0.0	22.4	57.7	0.0	0.6	2.2
1486100	Andrews Branch near Delmar, MD			84.2		1.0							
1486980	*Toms Dam Branch near Greenwood, DE												
1487000	Nanticoke River near Bridgeville, DE												
1487900	Meadow Branch near Delmar, DE												
1488500	Marshyhope Creek near Adamsville, DE												
1489000	Faulkner Branch near Federalsburg, MD	3.2	0.0	18.6	0.0	3.0	2.1	0.3	75.4	19.6	0.0	1.4	4.5
1490000	Chicamacomico River near Salem, MD	0.0	0.0	46.4	0.1	0.2	0.5	0.0	51.8	39.6	3.1	0.4	1.5
1490600	Meredith Branch Near Sandtown, DE												
1490800	Oldtown Branch at Goldsboro, MD	0.6	0.0	33.1	0.0	0.7	6.0	0.4	62.0	31.5	0.0	2.0	9.4
1491000	Choptank River near Greensboro, MD	0.1	0.0	41.0	0.3	0.8	5.4	0.1	51.7	38.0	0.3	1.6	6.9
1491010	*Sangston Prong near Whiteleysburg, DE												
1491050	Spring Branch near Greensboro, MD	0.0	0.0	20.4	0.0	0.0	1.2	0.0	77.3	19.8	0.0	0.3	2.3
1492000	Beaverdam Branch at Matthews, MD	0.6	0.0	27.9	0.0	0.6	1.1	0.0	65.6	29.1	0.0	0.4	3.1
1492050	Gravel Run at Beulah, MD	1.3	0.0	15.0	0.3	1.3	0.4	0.0	71.0	15.0	0.4	0.5	4.6
1492500	Sallie Harris Creek near Carmicheal, MD	0.0	0.0	30.4	0.0	0.1	1.4	0.0	66.8	31.8	0.0	0.3	2.3
1492550	Mill Creek near Skipton, MD	0.0	0.0	12.2	0.0	0.0	0.0	0.0	93.1	7.4	0.0	0.0	0.5
1493000	*Unicorn Branch near Millington, MD												
1493500	Morgan Creek near Kennedyville, MD	0.4	0.0	8.9	0.2	0.6	0.9	0.3	89.8	8.5	0.6	0.6	1.1
1494000	Southeast Creek at Church Hill, DE	0.4	0.0	26.3	0.0	0.6	0.6	0.1	72.8	25.4	0.2	0.7	1.2
1495000	Big Elk Creek at Elk Mills, MD	5.7	0.0	36.3	0.0	6.4	5.2	0.3	58.8	36.2	0.0	2.1	5.8
1495500	Little Elk Creek at Childs, MD	1.1	0.0	30.9	0.0	2.5	12.5	0.8	58.9	27.1	0.3	4.2	18.7
1496000	Northeast River at Leslie, MD	0.7	0.0	22.8	0.0	1.9	6.7	0.4	68.5	23.1	0.0	2.5	7.7
1496200	Principio Creek near Principio Furnace, MD	0.0	0.0	14.8	0.0	1.0	4.4	0.0	78.6	17.0	0.0	1.2	9.7
1577940	Broad Creek tributary at Whiteford, MD	0.3	0.0	28.0	0.0	1.6	8.5	1.1	49.9	39.5	0.0	3.0	10.4
1578500	Octoraro Creek near Rising Sun, MD	0.6	0.0	33.6	0.2	1.9	10.3	0.6	59.3	31.7	0.3	3.5	14.2

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Com97 (%)	Ag97 (%)	For97 (%)	St97 (%)	IA97 (%)	CN70	CN97	Hyd. A (%)	Hyd. B (%)	Hyd. C (%)	Hyd. D (%)	Province
1483200	Blackbird Creek at Blackbird, DE								0.0	65.6	14.6	19.5	E
1483500	Leipsic River near Cheswold, DE								0.0	65.1	8.6	26.0	E
1483720	*Puncheon Branch at Dover, DE								0.0	78.2	3.2	18.6	E
1484000	Murderkill River near Felton, DE								14.3	29.2	11.1	45.3	E
1484002	*Murderkill River Tributary near Felton, DE								78.8	14.1	3.2	3.9	E
1484050	*Pratt Branch near Felton, DE								1.2	84.8	4.0	10.0	E
1484100	Beaverdam Branch at Houston, DE								17.7	10.3	23.5	48.5	E
1484300	*Sowbridge Branch near Milton, DE								50.7	37.7	2.0	8.7	E
1484500	Stockley Branch at Stockly, DE								5.1	50.1	15.5	29.3	E
1485000	Pocomoke River near Willards, MD	0.0	57.0	33.7	0.0	0.7	81.8	79.4	3.1	50.1	12.1	34.6	E
1485500	Nassawango Creek near Snow Hill, MD	1.3	19.5	64.6	0.3	2.0	70.1	70.9	8.6	31.0	20.6	39.7	E
1486000	Manokin Branch near Princess Anne, MD	0.0	22.1	51.3	0.0	0.8	74.4	74.5	1.1	31.5	13.5	53.8	E
1486100	Andrews Branch near Delmar, MD								8.7	22.1	26.1	43.1	E
1486980	*Toms Dam Branch near Greenwood, DE								9.3	23.9	35.0	31.8	E
1487000	Nanticoke River near Bridgeville, DE								10.1	33.6	20.5	35.7	E
1487900	Meadow Branch near Delmar, DE								0.2	9.6	32.4	57.7	E
1488500	Marshyhope Creek near Adamsville, DE								1.4	16.1	13.4	69.1	E
1489000	Faulkner Branch near Federalsburg, MD	0.8	73.2	18.7	0.0	2.1	78.3	81.4	0.8	43.0	20.5	35.6	E
1490000	Chicamacomico River near Salem, MD	0.1	50.9	41.9	0.5	0.8	74.3	77.2	10.9	32.5	26.6	29.9	E
1490600	Meredith Branch Near Sandtown, DE								0.1	10.4	17.2	72.3	E
1490800	Oldtown Branch at Goldsboro, MD	0.3	61.2	28.9	0.0	2.9	78.7	80.4	0.0	48.7	10.9	40.4	E
1491000	Choptank River near Greensboro, MD	0.3	50.9	36.3	0.3	2.2	77.1	77.1	3.4	23.7	13.8	58.8	E
1491010	*Sangston Prong near Whiteleysburg, DE								0.0	25.0	24.9	50.1	E
1491050	Spring Branch near Greensboro, MD	0.0	75.9	19.7	0.0	0.6	78.2	81.6	0.0	56.3	8.0	35.7	E
1492000	Beaverdam Branch at Matthews, MD	0.0	66.0	26.8	0.0	1.0	76.3	79.1	33.5	11.8	24.9	29.8	E
1492050	Gravel Run at Beulah, MD	0.2	74.9	13.5	0.6	2.0	76.7	80.5	18.7	23.3	47.7	9.9	E
1492500	Sallie Harris Creek near Carmicheal, MD	0.0	68.1	29.6	0.0	0.6	75.2	78.7	0.0	60.8	16.2	22.8	E
1492550	Mill Creek near Skipton, MD	0.0	91.8	8.2	0.0	0.1	80.3	84.4	29.5	39.7	16.4	14.4	E
1493000	*Unicorn Branch near Millington, MD								0.2	52.7	13.9	32.6	E
1493500	Morgan Creek near Kennedyville, MD	0.4	87.9	10.0	0.5	0.8	76.9	81.0	1.4	25.2	66.8	6.1	E
1494000	Southeast Creek at Church Hill, DE	0.3	74.9	22.5	0.2	0.9	77.5	80.1	2.4	51.8	26.7	19.1	E
1495000	Big Elk Creek at Elk Mills, MD	0.4	58.4	34.9	0.0	2.4	73.6	72.9	0.0	81.9	11.6	6.5	P
1495500	Little Elk Creek at Childs, MD	1.1	53.4	24.9	0.2	6.3	75.0	75.0	0.0	67.6	22.1	10.3	P
1496000	Northeast River at Leslie, MD	0.5	66.4	22.6	0.1	3.2	75.3	76.4	0.0	60.9	19.7	19.5	P
1496200	Principio Creek near Principio Furnace, MD	0.1	73.5	16.4	0.0	2.8	75.8	78.0	0.0	72.3	15.0	12.7	P
1577940	Broad Creek tributary at Whiteford, MD	1.2	49.0	38.3	0.0	3.8	67.5	70.5	1.2	83.8	15.0	0.0	P
1578500	Octoraro Creek near Rising Sun, MD	1.7	54.6	29.7	0.3	5.5	73.5	76.8	0.0	71.7	19.5	8.8	P

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Years of Record	Area (mi^2)	Perimeter (mi)	Length (mi)	Channel Slope (ft/mi)	Watershed Slope (ft/ft)	Basin Relief (ft)	Lime (%)	High Elev. (%)	Hypso
1578800	Basin Run at West Nottingham, MD	10	1.25				0.05000	77.8	0.0		
1579000	Basin Run at Liberty Grove, MD	23	5.08				0.06000	137.9	0.0		
1580000	Deer Creek at Rocks, MD	73	94.18	77.9	31.3	17.5	0.09710	379.1	0.0	0.0	0.48
1580200	Deer Creek at Kalmia, MD	11	127.16	103.8	43.8	14.2	0.09671	424.0	0.0	0.0	0.47
1581500	Bynum Run at Bel Air, MD	25	8.32	20.2	7.1	38.1	0.05467	144.4	0.0	0.0	0.47
1581700	Winter Run near Benson, MD	32	34.66	42.2	17.4	30.4	0.07969	315.5	0.0	0.0	0.55
1582000	Little Falls at Blue Mount, MD	56	53.63	53.4	18.6	18.8	0.10669	364.1	0.0	0.0	0.54
1582510	Piney Creek near Hereford, MD	14	1.39	7.3	2.4	92.5	0.07866	139.0	0.0	0.0	0.62
1583000	Slade Run near Glyndon, MD	34	2.04	10.0	2.8	96.5	0.09968	180.2	0.0	0.0	0.51
1583100	Piney Run at Dover, MD	10	12.44	28.3	9.0	51.1	0.09213	274.3	0.0	0.0	0.50
1583495	Western Run tributary at Western Run, MD	10	0.23	3.1	1.2	168.8	0.08274	110.5	0.0	0.0	0.53
1583500	Western Run at Western Run, MD	55	60.32	56.1	18.8	24.2	0.09060	282.2	0.0	0.0	0.43
1583580	Baisman Run at Broadmoor, MD	13	1.49				0.11000	218.9	0.0		
1583600	Beaverdam Run at Cockeysville, MD	16	20.68	30.1	11.8	36.7	0.08000	292.3	0.0	0.0	0.55
1584050	Long Green Creek at Glen Arm, MD	24	9.30	19.4	5.4	54.0	0.07000	167.0	0.0	0.0	0.47
1584500	Little Gunpowder Falls at Laurel Brook, MD	59	36.03	48.2	15.5	21.7	0.08000	251.5	0.0	0.0	0.50
1585100	White Marsh Run at White Marsh, MD	28	7.63	23.0	6.7	53.7	0.07000	159.8	0.0	0.0	0.38
1585200	West Branch Herring Run at Idlewylde, MD	31	2.16	8.8	2.5	62.5	0.06275	127.9	0.0	0.0	0.60
1585300	Stemmers Run at Rossville, MD	29	4.52	15.1	5.4	63.1	0.06403	167.2	0.0	0.0	0.46
1585400	Brien Run at Stemmers Run, MD	29	1.94	8.3	2.3	37.0	0.03603	62.3	0.0	0.0	0.38
1585500	Cranberry Branch near Westminster, MD	51	3.43	12.0	4.1	47.0	0.08999	164.9	0.0	0.0	0.46
1586000	North Branch Patapsco River at Cedarhurst, MD	54	56.27	48.8	16.2	28.2	0.09223	340.1	4.45	0.0	0.49
1586210	Beaver Run near Finksburg, MD	17	14.09	25.9	10.1	44.3	0.08905	297.5	2.47	0.0	0.57
1586610	Morgan Run near Louisville, MD	17	27.84	38.0	10.7	35.4	0.10010	285.6	0.0	0.0	0.54
1587000	North Branch Patapsco River near Marriottsville, MD	26	164.23	95.3	51.9	6.1	0.09138	413.3	1.74	0.0	0.48
1587050	Hay Meadow Branch tributary at Poplar Springs, MD	11	0.49	4.1	1.1	136.4	0.08716	82.4	0.0	0.0	0.52
1587500	South Branch Patapsco River at Henryton, MD	31	64.26	66.8	19.7	24.0	0.09709	349.9	0.0	0.0	0.55
1588000	Piney Run near Sykesville, MD	43	11.40	26.6	8.6	39.6	0.07545	216.8	0.0	0.0	0.49
1588500	Patapsco River at Woodstock, MD	10	258.07	122.7	57.2	7.7	0.09329	496.7	0.0	0.0	0.52
1589000	Patapsco River at Hollofield, MD	23	284.71	138.0	63.7	7.4	0.09301	475.6	0.0	0.0	0.49

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	# First Order Streams	Total Stream Length	Area in MD	2-yr Prec. (in x 100)	100-yr Prec. (in x100)	Res 70 (%)	Com70 (%)	Ag70 (%)	For70 (%)	St70 (%)	IA70 (%)	Res85 (%)
1578800	Basin Run at West Nottingham, MD												
1579000	Basin Run at Liberty Grove, MD												
1580000	Deer Creek at Rocks, MD	42	175.4	0.734	339.4	850.4	0.9	0.4	71.8	26.7	0.1	0.7	2.6
1580200	Deer Creek at Kalmia, MD	55	232.5	0.803	335.3	840.3	0.8	0.4	71.7	27.0	0.0	0.6	3.2
1581500	Bynum Run at Bel Air, MD	3	12.8	1.000	322.8	809.0	16.2	5.2	67.0	10.5	0.0	10.8	20.5
1581700	Winter Run near Benson, MD	13	61.5	1.000	323.0	809.6	6.6	0.3	71.1	20.6	0.0	2.8	14.2
1582000	Little Falls at Blue Mount, MD	22	96.6	0.919	334.6	839.0	0.2	0.9	67.2	31.6	0.0	1.0	4.5
1582510	Piney Creek near Hereford, MD	1	2.6	1.000	321.0	806.0	0.0	0.6	74.4	25.0	0.0	0.6	9.7
1583000	Slade Run near Glyndon, MD	3	5.5	1.000	328.0	822.0	5.4	0.0	45.4	49.2	0.0	2.1	3.3
1583100	Piney Run at Dover, MD	3	19.8	1.000	322.2	808.7	1.0	0.1	74.1	24.6	0.1	0.5	4.8
1583495	Western Run tributary at Western Run, MD	1	0.0	1.000	321.0	806.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
1583500	Western Run at Western Run, MD	32	107.4	1.000	321.8	807.7	0.8	0.1	71.8	27.2	0.1	0.4	4.5
1583580	Baisman Run at Broadmoor, MD												
1583600	Beaverdam Run at Cockeysville, MD	8	34.0	1.000	310.7	779.0	9.5	12.6	36.7	33.7	0.2	14.5	21.4
1584050	Long Green Creek at Glen Arm, MD	9	20.8	1.000	313.5	785.7	4.0	1.7	80.1	14.2	0.0	2.9	11.8
1584500	Little Gunpowder Falls at Laurel Brook, MD	14	60.8	1.000	320.4	803.2	2.9	0.0	74.8	22.0	0.0	1.1	11.1
1585100	White Marsh Run at White Marsh, MD	4	13.9	1.000	323.0	809.5	27.5	9.4	19.2	29.8	0.7	18.9	38.5
1585200	West Branch Herring Run at Idlewylde, MD	2	4.2	1.000	330.0	827.0	73.9	16.0	0.0	0.0	0.0	41.4	66.3
1585300	Stemmers Run at Rossville, MD	3	7.0	1.000	330.0	827.0	35.3	17.9	25.0	15.6	0.0	30.4	41.4
1585400	Brien Run at Stemmers Run, MD	1	1.7	1.000	330.0	827.0	26.5	24.7	7.9	18.6	0.0	31.1	32.5
1585500	Cranberry Branch near Westminster, MD	1	3.8	1.000	328.0	822.0	2.4	0.0	75.0	21.7	0.8	0.9	10.9
1586000	North Branch Patapsco River at Cedarhurst, MD	19	84.3	1.000	328.0	822.0	2.9	1.9	74.3	20.5	0.1	2.6	11.3
1586210	Beaver Run near Finksburg, MD	6	25.6	1.000	328.0	822.0	5.5	1.2	74.0	18.8	0.0	3.1	14.2
1586610	Morgan Run near Louisville, MD	20	56.6	1.000	326.4	818.2	1.1	0.3	77.1	21.1	0.0	0.7	10.7
1587000	North Branch Patapsco River near Marriottsville, MD	80	302.6	1.000	324.9	814.2	3.3	0.9	66.2	26.6	2.6	2.0	12.3
1587050	Hay Meadow Branch tributary at Poplar Springs, MD	1	1.1	1.000	310.3	778.5	0.0	0.6	99.4	0.0	0.0	0.6	26.2
1587500	South Branch Patapsco River at Henryton, MD	36	125.4	1.000	310.8	780.0	2.9	1.2	75.3	20.6	0.0	2.2	11.2
1588000	Piney Run near Sykesville, MD	5	21.2	1.000	312.9	784.9	2.7	0.5	84.7	10.2	1.9	1.5	13.6
1588500	Patapsco River at Woodstock, MD	130	485.5	1.000	320.0	802.1	3.3	1.1	68.0	25.6	1.8	2.1	12.2
1589000	Patapsco River at Hollofield, MD	145	533.9	1.000	319.2	800.3	3.9	1.1	65.9	27.0	1.6	2.4	12.4

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Com85 (%)	Ag85 (%)	For85 (%)	St85 (%)	IA85 (%)	Res90 (%)	Com90 (%)	Ag90 (%)	For90 (%)	St90 (%)	IA90 (%)	Res97 (%)
1578800	Basin Run at West Nottingham, MD			15.3		2.5							
1579000	Basin Run at Liberty Grove, MD			18.9		2.9							
1580000	Deer Creek at Rocks, MD	0.3	0.0	35.8	0.0	1.0	6.4	0.5	58.1	34.3	0.1	2.4	8.8
1580200	Deer Creek at Kalmia, MD	0.3	0.0	34.7	0.0	1.2	7.2	0.5	58.0	33.5	0.0	2.6	10.2
1581500	Bynum Run at Bel Air, MD	6.3	0.0	22.3	0.0	12.9	31.7	7.8	34.7	18.4	0.2	19.6	38.1
1581700	Winter Run near Benson, MD	0.7	0.0	29.3	0.0	4.6	19.0	0.4	49.1	27.6	0.0	6.4	25.4
1582000	Little Falls at Blue Mount, MD	0.2	0.0	41.0	0.0	1.3	7.6	0.2	51.7	39.4	0.0	2.6	10.4
1582510	Piney Creek near Hereford, MD	0.0	0.0	31.2	0.0	2.4	10.8	0.0	54.2	35.0	0.0	3.3	13.6
1583000	Slade Run near Glyndon, MD	0.4	0.0	46.2	0.0	1.2	5.9	0.2	50.0	42.9	0.0	2.5	4.5
1583100	Piney Run at Dover, MD	0.8	0.0	29.1	0.1	1.9	3.7	0.4	62.5	30.4	0.0	1.9	6.3
1583495	Western Run tributary at Western Run, MD	0.0	0.0	27.5	0.0	0.0	0.0	0.0	97.8	2.0	0.0	0.0	11.0
1583500	Western Run at Western Run, MD	0.4	0.0	34.0	0.0	1.5	6.1	0.1	59.8	31.9	0.0	2.1	8.3
1583580	Baisman Run at Broadmoor, MD			75.3		4.5							
1583600	Beaverdam Run at Cockeysville, MD	11.9	0.0	34.4	0.1	18.0	26.0	11.3	24.3	28.4	0.3	18.9	33.5
1584050	Long Green Creek at Glen Arm, MD	3.2	0.0	19.7	0.0	5.6	12.9	0.9	67.2	18.3	0.0	5.8	15.5
1584500	Little Gunpowder Falls at Laurel Brook, MD	0.9	0.0	28.2	0.0	3.5	14.5	0.2	56.4	28.3	0.0	4.3	17.7
1585100	White Marsh Run at White Marsh, MD	7.2	0.0	26.5	0.0	21.6	44.6	8.3	10.2	23.6	0.0	25.8	52.1
1585200	West Branch Herring Run at Idlewylde, MD	10.5	0.0	7.0	0.0	37.5	65.8	9.8	0.0	7.2	0.0	37.8	65.0
1585300	Stemmers Run at Rossville, MD	9.5	0.0	29.9	0.0	25.3	42.4	9.1	9.2	28.3	0.0	25.4	44.4
1585400	Brien Run at Stemmers Run, MD	27.2	0.0	21.4	0.0	36.8	33.5	25.4	2.8	25.2	0.0	39.4	34.4
1585500	Cranberry Branch near Westminster, MD	1.8	0.0	19.5	1.2	4.2	18.5	0.7	57.6	21.3	1.9	5.5	20.3
1586000	North Branch Patapsco River at Cedarhurst, MD	2.9	0.0	23.0	0.3	5.4	13.6	3.5	57.9	23.3	0.3	6.6	17.9
1586210	Beaver Run near Finksburg, MD	2.3	0.0	26.6	0.0	6.0	18.4	1.8	52.1	26.0	0.1	7.0	26.1
1586610	Morgan Run near Louisville, MD	0.3	0.0	31.6	0.0	3.0	14.0	0.4	54.9	30.1	0.0	4.0	17.5
1587000	North Branch Patapsco River near Marriottsville, MD	1.5	0.0	31.5	2.8	4.6	14.5	1.7	47.1	31.2	3.4	5.5	18.8
1587050	Hay Meadow Branch tributary at Poplar Springs, MD	4.3	0.0	5.9	0.0	10.0	29.7	3.5	60.5	6.3	0.0	10.3	33.5
1587500	South Branch Patapsco River at Henryton, MD	1.2	0.0	31.4	0.1	4.0	13.7	0.8	53.0	29.8	0.1	4.7	20.7
1588000	Piney Run near Sykesville, MD	1.0	0.0	20.5	4.0	4.6	13.9	0.4	56.6	20.8	4.0	4.7	22.0
1588500	Patapsco River at Woodstock, MD	1.3	0.0	32.0	2.0	4.5	14.1	1.3	47.9	31.5	2.3	5.4	19.3
1589000	Patapsco River at Hollofield, MD	1.4	0.0	33.3	1.8	4.7	14.2	1.4	46.4	32.8	2.1	5.6	19.4

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Com97 (%)	Ag97 (%)	For97 (%)	St97 (%)	IA97 (%)	CN70	CN97	Hyd. A (%)	Hyd. B (%)	Hyd. C (%)	Hyd. D (%)	Province
1578800	Basin Run at West Nottingham, MD								0.0			20.8	P
1579000	Basin Run at Liberty Grove, MD								0.0			12.1	P
1580000	Deer Creek at Rocks, MD	0.3	56.1	32.7	0.1	2.6	70.7	72.1	0.1	86.8	10.2	2.9	P
1580200	Deer Creek at Kalmia, MD	0.4	55.4	32.2	0.0	3.1	71.3	72.6	0.0	82.6	14.1	3.3	P
1581500	Bynum Run at Bel Air, MD	8.1	29.1	17.6	0.2	21.8	77.8	78.7	0.0	70.5	5.3	24.2	P
1581700	Winter Run near Benson, MD	0.8	45.8	26.0	0.0	7.9	72.7	73.1	0.0	77.8	14.6	7.6	P
1582000	Little Falls at Blue Mount, MD	0.4	49.5	37.4	0.0	3.3	70.6	71.0	0.0	87.7	9.2	3.1	P
1582510	Piney Creek near Hereford, MD	0.0	54.2	32.1	0.0	3.4	71.5	72.1	0.0	94.4	5.6	0.0	P
1583000	Slade Run near Glyndon, MD	0.9	51.1	42.3	0.0	2.7	67.7	70.0	0.0	99.9	0.1	0.0	P
1583100	Piney Run at Dover, MD	0.4	59.5	29.2	0.0	3.1	71.4	73.3	0.2	87.7	8.7	3.3	P
1583495	Western Run tributary at Western Run, MD	0.0	86.7	2.3	0.0	2.7	75.0	77.7	0.0	100.0	0.0	0.0	P
1583500	Western Run at Western Run, MD	0.2	58.7	30.4	0.0	2.7	71.2	72.8	0.2	85.4	10.3	4.1	P
1583580	Baisman Run at Broadmoor, MD								0.0			1.0	P
1583600	Beaverdam Run at Cockeysville, MD	11.2	19.7	25.3	0.1	21.2	72.8	74.0	0.0	84.4	8.9	6.7	P
1584050	Long Green Creek at Glen Arm, MD	1.0	64.5	18.0	0.0	5.6	73.5	74.8	0.0	83.2	12.2	4.6	P
1584500	Little Gunpowder Falls at Laurel Brook, MD	0.3	54.6	26.6	0.0	5.0	71.7	72.1	0.0	82.6	12.0	5.4	P
1585100	White Marsh Run at White Marsh, MD	13.0	6.9	16.6	0.0	34.9	79.2	81.3	8.9	23.9	64.5	2.7	P
1585200	West Branch Herring Run at Idlewylde, MD	10.0	0.0	4.4	0.0	37.6	78.5	78.9	0.0	62.3	36.3	1.3	P
1585300	Stemmers Run at Rossville, MD	11.1	2.7	22.0	0.0	29.3	80.3	78.5	1.9	16.3	80.5	1.3	W
1585400	Brien Run at Stemmers Run, MD	33.9	2.1	20.2	0.0	45.0	84.1	84.6	7.8	21.8	25.1	45.2	W
1585500	Cranberry Branch near Westminster, MD	0.7	58.8	19.1	1.1	5.9	72.0	73.5	30.8	58.1	5.0	6.1	P
1586000	North Branch Patapsco River at Cedarhurst, MD	4.1	51.5	24.4	0.2	8.6	72.2	73.8	21.0	67.6	5.9	5.5	P
1586210	Beaver Run near Finksburg, MD	2.1	42.4	26.8	0.1	9.4	72.5	72.8	32.4	58.4	3.7	5.6	P
1586610	Morgan Run near Louisville, MD	0.3	53.2	28.5	0.0	4.8	69.6	70.1	52.2	37.4	4.5	6.0	P
1587000	North Branch Patapsco River near Marriottsville, MD	2.3	42.4	30.8	3.2	7.2	72.0	72.7	23.5	65.8	6.5	4.2	P
1587050	Hay Meadow Branch tributary at Poplar Springs, MD	1.5	53.1	6.9	0.0	10.9	73.5	74.0	0.0	94.1	5.9	0.0	P
1587500	South Branch Patapsco River at Henryton, MD	1.5	47.7	27.5	0.0	7.1	68.7	68.7	27.8	64.0	4.6	3.6	P
1588000	Piney Run near Sykesville, MD	0.5	48.8	19.8	4.0	6.9	73.1	73.1	18.7	71.0	5.5	4.8	P
1588500	Patapsco River at Woodstock, MD	2.0	43.0	30.5	2.2	7.2	71.0	71.5	22.9	66.6	6.4	4.1	P
1589000	Patapsco River at Hollofield, MD	1.9	41.5	31.7	2.0	7.4	71.0	71.4	20.8	66.6	8.3	4.3	P

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Years of Record	Area (mi^2)	Perimeter (mi)	Length (mi)	Channel Slope (ft/mi)	Watershed Slope (ft/ft)	Basin Relief (ft)	Lime (%)	High Elev. (%)	Hypso
1589100	East Branch Herbert Run at Arbutus, MD	34	2.42	10.5	3.6	97.4	0.05790	116.2	0.0	0.0	0.33
1589200	Gwynns Falls near Owings Mills, MD	17	4.89	14.0	4.7	34.2	0.05587	131.4	0.0	0.0	0.58
1589240	Gwynns Falls at McDonough, MD	12	19.27	28.0	9.6	28.8	0.06318	180.8	0.0	0.0	0.56
1589300	Gwynns Falls at Villa Nova, MD	36	32.61	40.0	15.9	19.4	0.06068	198.4	0.0	0.0	0.51
1589330	Dead Run at Franklintown, MD	29	5.47	16.7	3.9	45.9	0.05263	122.2	0.0	0.0	0.48
1589440	Jones Fall at Sorrento, MD	34	25.26	32.3	10.6	32.2	0.08167	237.5	0.0	0.0	0.49
1589500	Sawmill Creek at Glen Burnie, MD	30	4.91	14.7	4.7	30.1	0.02750	75.5	0.0	0.0	0.40
1589795	South Fork Jabez Branch at Millersville, MD		1.01			44.8	0.04000	82.3			
1590000	North River near Annapolis, MD	42	8.93	23.7	6.0	24.4	0.08665	110.7	0.0	0.0	0.55
1590500	Bacon Ridge Branch at Chesterfield, MD	35	6.97	19.6	5.3	24.9	0.11030	115.1	0.0	0.0	0.57
1591000	Patuxent River near Unity, MD	55	34.85	46.3	13.2	30.1	0.10645	259.7	0.0	0.0	0.46
1591400	Cattail Creek near Glenwood, MD	21	22.94	32.6	9.6	30.4	0.09419	212.3	0.0	0.0	0.45
1591500	Cattail Creek at Roxbury Mills, MD	12	27.72	37.1	10.2	31.3	0.09381	211.7	0.0	0.0	0.44
1591700	Hawlings River near Sandy Spring, MD	21	26.13	34.9	11.2	26.8	0.06000	172.3	0.0	0.0	0.45
1592000	Patuxent River near Burtonsville, MD	32	127.03	91.7	30.8	12.9	0.09000	314.9	0.0	0.0	0.44
1593350	Little Patuxent River tributary at Guilford Downs, MD	10	1.06	6.2	2.2	66.5	0.05000	90.8	0.0	0.0	0.41
1593500	Little Patuxent River at Guilford, MD	67	38.12	48.9	17.3	16.0	0.06252	141.1	0.0	0.0	0.33
1594000	Little Patuxent River at Savage, MD	46	98.41	73.8	25.0	12.6	0.07582	266.5	0.0	0.0	0.48
1594400	Dorsey Run near Jessup, MD	19	11.86	27.5	8.2	35.6	0.05176	140.4	0.0	0.0	0.37
1594440	Patuxent River near Bowie, MD	22	349.60	165.0	55.9	10.1	0.07366	371.6	0.0	0.0	0.41
1594445	Mill Branch near Mitchellville, MD	10	1.28	8.7	2.6	39.2	0.02770	46.0	0.0	0.0	0.41
1594500	Western Branch near Largo, MD	25	29.53	39.3	11.3	9.9	0.04571	103.9	0.0	0.0	0.47
1594526	Western Branch at Upper Marlboro, MD	10	89.08	71.1	20.3	6.2	0.05202	129.0	0.0	0.0	0.45
1594600	Cocktown Creek near Huntington, MD	19	3.79	12.3	3.3	22.4	0.08602	77.3	0.0	0.0	0.53
1594670	Hunting Creek near Huntingtown, MD	10	9.27	18.8	5.7	18.5	0.08937	96.3	0.0	0.0	0.58
1594710	Killpeck Creek at Huntersville, MD	12	3.27	13.1	4.0	39.4	0.06064	98.6	0.0	0.0	0.67
1594800	St. Leonard Creek near St. Leonard, MD	11	6.82	17.1	5.1	22.3	0.09602	101.9	0.0	0.0	0.60
1594930	Laurel Run at Dobbin Road near Wilson, MD	20	8.26	18.1	6.3	87.8	0.15199	255.1	0.0	100.0	0.30
1594936	North Fork Sand Run near Wilson, MD	20	1.92	10.3	3.2	180.8	0.14094	277.4	0.0	100.0	0.38
1594950	McMillan Fork near Fort Pendleton, MD	11	2.33	10.8	3.1	221.5	0.12347	323.3	0.0	100.0	0.44
1596005	Savage River near Frostburg, MD	13	1.43	8.5	3.4	21.8	0.09877	93.3	0.0	100.0	0.35

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	# First Order Streams	Total Stream Length	Area in MD	2-yr Prec. (in x 100)	100-yr Prec. (in x100)	Res 70 (%)	Com70 (%)	Ag70 (%)	For70 (%)	St70 (%)	IA70 (%)	Res85 (%)
1589100	East Branch Herbert Run at Arbutus, MD	1	3.9	1.000	331.5	852.6	48.5	33.9	0.2	9.9	0.0	49.3	45.4
1589200	Gwynns Falls near Owings Mills, MD	2	7.1	1.000	313.8	786.4	31.4	4.3	49.1	11.9	0.0	15.5	33.7
1589240	Gwynns Falls at McDonough, MD	8	33.1	1.000	312.4	783.1	21.5	7.2	40.0	28.6	0.0	14.2	26.0
1589300	Gwynns Falls at Villa Nova, MD	11	52.0	1.000	312.4	782.9	34.3	7.7	30.3	24.4	0.0	19.7	37.1
1589330	Dead Run at Franklintown, MD	4	11.6	1.000	322.5	819.8	36.5	33.1	16.2	9.2	0.0	43.1	41.6
1589440	Jones Fall at Sorrento, MD	13	44.0	1.000	323.1	809.7	22.6	3.8	34.4	34.2	0.0	12.1	33.3
1589500	Sawmill Creek at Glen Burnie, MD	4	11.4	1.000	319.0	820.0	16.0	20.2	27.4	31.7	0.0	26.0	13.6
1589795	South Fork Jabez Branch at Millersville, MD			1.000									
1590000	North River near Annapolis, MD	4	14.4	1.000	339.2	871.2	5.3	0.0	30.1	64.6	0.0	2.0	9.8
1590500	Bacon Ridge Branch at Chesterfield, MD	4	14.3	1.000	328.7	844.0	5.6	2.8	28.1	63.5	0.0	4.5	5.8
1591000	Patuxent River near Unity, MD	16	67.7	1.000	315.3	790.7	1.0	0.1	77.7	21.2	0.0	0.4	4.9
1591400	Cattail Creek near Glenwood, MD	14	46.9	1.000	321.2	806.2	0.4	1.9	81.3	16.2	0.1	2.0	8.4
1591500	Cattail Creek at Roxbury Mills, MD	16	53.1	1.000	321.9	807.8	1.7	1.7	82.7	13.7	0.2	2.3	10.0
1591700	Hawlings River near Sandy Spring, MD	11	42.2	1.000	324.6	815.3	6.4	0.5	73.0	19.0	0.1	2.8	9.2
1592000	Patuxent River near Burtonsville, MD	63	234.0	1.000	321.6	808.5	3.8	0.5	70.2	23.7	1.4	1.9	9.7
1593350	Little Patuxent River tributary at Guilford Downs, MD	1	2.2	1.000	323.0	810.0	56.2	17.3	12.3	13.5	0.0	36.2	68.0
1593500	Little Patuxent River at Guilford, MD	25	79.6	1.000	320.1	803.7	29.5	6.5	37.2	17.9	0.3	16.9	38.5
1594000	Little Patuxent River at Savage, MD	56	191.5	1.000	321.9	809.3	14.4	3.9	51.4	25.3	0.1	9.0	23.7
1594400	Dorsey Run near Jessup, MD	3	15.3	1.000	367.7	943.6	10.5	20.6	27.3	33.4	0.0	22.0	9.2
1594440	Patuxent River near Bowie, MD	249	693.8	1.000	333.4	845.3	10.8	6.3	45.5	31.2	2.7	9.6	16.3
1594445	Mill Branch near Mitchellville, MD	1	2.5	1.000	348.4	895.6	7.0	0.1	77.9	3.7	0.0	2.7	9.5
1594500	Western Branch near Largo, MD	7	41.4	1.000	338.0	869.1	26.0	5.8	32.5	31.1	0.0	15.1	22.6
1594526	Western Branch at Upper Marlboro, MD	33	142.7	1.000	318.8	819.5	20.2	6.4	38.9	30.5	0.0	13.5	16.4
1594600	Cocktown Creek near Huntington, MD	2	5.6	0.984	323.3	831.7	56.9	0.0	11.9	31.2	0.0	21.6	26.8
1594670	Hunting Creek near Huntingtown, MD	3	13.9	1.000	364.0	936.0	16.1	1.5	10.6	70.9	0.0	7.4	2.3
1594710	Killpeck Creek at Huntersville, MD	2	5.9	1.000	339.0	872.0	23.6	12.1	10.3	54.1	0.0	19.2	2.0
1594800	St. Leonard Creek near St. Leonard, MD	5	16.0	1.000	364.0	936.0	7.9	0.4	10.2	81.6	0.0	3.3	0.4
1594930	Laurel Run at Dobbin Road near Wilson, MD	2	8.6	0.882	258.0	604.0	0.0	0.0	7.9	85.4	0.0	0.0	0.0
1594936	North Fork Sand Run near Wilson, MD	1	3.0	1.000	258.0	604.0	0.0	0.0	9.4	86.5	0.0	0.0	0.0
1594950	McMillan Fork near Fort Pendleton, MD	2	3.6	1.000	258.0	604.0	0.0	0.0	17.1	82.9	0.0	0.0	0.0
1596005	Savage River near Frostburg, MD	1	2.2	1.000	286.0	668.0	3.2	0.0	11.1	85.8	0.0	1.2	2.2

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Com85 (%)	Ag85 (%)	For85 (%)	St85 (%)	IA85 (%)	Res90 (%)	Com90 (%)	Ag90 (%)	For90 (%)	St90 (%)	IA90 (%)	Res97 (%)
1589100	East Branch Herbert Run at Arbutus, MD	17.0	0.0	24.5	0.0	33.8	44.8	21.8	0.0	21.4	0.0	39.0	43.0
1589200	Gwynns Falls near Owings Mills, MD	2.5	0.0	26.5	0.0	14.6	36.2	2.5	27.8	23.4	0.0	17.5	55.9
1589240	Gwynns Falls at McDonough, MD	5.8	0.0	35.1	0.0	16.6	28.7	6.1	18.4	32.6	0.0	19.3	39.2
1589300	Gwynns Falls at Villa Nova, MD	5.2	0.0	30.7	0.0	19.5	38.5	5.6	14.1	28.5	0.0	21.6	46.5
1589330	Dead Run at Franklintown, MD	25.6	0.0	8.4	0.0	41.1	47.7	26.1	5.5	3.1	0.0	43.8	41.3
1589440	Jones Fall at Sorrento, MD	0.5	0.0	35.9	0.0	11.4	38.7	0.5	21.6	30.6	0.0	13.7	41.3
1589500	Sawmill Creek at Glen Burnie, MD	5.4	0.0	47.1	0.0	11.5	23.3	18.1	9.3	43.9	0.0	23.5	28.1
1589795	South Fork Jabez Branch at Millersville, MD					8.2							
1590000	North River near Annapolis, MD	0.0	0.0	60.3	0.0	2.7	11.3	0.0	28.5	58.6	0.0	3.0	18.2
1590500	Bacon Ridge Branch at Chesterfield, MD	0.4	0.0	66.1	0.0	1.5	6.0	0.6	26.8	62.6	0.0	3.7	12.4
1591000	Patuxent River near Unity, MD	0.1	0.0	33.3	0.0	1.4	6.6	0.1	56.1	33.1	0.0	2.1	6.7
1591400	Cattail Creek near Glenwood, MD	0.8	0.0	26.1	0.0	2.9	10.5	0.2	61.1	26.1	0.0	3.0	13.3
1591500	Cattail Creek at Roxbury Mills, MD	0.9	0.0	24.6	0.0	3.5	11.9	0.2	61.7	23.9	0.0	3.4	16.3
1591700	Hawlings River near Sandy Spring, MD	0.8	0.0	27.0	0.1	3.8	15.5	2.0	48.6	25.3	0.1	8.9	19.2
1592000	Patuxent River near Burtonsville, MD	0.5	0.0	32.0	1.8	3.1	14.1	0.6	48.4	30.8	1.8	5.1	17.4
1593350	Little Patuxent River tributary at Guilford Downs, MD	13.2	0.0	5.4	0.0	34.8	69.2	9.4	6.7	5.1	0.0	32.5	64.4
1593500	Little Patuxent River at Guilford, MD	5.6	0.0	20.4	0.5	18.5	41.5	6.3	19.6	18.4	0.6	21.7	47.1
1594000	Little Patuxent River at Savage, MD	3.5	0.0	28.6	0.2	11.0	28.4	3.4	32.0	27.3	0.3	13.3	35.9
1594400	Dorsey Run near Jessup, MD	14.8	0.0	47.6	0.0	16.7	9.5	15.9	12.9	42.8	0.0	19.6	15.7
1594440	Patuxent River near Bowie, MD	2.9	0.0	38.7	1.0	8.6	19.5	3.1	30.7	37.0	1.1	10.7	24.4
1594445	Mill Branch near Mitchellville, MD	1.7	0.0	18.1	0.0	4.5	12.3	2.4	51.2	15.6	0.0	8.0	38.4
1594500	Western Branch near Largo, MD	3.9	0.0	41.6	0.3	11.4	26.0	4.2	23.6	37.6	0.8	13.8	38.7
1594526	Western Branch at Upper Marlboro, MD	3.9	0.0	43.9	0.2	9.5	18.8	4.1	29.0	40.5	0.4	11.8	29.3
1594600	Cocktown Creek near Huntington, MD	2.5	0.0	52.7	0.0	8.7	28.4	2.3	20.9	48.3	0.0	9.0	48.4
1594670	Hunting Creek near Huntingtown, MD	0.5	0.0	76.6	0.0	1.5	4.6	0.6	20.0	73.4	0.0	2.4	13.4
1594710	Killpeck Creek at Huntersville, MD	2.8	0.0	68.6	0.0	4.1	9.2	4.5	21.4	60.4	0.0	7.8	15.5
1594800	St. Leonard Creek near St. Leonard, MD	0.0	0.0	77.8	0.0	0.3	5.7	0.2	16.4	73.1	0.0	1.7	15.2
1594930	Laurel Run at Dobbin Road near Wilson, MD	0.0	0.0	72.6	0.0	1.3	0.0	0.0	7.6	80.8	0.0	1.4	0.7
1594936	North Fork Sand Run near Wilson, MD	0.0	0.0	78.6	0.0	0.9	0.0	0.0	12.9	79.3	0.0	0.9	0.0
1594950	McMillan Fork near Fort Pendleton, MD	0.0	0.0	76.0	0.0	0.6	0.0	0.0	18.9	77.7	0.0	0.4	2.0
1596005	Savage River near Frostburg, MD	0.5	0.0	66.7	15.9	1.0	1.3	0.3	12.5	66.8	16.0	0.8	7.1

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Com97 (%)	Ag97 (%)	For97 (%)	St97 (%)	IA97 (%)	CN70	CN97	Hyd. A (%)	Hyd. B (%)	Hyd. C (%)	Hyd. D (%)	Province
1589100	East Branch Herbert Run at Arbutus, MD	24.6	0.0	8.9	0.0	41.7	83.1	82.5	2.7	14.7	81.1	1.5	P
1589200	Gwynns Falls near Owings Mills, MD	6.8	14.7	16.5	0.0	26.7	73.8	75.2	0.0	86.4	5.9	7.7	P
1589240	Gwynns Falls at McDonough, MD	11.2	12.4	25.9	0.1	27.4	72.6	75.0	0.0	76.8	18.6	4.6	P
1589300	Gwynns Falls at Villa Nova, MD	9.3	9.0	23.9	0.1	27.7	73.7	75.2	0.0	66.8	25.1	8.2	P
1589330	Dead Run at Franklintown, MD	24.9	3.0	8.1	0.0	42.8	83.5	83.4	0.0	17.4	30.4	52.2	P
1589440	Jones Fall at Sorrento, MD	0.9	20.6	26.5	0.0	14.6	70.9	70.8	0.0	83.9	8.9	7.2	P
1589500	Sawmill Creek at Glen Burnie, MD	25.4	7.6	36.0	0.0	28.7	66.8	65.3	33.9	12.5	44.8	8.6	W
1589795	South Fork Jabez Branch at Millersville, MD								0.0	60.9	25.5	3.0	W
1590000	North River near Annapolis, MD	0.3	25.1	54.8	0.0	5.2	70.6	71.7	0.2	84.7	3.9	11.0	W
1590500	Bacon Ridge Branch at Chesterfield, MD	0.8	24.0	60.1	0.0	4.6	71.0	71.4	0.7	82.1	5.4	11.4	W
1591000	Patuxent River near Unity, MD	0.2	51.4	39.1	0.1	2.0	65.7	64.5	14.5	64.5	17.2	3.8	P
1591400	Cattail Creek near Glenwood, MD	0.5	59.3	23.5	0.1	4.3	73.2	73.4	3.2	88.1	4.3	4.4	P
1591500	Cattail Creek at Roxbury Mills, MD	0.4	58.1	21.9	0.1	5.0	73.6	73.4	2.7	88.5	4.3	4.5	P
1591700	Hawlings River near Sandy Spring, MD	1.0	41.2	30.5	0.2	8.3	72.2	71.6	0.0	82.1	5.5	12.4	P
1592000	Patuxent River near Burtonsville, MD	0.4	43.9	32.2	1.8	5.6	70.4	69.7	4.8	80.9	8.2	6.1	P
1593350	Little Patuxent River tributary at Guilford Downs, MD	14.3	0.0	15.5	0.0	32.9	76.2	76.0	0.0	87.4	12.6	0.0	P
1593500	Little Patuxent River at Guilford, MD	8.8	14.0	17.7	0.6	25.2	74.4	74.9	0.0	79.0	12.4	8.6	P
1594000	Little Patuxent River at Savage, MD	4.6	27.8	23.8	0.3	16.5	72.7	73.2	0.0	84.5	7.5	8.0	W
1594400	Dorsey Run near Jessup, MD	28.2	7.8	33.8	0.0	29.3	79.4	79.2	3.3	25.0	24.5	47.0	W
1594440	Patuxent River near Bowie, MD	4.2	27.3	34.8	1.1	12.9	73.3	72.4	5.8	65.8	19.7	8.7	W
1594445	Mill Branch near Mitchellville, MD	4.8	23.8	29.4	0.0	17.6	79.5	75.6	0.0	72.4	9.5	16.9	W
1594500	Western Branch near Largo, MD	5.9	19.4	28.1	0.6	19.0	76.4	77.2	0.4	58.8	25.2	14.9	W
1594526	Western Branch at Upper Marlboro, MD	6.1	23.1	34.7	0.3	17.5	75.6	76.0	0.7	55.3	25.5	18.0	W
1594600	Cocktown Creek near Huntington, MD	1.9	15.3	34.0	0.0	14.6	70.6	69.9	0.4	74.5	13.1	11.9	W
1594670	Hunting Creek near Huntingtown, MD	1.3	17.5	65.1	0.0	5.6	63.4	64.8	1.0	78.9	8.7	11.2	W
1594710	Killpeck Creek at Huntersville, MD	5.7	18.1	55.5	0.0	10.8	71.0	70.1	52.9	19.0	19.3	8.8	W
1594800	St. Leonard Creek near St. Leonard, MD	0.0	14.5	65.1	0.0	4.5	60.0	62.0	6.7	80.3	3.8	9.2	W
1594930	Laurel Run at Dobbin Road near Wilson, MD	0.0	7.4	83.4	0.0	1.1	63.0	63.7	0.0	26.6	66.8	6.6	A
1594936	North Fork Sand Run near Wilson, MD	0.0	14.6	80.9	0.0	0.5	62.6	64.0	0.0	16.3	75.7	8.0	A
1594950	McMillan Fork near Fort Pendleton, MD	0.5	19.1	74.9	0.0	1.3	62.7	64.4	0.0	34.4	64.2	1.4	A
1596005	Savage River near Frostburg, MD	1.3	12.3	62.7	14.4	3.7	68.1	74.0	3.7	42.7	26.3	27.2	A

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Years of Record	Area (mi^2)	Perimeter (mi)	Length (mi)	Channel Slope (ft/mi)	Watershed Slope (ft/ft)	BasinRelief (ft)	Lime (%)	High Elev. (%)	Hypso
1596500	Savage River near Barton, MD	51	48.91	54.5	20.9	64.5	0.20820	905.8	0.0	94.6	0.62
1597000	Crabtree Creek near Swanton, MD	33	16.75	29.5	10.7	117.2	0.19438	921.3	0.0	95.5	0.56
1598000	Savage River at Bloomington, MD	24	115.87	99.5	45.9	46.2	0.22653	1363.4	0.0	85.8	0.62
1599000	Georges Creek at Franklin, MD	70	72.99	57.2	19.6	57.3	0.17102	1181.4	0.0	64.7	0.58
1601500	Wills Creek near Cumberland, MD	70	247.57	107.3	46.5	41.3	0.19835	1205.5	0.0	42.4	0.52
1609000	Town Creek near Oldtown, MD	22	149.23	103.2	46.8	12.5	0.17223	730.4	0.0	7.4	0.33
1609500	Sawpit Run near Oldtown, MD	24	5.00	16.2	6.0	53.5	0.16636	235.6	0.0	0.0	0.54
1610105	Pratt Hollow Tributary at Pratt, MD	15	0.65				0.16000	377.2			
1610150	Bear Creek at Forest Park, MD	18	10.27	22.2	10.0	49.7	0.11542	402.3	0.0	0.0	0.36
1610155	Sideling Hill Creek near Bellegrove, MD	11	102.54	73.3	36.8	20.8	0.14148	632.8	0.0	0.0	0.40
1612500	Little Tonoloway Creek near Hancock, MD	17	17.28	26.3	7.5	82.9	0.14322	397.8	0.0	0.0	0.31
1613150	Ditch Run near Hancock, MD	21	4.60	17.7	6.8	55.0	0.11342	326.2	0.0	0.0	0.67
1614500	Conococheague Creek at Fairview, MD	72	500.32	249.7	68.0	9.4	0.11372	498.1	41.8	0.9	0.24
1617800	Marsh Run at Grimes, MD	35	18.91	35.8	10.1	25.9	0.06475	149.3	99.35	0.0	0.49
1619000	Antietam Creek near Waynesboro, PA	19	94.05	68.6	21.7	45.6	0.11056	489.2	60.26	0.3	0.30
1619475	Dog Creek tributary near Locust Grove, MD	11	0.11	2.2	0.8	242.3	0.08050	81.8	81.72	0.0	0.31
1619500	Antietam Creek near Sharpsburg, MD	72	280.97	135.8	57.9	8.8	0.09806	496.6	73.42	0.1	0.27
1637000	Little Catoctin Creek at Harmony, MD	29	8.76	18.9	6.7	186.2	0.15203	490.3	0.0	0.0	0.41
1637500	Catoctin Creek near Middletown, MD	52	67.30	60.0	25.3	45.6	0.13474	665.5	0.0	0.0	0.43
1637600	Hollow Road Creek near Middletown, MD	10	2.32	9.4	3.1	217.8	0.13042	246.4	0.0	0.0	0.26
1639000	Monocacy River at Bridgeport, MD	58	172.50	104.2	32.4	19.7	0.05663	285.8	14.03	0.0	0.18
1639095	Piney Creek tributary at Taneytown, MD	10	0.61	4.5	1.7	74.3	0.03380	63.7	0.0	0.0	0.55
1639500	Big Pipe Creek at Bruceville, MD	52	102.71	77.0	28.8	15.0	0.09137	305.4	4.57	0.0	0.39
1640000	Little Pipe Creek at Bruceville, MD	30	8.11	20.5	4.9	66.7	0.09645	187.4	76.53	0.0	0.47
1640500	Owens Creek at Lantz, MD	53	6.10	17.2	4.5	198.8	0.12628	505.5	0.0	0.0	0.55
1640700	Owens Creek tributary near Rocky Ridge, MD	10	1.12	6.4	2.1	48.5	0.04022	72.4	0.0	0.0	0.60
1640965	Hunting Creek near Foxville, MD	13	2.19	9.2	3.8	250.6	0.14899	492.1	0.0	0.0	0.58
1640970	Hunting Creek tributary near Foxville, MD	10	3.91	11.9	4.1	156.5	0.11883	591.4	0.0	0.0	0.65
1641000	Hunting Creek at Jimtown, MD	42	18.69	30.5	11.3	128.8	0.13256	745.6	16.23	0.0	0.48
1641500	Fishing Creek near Lewistown, MD	37	7.29	15.1	5.3	242.8	0.13680	730.0	0.0	0.0	0.67

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	# First Order Streams	Total Stream Length	Area in MD	2-yr Prec. (in x 100)	100-yr Prec. (in x100)	Res 70 (%)	Com70 (%)	Ag70 (%)	For70 (%)	St70 (%)	IA70 (%)	Res85 (%)
1596500	Savage River near Barton, MD	17	86.1	1.000	250.3	585.0	0.1	0.1	18.2	81.4	0.1	0.1	0.3
1597000	Crabtree Creek near Swanton, MD	6	26.9	1.000	262.3	614.1	0.3	0.2	11.8	87.8	0.0	0.2	0.7
1598000	Savage River at Bloomington, MD	42	199.1	1.000	256.3	599.6	0.1	0.1	13.1	85.5	0.4	0.1	0.3
1599000	Georges Creek at Franklin, MD	29	118.8	1.000	262.1	612.9	3.9	0.9	9.2	80.3	0.0	2.2	6.7
1601500	Wills Creek near Cumberland, MD	110	417.1	0.220	247.0	576.9	1.7	0.3	15.4	82.2	0.0	1.0	9.7
1609000	Town Creek near Oldtown, MD	89	327.9	0.399	252.0	588.6	0.0	0.2	15.0	84.7	0.0	0.2	0.5
1609500	Sawpit Run near Oldtown, MD	3	12.0	1.000	248.0	579.0	0.0	0.0	10.4	89.6	0.0	0.0	0.0
1610105	Pratt Hollow Tributary at Pratt, MD												
1610150	Bear Creek at Forest Park, MD	7	22.7	0.298	271.0	632.0	0.0	1.4	46.4	52.2	0.0	1.4	0.0
1610155	Sideling Hill Creek near Bellegrove, MD	55	202.0	0.214	273.8	638.9	0.0	0.4	23.2	76.4	0.0	0.4	0.0
1612500	Little Tonoloway Creek near Hancock, MD	10	34.1	0.609	273.3	637.5	0.0	1.7	18.4	79.3	0.0	1.7	0.0
1613150	Ditch Run near Hancock, MD	3	10.5	0.461	270.4	630.6	0.5	0.1	74.8	24.5	0.0	0.3	0.0
1614500	Conococheague Creek at Fairview, MD	236	856.3	0.005	284.2	664.2	1.7	2.0	59.9	35.8	0.1	2.4	4.6
1617800	Marsh Run at Grimes, MD	5	20.0	1.000	291.3	680.8	4.9	1.6	92.2	1.3	0.0	3.2	8.2
1619000	Antietam Creek near Waynesboro, PA	49	161.1	0.074	342.1	799.8	3.6	1.4	51.8	42.5	0.1	2.6	4.3
1619475	Dog Creek tributary near Locust Grove, MD	1	0.0	1.000	292.0	682.0	0.0	0.0	84.7	15.3	0.0	0.0	0.0
1619500	Antietam Creek near Sharpsburg, MD	119	467.3	0.619	307.1	717.8	3.9	2.5	68.6	24.4	0.1	3.6	7.5
1637000	Little Catoctin Creek at Harmony, MD	6	14.7	1.000	295.4	741.7	0.1	0.6	47.4	51.9	0.0	0.6	3.0
1637500	Catoctin Creek near Middletown, MD	29	117.7	1.000	318.0	760.8	0.6	1.0	60.3	37.9	0.0	1.2	2.6
1637600	Hollow Road Creek near Middletown, MD	2	5.2	1.000	295.0	741.0	2.8	4.9	64.9	27.4	0.0	6.0	6.1
1639000	Monocacy River at Bridgeport, MD	89	344.3	0.068	313.8	738.5	1.5	0.8	77.6	19.7	0.1	1.2	2.3
1639095	Piney Creek tributary at Taneytown, MD	1	1.4	1.000	293.0	734.0	16.4	0.0	83.6	0.0	0.0	6.2	19.1
1639500	Big Pipe Creek at Bruceville, MD	50	179.7	1.000	320.1	802.1	0.6	0.0	85.2	14.2	0.0	0.2	4.8
1640000	Little Pipe Creek at Bruceville, MD	4	13.3	1.000	328.0	822.0	15.5	2.0	68.9	11.4	0.3	7.6	17.8
1640500	Owens Creek at Lantz, MD	2	8.6	1.000	375.4	877.6	0.5	0.0	17.4	82.1	0.0	0.2	1.2
1640700	Owens Creek tributary near Rocky Ridge, MD	1	2.5	1.000	293.0	734.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
1640965	Hunting Creek near Foxville, MD	1	2.9	1.000	376.0	879.0	0.0	0.0	2.9	97.1	0.0	0.0	0.0
1640970	Hunting Creek tributary near Foxville, MD	2	6.4	1.000	376.0	879.0	1.1	0.8	24.4	73.1	0.4	1.1	4.7
1641000	Hunting Creek at Jimtown, MD	10	32.5	1.000	376.0	879.0	4.5	0.5	18.4	75.8	0.4	2.1	5.9
1641500	Fishing Creek near Lewistown, MD	4	12.6	1.000	360.7	852.9	0.0	0.0	0.0	100.0	0.0	0.0	0.0

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Com85 (%)	Ag85 (%)	For85 (%)	St85 (%)	IA85 (%)	Res90 (%)	Com90 (%)	Ag90 (%)	For90 (%)	St90 (%)	IA90 (%)	Res97 (%)
1596500	Savage River near Barton, MD	0.3	0.0	76.4	0.6	0.3	0.5	0.2	20.2	76.0	0.7	0.3	1.6
1597000	Crabtree Creek near Swanton, MD	0.4	0.0	77.6	0.0	0.5	0.6	0.3	14.6	82.0	0.0	0.4	2.2
1598000	Savage River at Bloomington, MD	0.2	0.0	79.6	0.8	0.3	0.4	0.2	15.0	79.8	0.8	0.4	1.4
1599000	Georges Creek at Franklin, MD	0.3	0.0	64.4	0.0	3.7	6.0	0.3	11.3	64.0	0.0	3.4	6.7
1601500	Wills Creek near Cumberland, MD	1.4	0.0	69.7	0.1	4.2	10.4	1.5	11.0	69.4	0.1	4.4	12.1
1609000	Town Creek near Oldtown, MD	0.2	0.0	78.0	0.0	0.3	0.5	0.0	20.7	79.4	0.0	0.1	1.8
1609500	Sawpit Run near Oldtown, MD	0.0	0.0	88.9	0.0	0.0	0.0	0.0	10.5	88.6	0.0	0.0	1.2
1610105	Pratt Hollow Tributary at Pratt, MD			97.3		0.0							
1610150	Bear Creek at Forest Park, MD	0.0	0.0	77.8	0.0	0.0	0.0	0.0	18.4	67.8	0.0	3.2	0.6
1610155	Sideling Hill Creek near Bellegrove, MD	0.0	0.0	76.6	0.0	0.0	0.0	0.0	22.9	77.4	0.0	0.5	2.8
1612500	Little Tonoloway Creek near Hancock, MD	0.0	0.0	86.2	0.2	0.0	3.7	0.0	16.5	74.8	0.2	1.4	5.9
1613150	Ditch Run near Hancock, MD	0.0	0.0	72.7	0.0	0.0	3.2	0.0	47.4	47.6	0.0	0.8	7.6
1614500	Conococheague Creek at Fairview, MD	0.5	0.0	32.6	0.0	1.6	10.4	5.4	70.4	40.7	0.0	7.1	11.3
1617800	Marsh Run at Grimes, MD	0.7	0.0	8.3	0.0	3.4	11.5	1.1	75.6	8.1	0.2	5.1	13.4
1619000	Antietam Creek near Waynesboro, PA	0.0	0.0	56.9	0.3	3.9	7.5	0.7	46.7	56.1	0.6	5.9	15.2
1619475	Dog Creek tributary near Locust Grove, MD	0.0	0.0	9.7	0.0	0.0	0.0	0.0	76.6	23.4	0.0	0.0	0.0
1619500	Antietam Creek near Sharpsburg, MD	2.6	0.0	24.8	0.1	4.8	8.8	2.7	61.3	24.4	0.1	5.4	14.1
1637000	Little Catoctin Creek at Harmony, MD	0.0	0.0	54.8	0.0	0.8	6.9	0.0	40.3	52.8	0.0	2.5	11.1
1637500	Catoctin Creek near Middletown, MD	0.1	0.0	46.6	0.0	0.8	4.6	0.2	48.9	45.2	0.0	1.5	8.8
1637600	Hollow Road Creek near Middletown, MD	0.0	0.0	37.6	0.0	1.5	5.3	0.6	58.6	35.6	0.0	1.8	11.2
1639000	Monocacy River at Bridgeport, MD	0.1	0.0	13.1	0.0	0.8	3.4	0.0	84.0	14.0	0.0	0.9	3.5
1639095	Piney Creek tributary at Taneytown, MD	3.8	0.0	2.7	0.0	11.4	14.0	5.2	76.8	3.9	0.0	10.9	47.5
1639500	Big Pipe Creek at Bruceville, MD	0.6	0.0	22.0	0.0	1.8	7.0	0.3	69.8	22.0	0.0	2.5	9.7
1640000	Little Pipe Creek at Bruceville, MD	1.2	0.0	19.5	0.1	6.9	23.0	1.9	47.9	18.0	0.1	11.1	31.8
1640500	Owens Creek at Lantz, MD	0.0	0.0	80.8	0.0	0.5	0.6	0.0	21.5	77.4	0.0	0.4	3.5
1640700	Owens Creek tributary near Rocky Ridge, MD	0.0	0.0	4.7	0.0	0.0	0.0	0.0	97.3	2.7	0.0	0.0	0.7
1640965	Hunting Creek near Foxville, MD	0.0	0.0	96.0	0.0	0.0	1.8	0.0	3.7	94.5	0.0	0.8	1.5
1640970	Hunting Creek tributary near Foxville, MD	0.0	0.0	76.7	0.0	1.2	4.2	0.0	18.7	76.8	0.1	1.1	4.6
1641000	Hunting Creek at Jimtown, MD	0.3	0.0	77.3	0.4	1.8	4.9	1.0	14.1	77.6	0.4	2.3	9.6
1641500	Fishing Creek near Lewistown, MD	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	98.8	0.1	0.2	0.8

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Com97 (%)	Ag97 (%)	For97 (%)	St97 (%)	IA97 (%)	CN70	CN97	Hyd. A (%)	Hyd. B (%)	Hyd. C (%)	Hyd. D (%)	Province
1596500	Savage River near Barton, MD	0.2	19.7	75.5	0.6	0.6	63.4	64.5	0.4	15.5	80.9	3.2	A
1597000	Crabtree Creek near Swanton, MD	0.0	13.7	81.7	0.0	0.5	63.2	63.7	0.0	29.8	69.8	0.4	A
1598000	Savage River at Bloomington, MD	0.1	14.4	79.5	0.8	0.6	59.9	60.7	0.2	21.0	76.8	1.9	A
1599000	Georges Creek at Franklin, MD	0.4	12.1	64.6	0.0	3.6	63.7	64.7	0.0	15.3	76.2	8.5	A
1601500	Wills Creek near Cumberland, MD	1.6	10.1	67.6	0.1	5.3	68.9	66.2	3.1	14.6	78.1	4.3	A
1609000	Town Creek near Oldtown, MD	0.0	20.9	77.1	0.0	0.5	67.9	71.3	9.5	9.4	80.6	0.5	A
1609500	Sawpit Run near Oldtown, MD	0.0	10.7	86.8	0.0	0.4	71.3	71.6	0.0	11.7	83.6	4.7	A
1610105	Pratt Hollow Tributary at Pratt, MD								0.0			0.0	A
1610150	Bear Creek at Forest Park, MD	0.0	17.8	65.9	0.0	3.3	77.2	73.9	0.0	14.6	83.5	1.8	A
1610155	Sideling Hill Creek near Bellegrove, MD	0.1	21.6	74.4	0.0	1.2	73.8	74.4	0.0	14.6	84.3	1.2	A
1612500	Little Tonoloway Creek near Hancock, MD	0.0	15.3	72.8	0.1	2.0	72.8	72.2	0.1	7.6	91.8	0.6	A
1613150	Ditch Run near Hancock, MD	0.0	44.5	42.6	0.0	1.9	78.3	76.2	0.0	1.6	95.7	2.7	A
1614500	Conococheague Creek at Fairview, MD	6.6	59.8	34.5	0.0	7.9	74.2	79.6	0.0	29.5	68.9	1.6	B
1617800	Marsh Run at Grimes, MD	1.2	73.6	7.7	0.2	5.8	76.1	77.4	0.0	96.1	1.6	2.3	B
1619000	Antietam Creek near Waynesboro, PA	0.3	40.7	46.4	0.1	8.4	70.2	71.3	0.0	82.7	17.3	0.0	B
1619475	Dog Creek tributary near Locust Grove, MD	0.0	85.4	14.6	0.0	0.0	73.4	77.4	0.0	90.3	9.7	0.0	B
1619500	Antietam Creek near Sharpsburg, MD	2.7	57.3	22.7	0.1	7.3	73.6	75.3	0.0	89.0	10.1	0.9	B
1637000	Little Catoctin Creek at Harmony, MD	0.0	38.9	49.9	0.0	2.8	69.5	71.1	0.0	93.7	4.9	1.3	B
1637500	Catoctin Creek near Middletown, MD	0.3	46.8	42.9	0.0	2.5	71.7	72.2	0.0	90.4	7.9	1.8	B
1637600	Hollow Road Creek near Middletown, MD	0.9	54.0	34.0	0.0	3.6	73.5	73.3	0.0	91.5	0.6	7.8	B
1639000	Monocacy River at Bridgeport, MD	0.0	79.5	14.0	0.0	0.9	79.0	81.8	0.0	20.6	77.6	1.7	B
1639095	Piney Creek tributary at Taneytown, MD	3.5	45.1	3.8	0.0	19.7	80.0	82.8	0.0	15.9	84.1	0.0	B
1639500	Big Pipe Creek at Bruceville, MD	0.4	66.8	22.0	0.0	3.0	69.2	70.3	50.6	15.0	30.5	3.9	B
1640000	Little Pipe Creek at Bruceville, MD	1.4	35.2	20.2	0.1	15.4	67.2	68.1	66.2	13.0	20.4	0.4	P
1640500	Owens Creek at Lantz, MD	0.0	20.2	75.8	0.0	1.1	67.3	68.5	0.0	98.6	0.9	0.5	B
1640700	Owens Creek tributary near Rocky Ridge, MD	0.0	96.3	3.0	0.0	0.2	80.0	83.6	0.0	7.3	91.9	0.8	B
1640965	Hunting Creek near Foxville, MD	0.0	3.1	95.4	0.0	0.4	64.3	64.7	0.0	66.8	29.1	4.1	B
1640970	Hunting Creek tributary near Foxville, MD	0.0	18.1	77.2	0.0	1.2	68.7	68.4	0.0	71.0	20.3	8.7	B
1641000	Hunting Creek at Jimtown, MD	1.7	13.1	73.5	0.3	4.3	66.0	66.7	0.0	64.7	27.7	7.6	B
1641500	Fishing Creek near Lewistown, MD	0.0	0.0	98.0	0.1	0.2	57.0	57.1	0.0	71.5	28.5	0.0	B

Station Number	Station Name	Years of Record	Area (mi^2)	Perimeter (mi)	Length (mi)	Channel Slope (ft/mi)	Watershed Slope (ft/ft)	Basin Relief (ft)	Lime (%)	High Elev. (%)	Hypso
1642000	Monocacy River near Frederick, MD	33	665.10	213.2	62.3	6.4	0.08206	428.3	14.14	0.0	0.25
1642400	Dollyhyde Creek at Libertytown, MD	10	2.67	9.3	3.0	49.8	0.07329	101.3	0.0	0.0	0.48
1642500	Lingamore Creek near Frederick, MD	49	82.37	61.7	20.6	24.2	0.09365	295.3	0.0	0.0	0.47
1643000	Monocacy River at Jug Bridge near Frederick, MD	70	820.00	207.3	72.4	5.2	0.08291	520.4	15.73	0.0	0.28
1643500	Bennett Creek at Park Mills, MD	49	63.31	54.0	18.4	29.5	0.10535	304.8	0.0	0.0	0.30
1644420	Bucklodge Branch tributary near Barnesville, MD	10	0.28	2.9	1.0	91.9	0.07449	68.9	0.0	0.0	0.57
1645000	Seneca Creek near Dawsonville, MD	69	102.05	65.1	24.3	14.2	0.07600	256.7	0.0	0.0	0.37
1645200	Watts Branch at Rockville, MD	30	3.70	11.0	3.2	58.8	0.05605	111.8	0.0	0.0	0.49
1646550	Little Falls Branch near Bethesda, MD	40	4.09	12.6	3.6	57.3	0.05174	126.8	0.0	0.0	0.53
1647720	North Branch Rock Creek near Norbeck, MD	11	9.68	19.7	6.4	26.4	0.05331	134.7	0.0	0.0	0.54
1649500	North East Branch Anacostia River at Riverdale, MD	61	73.35	66.6	17.8	27.2	0.07059	211.4	0.0	0.0	0.37
1650050	Northwest Branch Anacostia River at Norwood, MD	10	2.51				0.05000	90.8			
1650085	Nursery Run at Cloverly, MD	10	0.35				0.08000	83.9			
1650190	Batchellors Run at Oakdale, MD	10	0.49	4.0	1.4	109.0	0.06000	84.7	0.0	0.0	0.56
1650500	Northwest Branch Anacostia River near Colesville, MD	62	21.21	29.1	9.5	20.4	0.06496	150.2	0.0	0.0	0.48
1651000	Northwest Branch Anacostia River near Hyattsville, MD	61	49.42	58.6	20.5	20.3	0.06941	298.9	0.0	0.0	0.54
1653500	Henson Creek at Oxon Hill, MD	30	17.37	31.1	10.1	24.5	0.06079	168.7	0.0	0.0	0.65
1653600	Piscataway Creek at Piscataway, MD	34	39.75	50.3	15.9	15.8	0.05524	189.0	0.0	0.0	0.69
1658000	Mattawoman Creek near Pomonkey, MD	36	55.61	73.7	20.7	10.4	0.02942	142.2	0.0	0.0	0.71
1660900	Wolf Den Branch near Cedarville, MD	13	1.98	11.7	3.4	17.0	0.01344	45.8	0.0	0.0	0.70
1660920	Zekiah Swamp Run near Newtown, MD	16	81.02	73.6	19.3	10.8	0.03440	137.0	0.0	0.0	0.69
1660930	Clark Run near Bel Alton, MD	11	11.21				0.04000	105.2			
1661000	Chaptico Creek at Chaptico, MD	25	10.50	30.5	8.5	21.1	0.05740	124.6	0.0	0.0	0.73
1661050	St. Clements Creek near Clements, MD	30	18.21	31.2	8.4	13.9	0.04937	103.1	0.0	0.0	0.61
1661430	Glebe Branch at Valley Lee, MD	11	0.41	2.0	0.8	56.7	0.02290	21.3	0.0	0.0	0.34
1661500	St. Marys River at Great Mills, MD	53	25.28	34.8	10.0	13.7	0.02690	93.7	0.0	0.0	0.61
3075450	Little Youghiogheny River tributary at Deer Park, MD	11	0.55	3.9	1.3	106.7	0.06632	76.3	0.0	100.0	0.47
3075500	Youghiogheny River near Oakland, MD	59	133.58	97.6	29.3	7.0	0.11647	239.6	0.0	100.0	0.24
3075600	Toliver Run tributary near Hoyes Run, MD	21	0.52	3.9	1.4	206.3	0.07148	175.8	0.0	100.0	0.65
3076500	Youghiogheny River at Friendsville, MD	76	293.72	140.5	48.8	15.6	0.11548	1149.6	0.0	98.7	0.60

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	# First Order Streams	Total Stream Length	Area in MD	2-yr Prec. (in x 100)	100-yr Prec. (in x100)	Res 70 (%)	Com70 (%)	Ag70 (%)	For70 (%)	St70 (%)	IA70 (%)	Res85 (%)
1642000	Monocacy River near Frederick, MD	312	1220.3	0.659	318.0	772.4	1.3	0.5	72.9	24.4	0.1	0.9	3.9
1642400	Dollyhyde Creek at Libertytown, MD	2	4.7	1.000	309.0	776.0	0.0	0.0	96.9	3.1	0.0	0.0	0.3
1642500	Lingamore Creek near Frederick, MD	52	174.8	1.000	308.0	773.4	0.9	0.1	78.7	17.3	0.4	0.4	4.0
1643000	Monocacy River at Jug Bridge near Frederick, MD	405	1546.9	0.723	315.3	770.5	1.8	0.9	73.4	22.7	0.1	1.4	4.7
1643500	Bennett Creek at Park Mills, MD	46	142.4	1.000	307.0	769.5	2.2	0.8	73.4	23.1	0.0	1.7	6.5
1644420	Bucklodge Branch tributary near Barnesville, MD	1	0.5	1.000	300.0	752.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
1645000	Seneca Creek near Dawsonville, MD	64	223.2	1.000	305.6	766.2	6.5	2.1	65.0	24.3	0.1	4.4	15.1
1645200	Watts Branch at Rockville, MD	3	6.7	1.000	305.0	766.0	31.7	17.5	39.9	9.5	0.0	27.2	25.8
1646550	Little Falls Branch near Bethesda, MD	2	4.9	0.967	342.0	878.0	68.2	24.0	0.0	0.7	0.0	46.3	68.7
1647720	North Branch Rock Creek near Norbeck, MD	5	16.1	1.000	308.0	773.5	16.9	0.2	66.5	13.5	0.0	6.6	32.6
1649500	North East Branch Anacostia River at Riverdale, MD	44	131.4	1.000	332.4	854.8	31.3	19.0	8.8	34.0	0.9	28.6	29.9
1650050	Northwest Branch Anacostia River at Norwood, MD												
1650085	Nursery Run at Cloverly, MD												
1650190	Batchellors Run at Oakdale, MD	1	1.1	1.000	305.0	766.0	0.0	0.0	88.7	0.0	0.0	0.0	21.6
1650500	Northwest Branch Anacostia River near Colesville, MD	11	37.1	1.000	309.1	777.1	26.3	1.0	44.1	19.4	0.0	10.9	29.8
1651000	Northwest Branch Anacostia River near Hyattsville, MD	16	72.0	0.969	311.7	793.2	54.5	7.5	18.9	13.3	0.0	27.2	51.5
1653500	Henson Creek at Oxon Hill, MD	7	23.3	1.000	325.4	836.2	51.1	24.3	0.5	18.3	0.0	40.9	41.4
1653600	Piscataway Creek at Piscataway, MD	16	57.5	1.000	357.3	917.8	26.1	8.9	21.8	37.8	0.2	17.5	12.8
1658000	Mattawoman Creek near Pomonkey, MD	31	96.1	1.000	302.3	777.3	16.4	1.9	21.7	58.6	0.1	7.8	10.9
1660900	Wolf Den Branch near Cedarville, MD	1	3.6	1.000	287.4	739.1	24.3	0.0	3.3	72.4	0.0	9.2	0.0
1660920	Zekiah Swamp Run near Newtown, MD	43	143.3	1.000	306.0	786.8	16.2	0.9	21.4	53.9	5.0	6.9	8.1
1660930	Clark Run near Bel Alton, MD												
1661000	Chaptico Creek at Chaptico, MD	5	18.0	1.000	339.0	872.0	21.5	0.0	22.8	55.7	0.0	8.2	7.1
1661050	St. Clements Creek near Clements, MD	7	31.2	1.000	320.0	823.0	15.1	0.3	28.6	56.0	0.0	6.0	5.8
1661430	Glebe Branch at Valley Lee, MD	0	0.0	1.000	334.0	858.0	82.6	0.0	17.4	0.0	0.0	31.4	8.4
1661500	St. Marys River at Great Mills, MD	15	48.2	1.000	334.0	858.0	9.3	2.2	12.8	75.5	0.0	5.4	8.1
3075450	Little Youghiogheny River tributary at Deer Park, MD	1	1.2	1.000	246.0	575.0	0.0	0.0	0.0	100.0	0.0	0.0	0.3
3075500	Youghiogheny River near Oakland, MD	69	234.5	0.610	248.5	581.0	2.3	0.6	42.3	53.7	0.5	1.3	3.3
3075600	Toliver Run tributary near Hoyes Run, MD	1	0.0	1.000	245.9	574.7	0.0	0.0	35.9	64.1	0.0	0.0	0.0
3076500	Youghiogheny River at Friendsville, MD	126	466.1	0.770	235.5	550.7	1.6	0.3	30.3	63.4	2.8	0.9	2.8

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Com85 (%)	Ag85 (%)	For85 (%)	St85 (%)	IA85 (%)	Res90 (%)	Com90 (%)	Ag90 (%)	For90 (%)	St90 (%)	IA90 (%)	Res97 (%)
1642000	Monocacy River near Frederick, MD	0.5	0.0	28.0	0.0	1.7	5.3	0.4	65.3	27.7	0.0	2.2	7.5
1642400	Dollyhyde Creek at Libertytown, MD	0.0	0.0	6.8	0.0	0.1	1.3	0.0	92.7	6.0	0.0	0.5	5.7
1642500	Lingamore Creek near Frederick, MD	0.2	0.0	26.4	0.3	1.3	6.9	0.3	64.9	25.4	0.5	2.6	12.8
1643000	Monocacy River at Jug Bridge near Frederick, MD	1.0	0.0	27.0	0.1	2.4	6.4	0.9	64.2	26.5	0.1	3.1	9.3
1643500	Bennett Creek at Park Mills, MD	0.3	0.0	38.3	0.0	2.0	8.2	0.3	53.9	35.5	0.0	2.6	11.2
1644420	Bucklodge Branch tributary near Barnesville, MD	0.0	0.0	15.2	0.0	0.0	0.0	0.0	82.8	17.2	0.0	0.0	0.0
1645000	Seneca Creek near Dawsonville, MD	2.4	0.0	29.3	0.4	8.3	19.5	3.1	42.0	27.2	1.1	11.6	25.8
1645200	Watts Branch at Rockville, MD	18.3	0.0	13.6	0.0	26.2	23.4	23.2	28.5	11.7	0.0	30.4	27.0
1646550	Little Falls Branch near Bethesda, MD	13.1	0.0	5.2	0.0	32.4	67.6	13.9	0.0	5.0	0.0	33.6	64.4
1647720	North Branch Rock Creek near Norbeck, MD	0.3	0.0	23.2	0.0	9.9	42.7	0.5	24.2	20.4	0.0	14.3	45.5
1649500	North East Branch Anacostia River at Riverdale, MD	6.2	0.0	37.9	0.1	18.9	31.0	6.5	11.3	34.4	0.2	21.4	34.5
1650050	Northwest Branch Anacostia River at Norwood, MD			33.6		5.1							
1650085	Nursery Run at Cloverly, MD			66.2		3.8							
1650190	Batchellors Run at Oakdale, MD	0.0	0.0	4.4	0.0	5.4	24.7	0.0	40.0	16.0	0.0	14.6	21.0
1650500	Northwest Branch Anacostia River near Colesville, MD	1.3	0.0	26.3	0.0	11.6	37.6	1.7	17.8	25.5	0.0	16.9	47.1
1651000	Northwest Branch Anacostia River near Hyattsville, MD	3.8	0.0	20.7	0.1	22.3	54.2	4.2	7.9	19.7	0.1	25.1	57.7
1653500	Henson Creek at Oxon Hill, MD	10.0	0.0	34.2	0.0	26.5	40.9	10.3	3.2	31.9	0.0	28.2	47.0
1653600	Piscataway Creek at Piscataway, MD	0.7	0.0	56.0	0.2	7.7	16.3	0.6	19.5	51.8	0.2	9.9	23.2
1658000	Mattawoman Creek near Pomonkey, MD	2.1	0.0	67.1	0.1	5.0	15.4	2.4	17.6	61.6	0.2	7.1	21.2
1660900	Wolf Den Branch near Cedarville, MD	0.0	0.0	81.8	0.0	0.0	10.0	0.0	10.4	74.9	0.0	4.6	12.3
1660920	Zekiah Swamp Run near Newtown, MD	1.4	0.0	62.6	0.2	4.0	11.3	1.5	23.3	58.8	0.3	5.3	12.4
1660930	Clark Run near Bel Alton, MD			59.2		6.4							
1661000	Chaptico Creek at Chaptico, MD	0.2	0.0	56.3	0.0	1.9	11.8	0.4	37.0	49.6	0.0	3.3	14.9
1661050	St. Clements Creek near Clements, MD	0.1	0.0	58.1	0.0	1.8	7.8	0.0	34.8	55.9	0.0	2.3	11.5
1661430	Glebe Branch at Valley Lee, MD	0.0	0.0	20.2	0.0	2.1	33.4	0.0	24.0	42.5	0.0	8.4	36.9
1661500	St. Marys River at Great Mills, MD	1.4	0.0	72.1	1.4	4.0	10.7	2.3	13.5	68.0	1.4	6.1	15.6
3075450	Little Youghiogheny River tributary at Deer Park, MD	0.0	0.0	95.3	0.0	0.1	2.9	0.0	4.4	90.7	0.0	0.7	7.1
3075500	Youghiogheny River near Oakland, MD	0.6	0.0	44.3	0.4	1.6	5.3	0.9	45.0	44.4	0.5	2.5	8.1
3075600	Toliver Run tributary near Hoyes Run, MD	0.0	0.0	61.2	0.0	0.0	0.0	0.0	44.5	55.5	0.0	0.0	0.0
3076500	Youghiogheny River at Friendsville, MD	0.5	0.0	60.6	3.6	1.3	5.0	0.6	27.7	59.1	3.8	2.1	7.5

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Com97 (%)	Ag97 (%)	For97 (%)	St97 (%)	IA97 (%)	CN70	CN97	Hyd. A (%)	Hyd. B (%)	Hyd. C (%)	Hyd. D (%)	Province
1642000	Monocacy River near Frederick, MD	0.5	63.1	27.1	0.0	2.8	71.9	73.4	18.1	33.9	44.7	3.3	P
1642400	Dollyhyde Creek at Libertytown, MD	0.0	89.6	4.7	0.0	1.4	66.4	72.2	0.0	67.9	31.0	1.1	P
1642500	Lingamore Creek near Frederick, MD	0.5	61.8	23.4	0.3	3.9	64.3	66.2	6.2	73.7	16.0	4.0	P
1643000	Monocacy River at Jug Bridge near Frederick, MD	1.2	61.7	25.6	0.1	4.0	70.7	72.1	14.3	44.7	37.8	3.2	P
1643500	Bennett Creek at Park Mills, MD	0.8	48.1	37.4	0.0	3.9	63.1	61.7	0.0	72.5	22.0	5.5	B
1644420	Bucklodge Branch tributary near Barnesville, MD	0.0	70.0	30.0	0.0	0.0	67.0	65.5	0.0	36.8	48.1	15.1	B
1645000	Seneca Creek near Dawsonville, MD	3.9	31.2	31.7	1.1	14.3	69.7	69.9	0.0	79.9	11.0	9.1	B
1645200	Watts Branch at Rockville, MD	22.8	26.6	8.9	0.0	31.6	76.8	78.0	0.0	81.8	3.1	15.1	P
1646550	Little Falls Branch near Bethesda, MD	13.5	0.0	1.0	0.0	35.3	78.7	77.2	0.0	97.5	0.9	1.6	P
1647720	North Branch Rock Creek near Norbeck, MD	0.5	17.8	28.8	0.1	15.9	72.7	70.8	0.0	80.4	3.5	16.1	P
1649500	North East Branch Anacostia River at Riverdale, MD	8.2	8.9	29.9	0.2	24.8	78.1	77.9	3.4	32.1	43.7	20.3	W
1650050	Northwest Branch Anacostia River at Norwood, MD								0.0			7.2	P
1650085	Nursery Run at Cloverly, MD								0.0			4.0	P
1650190	Batchellors Run at Oakdale, MD	0.0	27.6	37.6	0.8	6.7	74.3	66.9	0.0	90.1	4.7	5.2	P
1650500	Northwest Branch Anacostia River near Colesville, MD	0.7	9.2	27.2	0.1	20.1	71.9	70.8	0.0	86.5	3.7	9.8	P
1651000	Northwest Branch Anacostia River near Hyattsville, MD	3.9	4.1	18.6	0.1	27.8	75.1	74.4	1.9	41.4	38.9	17.8	W
1653500	Henson Creek at Oxon Hill, MD	12.0	2.2	23.4	0.0	34.8	82.1	81.4	0.3	46.6	30.6	22.5	W
1653600	Piscataway Creek at Piscataway, MD	1.2	17.6	48.3	0.2	11.6	78.1	76.2	1.0	52.7	32.5	13.7	W
1658000	Mattawoman Creek near Pomonkey, MD	3.8	15.8	55.4	0.1	10.0	74.6	75.2	0.3	24.7	52.2	22.5	W
1660900	Wolf Den Branch near Cedarville, MD	0.0	9.5	64.2	0.0	6.2	72.7	73.2	0.0	34.5	53.5	11.2	W
1660920	Zekiah Swamp Run near Newtown, MD	2.4	22.7	56.8	0.2	6.7	76.1	75.4	1.2	36.6	42.5	19.3	W
1660930	Clark Run near Bel Alton, MD								0.9	31.6	48.7	18.2	W
1661000	Chaptico Creek at Chaptico, MD	0.9	34.9	47.9	0.0	4.6	75.0	76.7	19.9	36.9	29.4	13.8	W
1661050	St. Clements Creek near Clements, MD	0.1	31.8	55.0	0.0	3.4	74.7	75.6	15.3	38.3	31.0	15.4	W
1661430	Glebe Branch at Valley Lee, MD	0.0	25.4	37.6	0.0	9.2	82.8	79.1	1.4	55.2	35.9	7.2	W
1661500	St. Marys River at Great Mills, MD	4.9	10.9	63.4	1.7	9.4	72.1	74.0	8.2	21.7	56.6	13.4	W
3075450	Little Youghiogheny River tributary at Deer Park, MD	0.0	2.8	87.7	0.0	1.8	64.0	65.2	0.0	0.0	63.7	36.3	A
3075500	Youghiogheny River near Oakland, MD	1.4	42.8	43.2	0.4	3.5	68.7	70.9	0.0	21.5	63.5	15.0	A
3075600	Toliver Run tributary near Hoyes Run, MD	0.0	44.4	55.6	0.0	0.0	68.1	71.6	0.0	79.1	15.5	5.3	A
3076500	Youghiogheny River at Friendsville, MD	1.1	26.5	57.5	3.7	3.1	67.3	68.6	0.4	35.8	53.3	10.5	A

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Years of Record	Area (mi^2)	Perimeter (mi)	Length (mi)	Channel Slope (ft/mi)	Watershed Slope (ft/ft)	Basin Relief (ft)	Lime (%)	High Elev. (%)	Hypso
3076505	Youghiogheny River Tributary near Friendsville, MD	11	0.21				0.20000	259.7			
3076600	Bear Creek at Friendsville, MD	35	48.84	49.4	17.1	65.6	0.16886	928.1	0.0	96.3	0.63
3077700	North Branch Casselman River tributary at Foxtown, MD	11	1.07	7.8	2.4	140.0	0.08474	164.2	0.0	100.0	0.47
3078000	Casselman River at Grantsville, MD	52	63.37	61.2	24.5	30.2	0.11771	508.0	0.0	100.0	0.50

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	# First Order Streams	Total Stream Length	Area in MD	2-yr Prec. (in x 100)	100-yr Prec. (in x100)	Res70 (%)	Com70 (%)	Ag70 (%)	For70 (%)	St70 (%)	IA70 (%)	Res85 (%)
3076505	Youghiogheny River Tributary near Friendsville, MD												
3076600	Bear Creek at Friendsville, MD	22	81.2	1.000	224.3	524.7	0.4	0.4	37.3	61.9	0.0	0.5	0.5
3077700	North Branch Casselman River tributary at Foxtown, MD	1	2.3	1.000	238.0	557.0	0.0	0.0	0.4	99.6	0.0	0.0	0.0
3078000	Casselman River at Grantsville, MD	17	83.0	0.943	238.4	557.2	0.4	0.1	24.0	73.5	0.9	0.2	0.8

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Com85 (%)	Ag85 (%)	For85 (%)	St85 (%)	IA85 (%)	Res90 (%)	Com90 (%)	Ag90 (%)	For90 (%)	St90 (%)	IA90 (%)	Res97 (%)
3076505	Youghiogheny River Tributary near Friendsville, MD			72.5		0.0							
3076600	Bear Creek at Friendsville, MD	0.1	0.0	59.9	0.0	0.3	1.8	0.2	37.2	58.3	0.0	0.9	3.2
3077700	North Branch Casselman River tributary at Foxtown, MD	0.0	0.0	95.4	0.0	0.0	0.0	0.0	0.3	92.9	0.0	0.0	1.0
3078000	Casselman River at Grantsville, MD	0.4	0.0	64.9	1.0	0.8	1.1	0.3	26.3	63.6	1.3	0.8	3.3

Appendix 1: Watershed Properties for USGS Stream Gages in Maryland and Delaware (continued)

Station Number	Station Name	Com97 (%)	Ag97 (%)	For97 (%)	St97 (%)	IA97 (%)	CN70	CN97	Hyd. A (%)	Hyd. B (%)	Hyd. C (%)	Hyd. D (%)	Province
3076505	Youghiogheny River Tributary near Friendsville, MD								0.0			6.0	A
3076600	Bear Creek at Friendsville, MD	0.2	31.2	62.9	0.0	1.3	68.8	69.4	0.0	35.3	62.9	1.8	A
3077700	North Branch Casselman River tributary at Foxtown, MD	0.0	0.3	91.8	0.0	0.2	60.1	60.0	0.0	70.5	19.0	10.5	A
3078000	Casselman River at Grantsville, MD	0.4	25.2	62.6	1.3	1.4	65.9	66.9	0.4	20.2	66.8	12.6	A

APPENDIX 2
FLOOD FREQUENCY RESULTS FOR USGS GAGES IN MARYLAND

Appendix 2: Flood Frequency Results for USGS Stream Gages in Maryland and Delaware (all flows are in ft^3/s)

Station Number	Station Name	Years of Record	1.25	1.50	2	5	10	25	50	100	200	500
1483200	Blackbird Creek at Blackbird, DE	47	84	109	145	264	368	531	678	849	1,050	1,360
1483500	Leipsic River near Cheswold, DE	33	125	161	216	414	608	947	1,290	1,710	2,260	3,190
1483720	*Puncheon Branch at Dover, DE		91	115	148	258	354	507	646	810	1,000	1,310
1484000	Murderkill River near Felton, DE	31	191	241	312	540	737	1,050	1,330	1,650	2,040	2,640
1484002	*Murderkill River Tributary near Felton, DE		12	15	19	32	45	66	87	113	146	200
1484050	*Pratt Branch near Felton, DE		38	48	62	112	158	236	312	404	518	709
1484100	Beaverdam Branch at Houston, DE	42	33	41	51	80	103	134	159	187	216	259
1484300	*Sowbridge Branch near Milton, DE		25	29	36	56	72	98	120	146	176	223
1484500	Stockley Branch at Stockly, DE	57	45	56	70	114	152	209	261	320	387	493
1485000	Pocomoke River near Willards, MD	50	530	609	715	1,030	1,290	1,670	2,000	2,380	2,800	3,460
1485500	Nassawango Creek near Snow Hill, MD	49	348	447	586	1,030	1,410	1,990	2,510	3,110	3,790	4,860
1486000	Manokin Branch near Princess Anne, MD	46	82	107	142	248	333	458	565	682	812	1,000
1486100	Andrews Branch near Delmar, MD	10	55	75	90	143	191	272	347	439	560	741
1486980	*Toms Dam Branch near Greenwood, DE		25	31	38	59	75	98	117	137	159	191
1487000	Nanticoke River near Bridgeville, DE	56	380	487	643	1,160	1,630	2,390	3,090	3,930	4,940	6,560
1487900	Meadow Branch near Delmar, DE	9	64	68	77	106	140	207	278	370	490	710
1488500	Marshyhope Creek near Adamsville, DE	54	583	778	1,050	1,900	2,580	3,580	4,430	5,360	6,390	7,890
1489000	Faulkner Branch near Federalsburg, MD	42	106	172	241	558	873	1,420	1,940	2,590	3,380	4,670
1490000	Chicamacomico River near Salem, MD	29	138	175	227	401	558	814	1,050	1,340	1,690	2,250
1490600	Meredith Branch Near Sandtown, DE	10	134	164	208	356	491	715	931	1,190	1,510	2,040
1490800	Oldtown Branch at Goldsboro, MD	10	111	139	176	289	379	512	626	752	893	1,100
1491000	Choptank River near Greensboro, MD	52	1,040	1,380	1,860	3,340	4,550	6,320	7,830	9,500	11,300	14,100
1491010	*Sangston Prong near Whiteleysburg, DE		35	47	66	145	232	404	595	860	1,220	1,920
1491050	Spring Branch near Greensboro, MD	10	41	51	66	120	172	265	357	475	625	880
1492000	Beaverdam Branch at Matthews, MD	32	151	210	271	538	802	1,270	1,740	2,345	3,110	4,440
1492050	Gravel Run at Beulah, MD	10	64	87	111	215	317	497	679	910	1,200	1,720
1492500	Sallie Harris Creek near Carmicheal, MD	30	114	155	219	452	680	1,070	1,460	1,930	2,520	3,510
1492550	Mill Creek near Skipton, MD	11	76	92	113	186	252	362	466	593	748	1,000
1493000	*Unicorn Branch near Millington, MD		183	244	332	626	883	1,290	1,650	2,080	2,570	3,340
1493500	Morgan Creek near Kennedyville, MD	49	187	258	372	845	1,370	2,410	3,550	5,120	7,270	11,300
1494000	Southeast Creek at Church Hill, DE	14	287	362	471	835	1,160	1,690	2,190	2,780	3,500	4,660
1495000	Big Elk Creek at Elk Mills, MD	68	1,761	2,306	2,877	4,929	6,659	9,316	11,670	14,370	17,470	22,280
1495500	Little Elk Creek at Childs, MD	10	1,241	1,469	1,709	2,543	3,233	4,287	5,219	6,291	7,527	9,457
1496000	Northeast River at Leslie, MD	37	1,006	1,260	1,527	2,523	3,400	4,808	6,111	7,663	9,514	12,510
1496200	Principio Creek near Principio Furnace, MD	27	567	813	1,072	2,175	3,239	5,066	6,847	9,054	11,770	16,340
1577940	Broad Creek tributary at Whiteford, MD	15	91	121	153	297	443	711	989	1,354	1,832	2,692
1578500	Octoraro Creek near Rising Sun, MD	19	2,500	3,423	4,391	8,508	12,530	19,540	26,510	35,310	46,380	65,420

Appendix 2: Flood Frequency Results for USGS Stream Gages in Maryland and Delaware (all flows are in ft^3/s) **(continued)**

Station Number	Station Name	Years of Record	1.25	1.50	2	5	10	25	50	100	200	500
1578800	Basin Run at West Nottingham, MD	10	281	314	364	556	725	1,030	1,340	1,750	2,256	3,140
1579000	Basin Run at Liberty Grove, MD	23	444	552	720	1,350	1,980	3,130	4,350	6,000	8,114	12,000
1580000	Deer Creek at Rocks, MD	73	2,417	3,011	3,633	5,693	7,325	9,710	11,740	13,990	16,490	20,240
1580200	Deer Creek at Kalmia, MD	11	2,885	3,680	4,514	7,577	10,230	14,410	18,210	22,670	27,920	36,260
1581500	Bynum Run at Bel Air, MD	25	589	822	1,066	2,026	2,891	4,290	5,582	7,114	8,925	11,820
1581700	Winter Run near Benson, MD	32	1,414	2,002	2,618	4,897	6,819	9,737	12,280	15,140	18,350	23,210
1582000	Little Falls at Blue Mount, MD	56	1,500	1,883	2,285	3,643	4,736	6,356	7,750	9,313	11,070	13,730
1582510	Piney Creek near Hereford, MD	14	89	125	185	439	729	1,320	1,990	2,920	4,192	6,643
1583000	Slade Run near Glyndon, MD	34	100	126	154	251	330	449	553	670	803	1,006
1583100	Piney Run at Dover, MD	10	394	558	729	1,455	2,153	3,348	4,513	5,957	7,740	10,730
1583495	Western Run tributary at Western Run, MD	10	48	62	86	178	274	454	647	900	1,239	1,857
1583500	Western Run at Western Run, MD	55	1,231	1,691	2,174	4,324	6,510	10,470	14,550	19,870	26,740	38,980
1583580	Baisman Run at Broadmoor, MD	13	92	116	152	282	407	629	848	1,120	1,469	2,073
1583600	Beaverdam Run at Cockeysville, MD	16	717	886	1,064	1,674	2,173	2,926	3,584	4,332	5,184	6,495
1584050	Long Green Creek at Glen Arm, MD	24	370	536	710	1,482	2,253	3,618	4,987	6,723	8,914	12,680
1584500	Little Gunpowder Falls at Laurel Brook, MD	59	1,708	2,272	2,864	5,020	6,852	9,682	12,200	15,090	18,420	23,580
1585100	White Marsh Run at White Marsh, MD	28	759	1,027	1,307	2,346	3,242	4,638	5,889	7,337	9,010	11,620
1585200	West Branch Herring Run at Idlewylde, MD	31	357	478	604	1,061	1,446	2,036	2,556	3,151	3,829	4,872
1585300	Stemmers Run at Rossville, MD	29	788	1,011	1,244	2,066	2,749	3,788	4,702	5,744	6,936	8,772
1585400	Brien Run at Stemmers Run, MD	29	188	255	327	648	979	1,590	2,230	3,070	4,170	6,160
1585500	Cranberry Branch near Westminster, MD	51	114	178	245	576	934	1,610	2,325	3,271	4,512	6,742
1586000	North Branch Patapsco River at Cedarhurst, MD	54	1,522	1,920	2,338	4,078	5,762	8,700	11,630	15,370	20,110	28,370
1586210	Beaver Run near Finksburg, MD	17	434	575	723	1,278	1,762	2,529	3,226	4,045	5,004	6,525
1586610	Morgan Run near Louisville, MD	17	686	950	1,227	2,317	3,302	4,904	6,391	8,163	10,270	13,650
1587000	North Branch Patapsco River near Marriottsville, MD	26	2,268	2,932	3,628	6,333	8,787	12,820	16,630	21,240	26,820	36,010
1587050	Hay Meadow Branch tributary at Poplar Springs, MD	11	62	78	104	190	270	408	544	710	913	1,258
1587500	South Branch Patapsco River at Henryton, MD	31	1,505	2,007	2,534	4,860	7,220	11,500	15,930	21,710	29,240	42,720
1588000	Piney Run near Sykesville, MD	43	332	496	668	1,516	2,443	4,225	6,151	8,752	12,240	18,660
1588500	Patapsco River at Woodstock, MD	10	9,761	11,718	13,770	20,140	24,930	31,660	37,170	43,130	49,590	59,010

Appendix 2: Flood Frequency Results for USGS Stream Gages in Maryland and Delaware (all flows are in ft^3/s) **(continued)**

Station Number	Station Name	Years of Record	1.25	1.50	2	5	10	25	50	100	200	500
1589000	Patapsco River at Hollofield, MD	23	4,866	6,828	8,886	18,360	28,260	46,630	65,930	91,450	125,000	185,700
1589100	East Branch Herbert Run at Arbutus, MD	34	436	537	643	1,037	1,382	1,933	2,441	3,045	3,765	4,929
1589200	Gwynns Falls near Owings Mills, MD	17	141	221	305	799	1,429	2,830	4,559	7,171	11,080	19,270
1589240	Gwynns Falls at McDonough, MD	12	579	892	1,220	3,046	5,277	10,030	15,670	23,930	35,900	60,090
1589300	Gwynns Falls at Villa Nova, MD	36	903	1,239	1,592	3,186	4,834	7,866	11,030	15,210	20,680	30,540
1589330	Dead Run at Franklintown, MD	29	935	1,195	1,467	2,560	3,581	5,307	6,981	9,055	11,620	15,960
1589440	Jones Fall at Sorrento, MD	34	525	748	983	2,188	3,578	6,407	9,646	14,250	20,770	33,590
1589500	Sawmill Creek at Glen Burnie, MD	40	48	60	77	125	162	216	260	308	360	435
1589795	South Fork Jabez Branch at Millersville, MD	13	36	53	83	213	362	659	987	1,440	2,050	3,180
1590000	North River near Annapolis, MD	42	82	110	139	278	429	720	1,040	1,480	2,080	3,210
1590500	Bacon Ridge Branch at Chesterfield, MD	35	112	156	202	397	586	912	1,230	1,635	2,140	2,990
1591000	Patuxent River near Unity, MD	55	771	1,133	1,512	3,393	5,478	9,548	14,010	20,130	28,450	44,080
1591400	Cattail Creek near Glenwood, MD	21	1,446	1,806	2,184	3,370	4,265	5,521	6,548	7,652	8,844	10,570
1591500	Cattail Creek at Roxbury Mills, MD	12	479	661	852	1,743	2,688	4,472	6,379	8,941	12,360	18,670
1591700	Hawlings River near Sandy Spring, MD	21	766	1,056	1,359	2,598	3,758	5,708	7,577	9,865	12,660	17,290
1592000	Patuxent River near Burtonsville, MD	32	1,767	2,148	2,548	3,937	5,089	6,846	8,398	10,180	12,230	15,430
1593350	Little Patuxent River tributary at Guilford Downs, MD	10	87	126	166	346	526	845	1,167	1,575	2,092	2,985
1593500	Little Patuxent River at Guilford, MD	67	874	1,144	1,426	2,580	3,673	5,541	7,367	9,645	12,480	17,300
1594000	Little Patuxent River at Savage, MD	46	2,007	2,600	3,221	5,705	8,016	11,900	15,650	20,270	25,950	35,490
1594400	Dorsey Run near Jessup, MD	19	324	386	451	683	876	1,180	1,440	1,750	2,110	2,680
1594440	Patuxent River near Bowie, MD	31	3,260	4,050	5,150	8,710	11,800	16,700	21,200	26,500	32,600	42,500
1594445	Mill Branch near Mitchellville, MD	10	93	123	154	278	391	580	759	977	1,240	1,680
1594500	Western Branch near Largo, MD	25	638	762	892	1,270	1,545	1,910	2,200	2,510	2,830	3,280
1594526	Western Branch at Upper Marlboro, MD	19	1,070	1,450	2,040	4,390	6,880	11,600	16,600	23,300	32,100	48,300
1594600	Cocktown Creek near Huntington, MD	19	71	105	142	327	537	958	1,430	2,085	2,990	4,730
1594670	Hunting Creek near Huntingtown, MD	10	156	208	262	452	609	846	1,050	1,290	1,550	1,950
1594710	Killpeck Creek at Huntersville, MD	12	123	140	158	209	244	290	326	363	402	457
1594800	St. Leonard Creek near St. Leonard, MD	14	62	77	98	159	208	282	345	416	496	616
1594930	Laurel Run at Dobbin Road near Wilson, MD	20	245	299	356	545	696	918	1,109	1,323	1,563	1,926
1594936	North Fork Sand Run near Wilson, MD	20	63	89	116	247	387	652	936	1,318	1,830	2,772
1594950	McMillan Fork near Fort Pendleton, MD	11	61	78	96	168	235	348	456	590	754	1,030

Appendix 2: Flood Frequency Results for USGS Stream Gages in Maryland and Delaware (all flows are in ft^3/s) **(continued)**

Station Number	Station Name	Years of Record	1.25	1.50	2	5	10	25	50	100	200	500
1596005	Savage River near Frostburg, MD	13	32	40	51	85	112	154	189	229	274	343
1596500	Savage River near Barton, MD	51	970	1,196	1,433	2,310	3,075	4,293	5,414	6,743	8,322	10,870
1597000	Crabtree Creek near Swanton, MD	33	305	391	481	840	1,176	1,740	2,286	2,960	3,793	5,196
1598000	Savage River at Bloomington, MD	24	2,185	2,790	3,425	5,859	8,046	11,610	14,960	18,990	23,840	31,790
1599000	Georges Creek at Franklin, MD	70	1,210	1,507	1,819	2,926	3,859	5,301	6,589	8,080	9,809	12,520
1601500	Wills Creek near Cumberland, MD	70	3,939	4,969	6,050	10,370	14,410	21,230	27,850	36,060	46,230	63,460
1609000	Town Creek near Oldtown, MD	22	2,410	3,095	3,813	6,536	8,956	12,860	16,500	20,840	26,020	34,430
1609500	Sawpit Run near Oldtown, MD	24	187	223	262	393	502	666	810	974	1,163	1,456
1610105	Pratt Hollow Tributary at Pratt, MD	15	50	57	66	92	110	137	159	183	209	248
1610150	Bear Creek at Forest Park, MD	18	218	294	372	664	915	1,306	1,656	2,062	2,531	3,264
1610155	Sideling Hill Creek near Bellegrove, MD	11	2,192	3,018	3,885	7,289	10,360	15,360	20,000	25,540	32,120	42,720
1612500	Little Tonoloway Creek near Hancock, MD	17	315	412	514	893	1,222	1,741	2,212	2,763	3,409	4,432
1613150	Ditch Run near Hancock, MD	21	154	194	236	382	501	681	838	1,016	1,219	1,530
1614500	Conococheague Creek at Fairview, MD	72	5,394	6,456	7,570	11,330	14,370	18,900	22,830	27,290	32,330	40,070
1617800	Marsh Run at Grimes, MD	35	58	79	101	188	270	405	533	689	878	1,189
1619000	Antietam Creek near Waynesboro, PA	19	886	1,163	1,454	2,586	3,610	5,290	6,868	8,773	11,070	14,820
1619475	Dog Creek tributary near Locust Grove, MD	11	11	16	21	44	68	112	158	218	296	436
1619500	Antietam Creek near Sharpsburg, MD	72	1,581	2,078	2,600	4,521	6,177	8,770	11,110	13,830	17,010	22,000
1637000	Little Catoctin Creek at Harmony, MD	29	263	400	544	1,245	2,000	3,425	4,935	6,941	9,580	14,350
1637500	Catoctin Creek near Middletown, MD	52	1,438	1,911	2,406	4,320	6,038	8,827	11,420	14,530	18,240	24,250
1637600	Hollow Road Creek near Middletown, MD	10	143	187	233	411	571	832	1,075	1,367	1,717	2,288
1639000	Monocacy River at Bridgeport, MD	58	6,341	7,394	8,498	11,930	14,520	18,170	21,190	24,460	28,040	33,290
1639095	Piney Creek tributary at Taneytown, MD	10	69	83	103	162	209	282	347	419	501	628
1639500	Big Pipe Creek at Bruceville, MD	52	2,202	2,755	3,335	5,685	7,903	11,690	15,400	20,040	25,840	35,760
1640000	Little Pipe Creek at Bruceville, MD	30	221	314	412	848	1,289	2,081	2,888	3,927	5,257	7,588
1640500	Owens Creek at Lantz, MD	53	179	275	376	874	1,418	2,457	3,571	5,063	7,043	10,650
1640700	Owens Creek tributary near Rocky Ridge, MD	10	107	134	163	266	353	486	606	744	904	1,155
1640965	Hunting Creek near Foxville, MD	13	59	86	114	249	394	668	960	1,350	1,867	2,813
1640970	Hunting Creek tributary near Foxville, MD	10	146	231	321	791	1,329	2,400	3,589	5,227	7,462	11,660
1641000	Hunting Creek at Jimtown, MD	42	510	672	842	1,411	1,858	2,504	3,044	3,634	4,279	5,227

Appendix 2: Flood Frequency Results for USGS Stream Gages in Maryland and Delaware (all flows are in ft^3/s) **(continued)**

Station Number	Station Name	Years of Record	1.25	1.50	2	5	10	25	50	100	200	500
1641500	Fishing Creek near Lewistown, MD	37	68	100	134	308	505	899	1,341	1,959	2,814	4,457
1642000	Monocacy River near Frederick, MD	33	13,010	14,919	16,920	22,640	26,690	32,090	36,330	40,770	45,430	52,000
1642400	Dollyhyde Creek at Libertytown, MD	10	217	274	360	659	937	1,410	1,880	2,440	3,141	4,323
1642500	Lingamore Creek near Frederick, MD	49	1,601	2,023	2,465	4,134	5,611	7,994	10,210	12,850	16,010	21,140
1643000	Monocacy River at Jug Bridge near Frederick, MD	70	12,750	15,503	18,390	27,580	34,630	44,700	53,060	62,200	72,220	86,980
1643500	Bennett Creek at Park Mills, MD	49	1,468	1,935	2,424	4,606	6,842	10,940	15,220	20,870	28,280	41,720
1644420	Bucklodge Branch tributary near Barnesville, MD	10	49	61	79	140	195	287	376	483	613	829
1645000	Seneca Creek near Dawsonville, MD	69	1,704	2,301	2,927	5,795	8,798	14,410	20,350	28,280	38,830	58,170
1645200	Watts Branch at Rockville, MD	30	341	476	618	1,206	1,765	2,714	3,632	4,764	6,152	8,471
1646550	Little Falls Branch near Bethesda, MD	40	464	661	868	1,592	2,170	3,003	3,692	4,437	5,240	6,398
1647720	North Branch Rock Creek near Norbeck, MD	11	423	556	766	1,590	2,460	4,090	5,840	8,130	11,214	16,852
1649500	North East Branch Anacostia River at Riverdale, MD	45?	3,260	3,900	4,720	6,980	8,640	10,900	12,800	14,700	16,800	19,800
1650050	Northwest Branch Anacostia River at Norwood, MD	10	326	422	575	1,210	1,900	3,260	4,790	6,950	9,929	15,660
1650085	Nursery Run at Cloverly, MD	10	38	53	79	200	351	681	1,080	1,680	2,578	4,440
1650190	Batchellors Run at Oakdale, MD	10	88	111	148	280	411	643	880	1,180	1,563	2,236
1650500	Northwest Branch Anacostia River near Colesville, MD	62	790	1,016	1,254	2,257	3,236	4,958	6,688	8,900	11,720	16,650
1651000	Northwest Branch Anacostia River near Hyattsville, MD	43?	2,580	3,200	4,070	6,940	9,470	13,500	17,200	21,700	27,000	35,400
1653500	Henson Creek at Oxon Hill, MD	30	753	970	1,200	1,990	2,650	3,650	4,530	5,520	6,660	8,390
1653600	Piscataway Creek at Piscataway, MD	42	586	770	1,060	2,240	3,540	6,060	8,830	12,600	17,900	27,800
1658000	Mattawoman Creek near Pomonkey, MD	45	638	910	1,330	2,920	4,480	7,160	9,770	13,000	17,000	23,500
1660900	Wolf Den Branch near Cedarville, MD	13	72	102	132	271	414	677	951	1,310	1,780	2,620
1660920	Zekiah Swamp Run near Newtown, MD	24	902	1,090	1,350	2,210	2,970	4,190	5,340	6,710	8,350	11,000
1660930	Clark Run near Bel Alton, MD	11	240	312	430	954	1,560	2,810	4,280	6,470	9,650	16,100
1661000	Chaptico Creek at Chaptico, MD	25	195	272	352	750	1,200	2,080	3,070	4,460	6,380	10,100
1661050	St. Clements Creek near Clements, MD	38	320	410	560	2,300	3,650	4,700	5,400	6,000	6,600	7,300
1661430	Glebe Branch at Valley Lee, MD	11	16	20	26	46	64	94	122	156	198	266
1661500	St. Marys River at Great Mills, MD	61	479	648	912	1,930	2,990	4,920	6,930	9,540	12,900	19,000
3075450	Little Youghiogheny River tributary at Deer Park, MD	11	15	19	25	42	57	79	99	122	147	187
3075500	Youghiogheny River near Oakland, MD	59	2,769	3,405	4,071	6,285	8,047	10,640	12,860	15,330	18,110	22,290
3075600	Toliver Run tributary near Hoyes Run, MD	21	18	23	29	51	72	107	140	182	233	319

Appendix 2: Flood Frequency Results for USGS Stream Gages in Maryland and Delaware (all flows are in ft^3/s) **(continued)**

Station Number	Station Name	Years of Record	1.25	1.50	2	5	10	25	50	100	200	500
3076500	Youghiogheny River at Friendsville, MD	76	4,547	5,405	6,304	8,813	10,540	12,780	14,490	16,250	18,050	20,530
3076505	Youghiogheny River Tributary near Friendsville, MD	11	9	11	13	19	23	28	33	37	42	48
3076600	Bear Creek at Friendsville, MD	35	961	1,191	1,432	2,184	2,749	3,539	4,184	4,876	5,623	6,703
3077700	North Branch Casselman River tributary at Foxtown, MD	11	31	37	46	72	92	121	146	175	207	255
3078000	Casselman River at Grantsville, MD	52	1,382	1,653	1,937	2,916	3,722	4,944	6,019	7,251	8,664	10,860

APPENDIX 3
FIXED REGION REGRESSION EQUATIONS FOR MARYLAND

The Fixed Region regression equations are summarized for each hydrologic region and then a report is provided that describes the development of the equations.

Fixed Region Regression Equations for the Eastern Coastal Plain Region

The following equations are based on 28 stations in Maryland and Delaware with drainage area (DA) ranging from 0.91 to 113.7 square miles, percent A soils (S_A) ranging from 0.0 to 78.8 percent, and land slope (LSLOPE) ranging from 0.00250 to 0.0160 ft/ft. All variables are statistically significant at the 5-percent level of significance except LSLOPE for flood discharges less than the 5-year event but LSLOPE is included in the regression equations for consistency. The equations, standard error of estimate in percent, and equivalent years of record are as follows:

Eastern Coastal Plain Fixed Region Regression Equation	Standard error (percent)	Equivalent years of record
$Q_{1.25} = 41.53\ DA^{0.815}\ (SA+1)^{-0.139}\ LSLOPE^{0.115}$	32.4	4.6
$Q_{1.50} = 78.75\ DA^{0.824}\ (SA+1)^{-0.144}\ LSLOPE^{0.194}$	32.3	4.1
$Q_{2} = 134.0\ DA^{0.836}\ (SA+1)^{-0.158}\ LSLOPE^{0.249}$	32.8	4.4
$Q_{5} = 477.5\ DA^{0.847}\ (SA+1)^{-0.184}\ LSLOPE^{0.385}$	35.1	7.0
$Q_{10} = 924.3\ DA^{0.844}\ (SA+1)^{-0.196}\ LSLOPE^{0.445}$	36.7	9.7
$Q_{25} = 1860.4\ DA^{0.834}\ (SA+1)^{-0.212}\ LSLOPE^{0.499}$	39.3	13
$Q_{50} = 2941.5\ DA^{0.824}\ (SA+1)^{-0.222}\ LSLOPE^{0.531}$	41.6	15
$Q_{100} = 4432.9\ DA^{0.812}\ (SA+1)^{-0.230}\ LSLOPE^{0.557}$	44.2	17
$Q_{200} = 6586.3\ DA^{0.800}\ (SA+1)^{-0.237}\ LSLOPE^{0.582}$	47.2	18
$Q_{500} = 10{,}587\ DA^{0.783}\ (SA+1)^{-0.247}\ LSLOPE^{0.610}$	51.6	19

Fixed Region Regression Equations for the Western Coastal Plain Region

The following equations are based on 24 stations in the Western Coastal Plain region of Maryland with drainage area (DA) ranging from 0.41 to 349.6 square miles, impervious area ranging from 0.0 to 36.8 percent, and the sum of the percentage of C and D soils ranging from 13 to 74.7 percent.

Drainage area (DA) and sum of percentage C and D soils (S_{CD}) are significant at the 5-percent level (p-level) for all recurrence intervals. Impervious area (IA) is statistically significant at the 10-percent level up to the 100-year event (Q_{100}). For Q_{200} and Q_{500}, the p-level for IA is 0.1237 and 0.1763, respectively, but this variable was retained in the equations for consistency. The equations, standard error of estimate in percent, and equivalent years of record are as follows:

Western Coastal Plain Fixed Region Regression Equation	Standard error (percent)	Equivalent years of record
$Q_{1.25} = 5.18\ DA^{0.694}\ (IA+1)^{0.382}\ (S_{CD}+1)^{0.414}$	39.0	3.6
$Q_{1.50} = 6.73\ DA^{0.682}\ (IA+1)^{0.374}\ (S_{CD}+1)^{0.429}$	36.4	3.6
$Q_{2} = 7.61\ DA^{0.678}\ (IA+1)^{0.362}\ (S_{CD}+1)^{0.475}$	33.2	4.6
$Q_{5} = 10.5\ DA^{0.665}\ (IA+1)^{0.290}\ (S_{CD}+1)^{0.612}$	38.2	6.7
$Q_{10} = 13.1\ DA^{0.653}\ (IA+1)^{0.270}\ (S_{CD}+1)^{0.669}$	42.7	8.2
$Q_{25} = 17.5\ DA^{0.634}\ (IA+1)^{0.264}\ (S_{CD}+1)^{0.719}$	48.1	10
$Q_{50} = 21.2\ DA^{0.621}\ (IA+1)^{0.263}\ (S_{CD}+1)^{0.751}$	54.0	11
$Q_{100} = 25.6\ DA^{0.608}\ (IA+1)^{0.262}\ (S_{CD}+1)^{0.781}$	61.2	11
$Q_{200} = 30.5\ DA^{0.596}\ (IA+1)^{0.261}\ (S_{CD}+1)^{0.812}$	69.6	10
$Q_{500} = 37.9\ DA^{0.579}\ (IA+1)^{0.261}\ (S_{CD}+1)^{0.849}$	82.5	10

Fixed Region Regression Equations for Rural Watersheds in the Piedmont and Blue Ridge Regions

The following equations are based on 53 rural stations in the Piedmont and Blue Ridge Regions with drainage area (DA) ranging from 0.11 to 820 square miles, percentage of carbonate/limestone rock (LIME) ranging from zero to 81.7 percent and percentage of forest cover ranging from 2.7 to 100 percent. Drainage area (DA) and percentage of carbonate/limestone rock (LIME) were significant at the 5-percent level of significance for all recurrence intervals. Forest cover is significant at the 5-percent level for the 10-year flood and less and significant at the 10-percent level for the 25-year flood. Forest cover is not statistically significant above the 25-year flood but was retained in the equations for consistency. The equations, the standard error of estimate in percent, and the equivalent years of record are as follows:

Piedmont (Rural) Fixed Region Regression Equation	Standard error (percent)	Equivalent years of record
$Q_{1.25} = 287.1\ DA^{0.774}\ (LIME+1)^{-0.118}\ (FOR+1)^{-0.418}$	42.1	2.8
$Q_{1.50} = 327.3\ DA^{0.758}\ (LIME+1)^{-0.121}\ (FOR+1)^{-0.358}$	37.6	3.1
$Q_{2} = 396.9\ DA^{0.743}\ (LIME+1)^{-0.124}\ (FOR+1)^{-0.332}$	35.6	3.7
$Q_{5} = 592.5\ DA^{0.705}\ (LIME+1)^{-0.133}\ (FOR+1)^{-0.237}$	31.4	9.0
$Q_{10} = 751.1\ DA^{0.682}\ (LIME+1)^{-0.138}\ (FOR+1)^{-0.183}$	30.9	14
$Q_{25} = 996.0\ DA^{0.655}\ (LIME+1)^{-0.145}\ (FOR+1)^{-0.122}$	32.2	20
$Q_{50} = 1{,}218.8\ DA^{0.635}\ (LIME+1)^{-0.150}\ (FOR+1)^{-0.082}$	34.5	23
$Q_{100} = 1{,}471.1\ DA^{0.617}\ (LIME+1)^{-0.154}\ (FOR+1)^{-0.045}$	37.5	24
$Q_{200} = 1{,}760.7\ DA^{0.600}\ (LIME+1)^{-0.159}\ (FOR+1)^{-0.009}$	41.0	25
$Q_{500} = 2{,}215.4\ DA^{0.577}\ (LIME+1)^{-0165}\ (FOR+1)^{0.035}$	46.3	25

Fixed Region Regression Equations for Urban Watersheds in the Piedmont Region

The regression equations for urban watersheds in the Piedmont Region were not updated in the current analysis. The equations listed below were taken from Moglen and others (2006). For the 16 watersheds used to derive the Piedmont urban equations, drainage area (DA) ranges from 0.49 to 102.05 square miles and impervious area ranges from 10 to 37.5 percent. The equations, standard error of estimate in percent, and equivalent years of record are as follows:

Piedmont (Urban) Fixed Region Regression Equation	Standard error (percent)	Equivalent years of record
$Q_{1.25} = 17.85\ DA^{0.652}\ (IA+1)^{0.635}$	41.7	3.3
$Q_{1.50} = 24.66\ DA^{0.648}\ (IA+1)^{0.631}$	36.9	3.8
$Q_{2} = 37.01\ DA^{0.635}\ (IA+1)^{0.588}$	35.1	4.5
$Q_{5} = 94.76\ DA^{0.624}\ (IA+1)^{0.499}$	28.5	13
$Q_{10} = 169.2\ DA^{0.622}\ (IA+1)^{0.435}$	26.2	24
$Q_{25} = 341.0\ DA^{0.619}\ (IA+1)^{0.349}$	26.0	38
$Q_{50} = 562.4\ DA^{0.619}\ (IA+1)^{0.284}$	27.7	44
$Q_{100} = 898.3\ DA^{0.619}\ (IA+1)^{0.222}$	30.7	45
$Q_{200} = 1413\ DA^{0.621}\ (IA+1)^{0.160}$	34.8	44
$Q_{500} = 2529\ DA^{0.623}\ (IA+1)^{0.079}$	41.2	40

Fixed Region Regression Equations for the Appalachian Plateau Region

The regression equations for the Appalachian Plateau Region were not updated in the current analysis. The equations listed below were taken from Moglen and others (2006). The equations are based on 23 stations in Maryland with drainage area (DA) ranging from 0.52 to 293.7 square miles and land slope (LSLOPE) ranging from 0.06632 to 0.22653 ft/ft. One station, 03076505, was an outlier and eliminated from the regression analysis. Basin relief, channel slope and basin shape have relatively high correlations with drainage areas of 0.78, -0.77 and 0.62, respectively, and were not statistically significant in the regression equations. The equations, standard error of estimate in percent, and equivalent years of record are as follows

Appalachian Plateau Fixed Region Regression Equation	Standard error (percent)	Equivalent years of record
$Q_{1.25} = 70.25\ DA^{0.837}\ LSLOPE^{0.327}$	23.6	5.7
$Q_{1.50} = 87.42\ DA^{0.837}\ LSLOPE^{0.321}$	21.9	5.9
$Q_{2} = 101.41\ DA^{0.834}\ LSLOPE^{0.300}$	20.7	7.1
$Q_{5} = 179.13\ DA^{0.826}\ LSLOPE^{0.314}$	21.6	12
$Q_{10} = 255.75\ DA^{0.821}\ LSLOPE^{0.340}$	24.2	14
$Q_{25} = 404.22\ DA^{0.812}\ LSLOPE^{0.393}$	29.1	15
$Q_{50} = 559.80\ DA^{0.806}\ LSLOPE^{0.435}$	33.1	16
$Q_{100} = 766.28\ DA^{0.799}\ LSLOPE^{0.478}$	37.4	15
$Q_{200} = 1046.9\ DA^{0.793}\ LSLOPE^{0.525}$	41.8	15
$Q_{500} = 1565.0\ DA^{0.784}\ LSLOPE^{0.589}$	48.0	15

An Update of Regional Regression Equations for Maryland

Wilbert O. Thomas, Jr. and Glenn E. Moglen

Maryland Hydrology Panel
July 30, 2010

Revised September 3, 2010

The following report describes the development of updated regression equations for the Eastern and Western Coastal Plain Regions and for rural watersheds in the Piedmont and Blue Ridge Regions. The regression equations for urban watersheds in the Piedmont Region and regression equations for the Appalachian Plateau are the same as those given in the August 2006 version of the Hydrology Panel report.

An Update of Regional Regression Equations for Maryland

Wilbert O. Thomas, Jr. and Glenn E. Moglen

Background

The last update of regional regression equations for Maryland streams by the U.S. Geological Survey was by Dillow (1996) using annual peak flow data through 1990. Dillow (1996) defined regression equations for five hydrologic regions (Appalachian Plateau, Blue Ridge, Piedmont and Western and Eastern Coastal Plain) as shown in Figure A3.1. Moglen and others (2006) evaluated alternative statistical methods for estimating peak flow frequency in Maryland by comparing Fixed Region equations (similar to Dillow (1996)), the Region of Influence Method and the method of L-moments. The recommendation by Moglen and others (2006) was to use the Fixed Region regression for estimating flood discharges for bridge and culvert design in Maryland because these equations resulted in the lowest standard errors of estimate. For the Piedmont Region, two sets of regression equations were developed for rural and urban watersheds. The Fixed Region regression equations are also documented in Appendix 3 of "Application of Hydrologic Methods in Maryland" prepared by the Maryland Hydrology Panel (2006) and available in GISHydro2000 (Moglen, 2007).

Since 2006, the Maryland State Highway Administration has been updating regression equations for Maryland as new data become available. In 2007, the Fixed Region regression equations were updated for the Eastern Coastal Plain Region as SSURGO soils data became available. In 2009, the Fixed Region regression equations were updated for the Western Coastal Plain Region as SSURGO soils data became available for that region. In 2010, the Maryland Hydrology Panel defined a new carbonate/limestone rock map for Maryland that included areas in the Blue Ridge and Piedmont Regions. This prompted the update of Fixed Region regression equations for rural watersheds in the Blue Ridge and Piedmont Regions. Also in 2010, a slightly revised version of the SSURGO soils data became available for the coastal plain regions and those equations were updated again. The revised regression equations are now incorporated into a 2010 revised version of the Hydrology Panel report and GISHydro2000.

The Fixed Region regression equations for the Appalachian Plateau and for the urban watersheds in the Piedmont Region were not updated in the current analysis (2010) and the equations given in Moglen and others (2006) and the Maryland Hydrology Panel report (2006) are still applicable. In summary, this report describes updated regression equations for:

- The Eastern and Western Coastal Plain Regions,
- Rural watersheds in the Blue Ridge and Piedmont Regions.

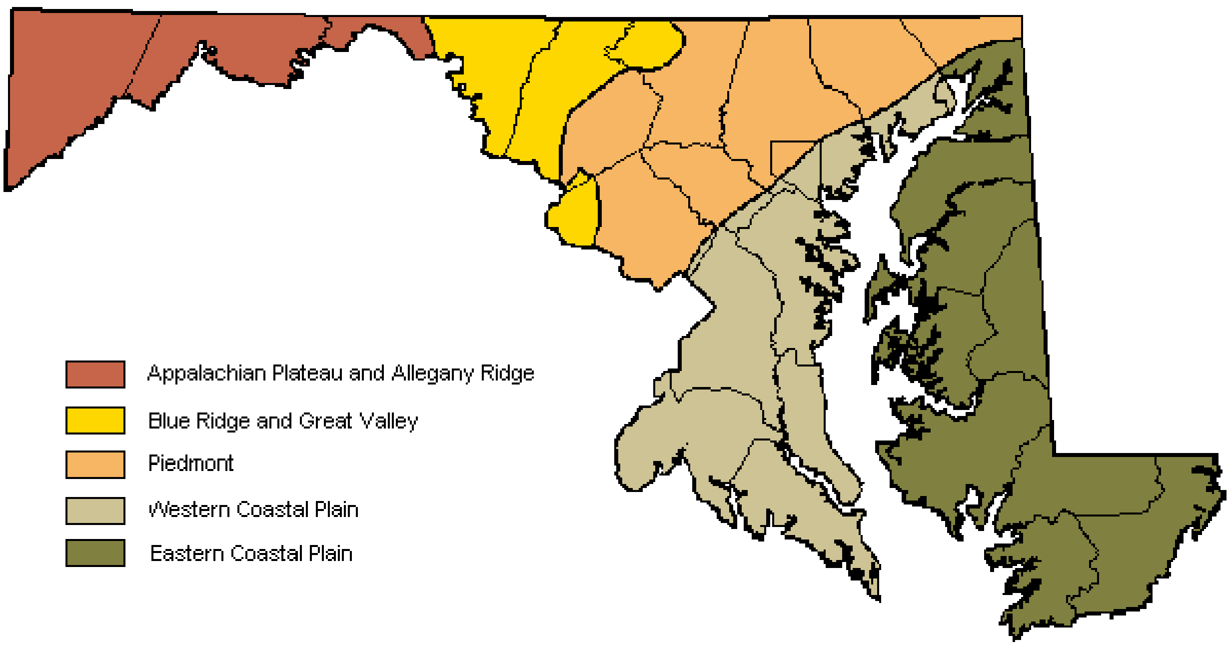


Figure A3.1. Hydrologic regions for Maryland as defined by Dillow (1996).

Statewide Regional Skew Analysis

The recommended approach in Bulletin 17B (Interagency Advisory Committee on Water Data (IACWD), 1982) is to estimate flood discharges based on a weighted skew that is computed by weighting station and generalized (regional) skew by their respective mean square error. Moglen and others (2006) evaluated if the generalized skew map in Bulletin 17B was applicable for Maryland streams. Station skews were computed at each gaging station using data through the 1999 water year by censoring low outliers and adjusting for high outliers and historical floods as described in Bulletin 17B. The station skew values were plotted on a map and compared to the skew map in Bulletin 17B. The new values were considered significantly different from the Bulletin 17B skew map and were used to define two regions of average skew.

Bulletin 17B guidelines recommends three approaches for defining generalized skew: a contour map of skew values (like Plate I in Bulletin 17B), a median or average skew value for a region, or a regression equation relating skew to watershed and climatic characteristics. For this study, there was no geographic or regional pattern in skew values, therefore, a contour map of skew values was not feasible. An attempt was made to relate the station skew values to many of the watershed and climatic variables described earlier in this report. None of the watershed or climatic characteristics were statistically significant in explaining the variability in the station skew values. Since there was not a lot of variation in station skew values across the State, an average value of skew was defined for two regions in Maryland.

The average skew for the Eastern Coastal Plains is 0.45 with a standard error of 0.41 and the average skew for the rest of the State was 0.55 with a standard error of 0.45. As described later, the flood frequency analyses were updated for the Eastern and Western Coastal Plain Regions. For these two analyses, a new skew analysis was performed. Because these subsequent analyses were consistent with the statewide analysis by Moglen and others (2006), the average skew and standard error were not revised.

Measures of Accuracy of the Regional Regression Equations

The accuracy of regression equations can be described by several measures. For this report, two measures of accuracy are provided: the standard error of estimate in percent and the equivalent years of record.

The standard error of estimate is a measure of how well the gaging station estimates of flood discharges agree with the computed regression equation. This value is estimated as the standard deviation of the residuals about the computed equation where the residuals are the difference between gaging station and regression estimates.

The equivalent years of record is defined as the number of years of actual streamflow record required at a site to achieve an accuracy equivalent to the standard error of estimate of the regional regression equation. The equivalent years of record (Nr) is computed as follows (Hardison, 1971):

$$Nr = (S/SE)^2\ R^2$$

where S is an estimate of the standard deviation of the logarithms of the annual peak discharges at the ungaged site, SE is the standard error of estimate of the Fixed Region regression estimates in logarithmic units, and R^2 is a function of recurrence interval and skewness and is computed as (Stedinger and others, 1993):

$$R^2 = 1 + G*Kx + 0.5 *(1+0.75*G^2)*Kx^2$$

where G is an estimate of the average skewness for a given hydrologic region, and Kx is the Pearson Type III frequency factor for recurrence interval x and skewness G. Average skewness values G were defined for each hydrologic region as follows: 0.489 for the Applachian Region, 0.527 for rural watershed in the Blue Ridge and Piedmont Regions, 0.585 for the urban equations in the Piedmont Region, 0.513 for the Western Coastal Plain Region, and 0.484 for the Eastern Coastal Plain Region.

In order to estimate the equivalent years of record at an ungaged site, the standard deviation of the logarithms of the annual peak discharges (S in the equation above) must be estimated. Average values of S were computed for each region and are as follows: 0.241 log units for the Applachian Region, 0.296 log units for rural stations in the Blue Ridge and Piedmont Regions, 0.324 log units for the urban equations in the Piedmont Region, 0.309 log units for the Western Coastal Plain Region, and 0.295 log units for the Eastern Coastal Plain Region.

Update of Regression Equations for the Eastern Coastal Plain Region

Previous Investigations in the Eastern Coastal Plain Region

The Fixed Region regression equations that are currently being used for bridge and culvert design in Maryland are documented in Moglen and others (2006) and are available in GISHydro2000 (Moglen, 2007). These equations for the Eastern Coastal Plain Region are based on STATSGO soils data and annual peak data through 1999. These Fixed Region regression equations are also summarized in “Application of Hydrologic Methods in Maryland” and prepared by the Maryland Hydrology Panel (2006).

In September 2007, the Fixed Region regression equations for the Eastern Coastal Plain Region were updated by including additional years of flow record through 2006 and incorporating recently released SSURGO soils data. A slightly revised version of the SSURGO soils data became available in early 2010 and the regression equations were updated to utilize this new information. The flood frequency analyses were not updated, only the new SSURGO data were incorporated in the analysis.

Data Compilation for the Eastern Coastal Plain Region

The annual peak flow data for gaging stations in the eastern coastal plain areas of Maryland and Delaware were reviewed for suitability for a regional analysis. Those stations with at least 10 years of annual peak flow data without regulation from flood-control structures were considered. Using these criteria, 31 stations were selected with 16 stations in Maryland and 15 stations in Delaware. These stations are listed in Table 1 at the end of the Eastern Coastal Plain section. Of the 31 stations, 24 were used previously in developing the Fixed Region regression equations (Moglen and others, 2006) that are also included in the Maryland Hydrology Panel report. Of the 24 stations used in the earlier regional analysis, 13 stations have additional peak flow data beyond 1999. Annual peak data are now available through the 2006 water year and the record lengths for the 31 stations ranged from 10 to 64 years with 17 stations having record lengths in excess of 30 years.

The following watershed characteristics were determined for the 31 gaging stations used in the current analysis using GISHydro2000 (Moglen, 2007).

1. Gage ID
2. Area (as calculated using GISHydro) in square miles
3. A soils: SSURGO in percent
4. B soils: SSURGO in percent
5. C soils: SSURGO in percent
6. D soils: SSURGO in percent
7. Land Slope: consistent with SCS definition in ft/ft
8. Channel Slope (10/85) in feet/mile

9. Mean Basin Slope (consistent with Ries and Dillow, 2006) in percent
10. Basin Relief (as defined by Dillow, 1996) in feet
11. Forest Cover: from Maryland Department of Planning/Delaware land use 2002
12. USGS Area: in square miles, for comparison purposes
13. Percent error: (GIS Area – USGS Area)/USGS Area * 100 (in percent)

Flood Frequency Analysis in the Eastern Coastal Plain Region

Annual peak data for the 31 stations were retrieved from the USGS web sites (http://water.usgs.gov/md/nwis/sw and http://water.usgs.gov/de/nwis/sw) and Bulletin 17B (Interagency Advisory Committee on Water Data, 1982) frequency analyses were performed using station skew. Flood frequency analyses were first done with station skew to determine if a change is needed in the generalized (regional) skew for the Eastern Coastal Plains Region. In Moglen and others (2006), a generalized skew value of 0.45 with a standard error of 0.41 was adopted for the Eastern Coastal Plain Region. An analysis of station skew based on the updated Bulletin 17B analyses for the 16 long-term stations indicated that the mean skew is 0.43 with a standard error of 0.385. The median skew was 0.44. Because the new analysis was very consistent with the previous analysis, a generalized skew of 0.45 with a standard error of 0.41 as determined in the previous analysis was used in developing the final frequency curves.

The final flood frequency estimates were determined by weighting the station skew and generalized skew of 0.45 using the USGS program PeakFQ (Flynn and others, 2006) that implements Bulletin 17B. Flood discharges were estimated for the 1.25-, 1.50-, 2-, 5-, 10-, 25-, 50-, 100-, 200- and 500-year events.

There were 8 small-stream stations where rainfall-runoff modeling results were available from an earlier study by Carpenter (1980). In the Carpenter study, a rainfall-runoff model was calibrated based on short-term rainfall and runoff data and then long-term annual peaks (approximately 65 years) were simulated using long-term precipitation data at Baltimore, Maryland or Atlantic City, New Jersey. The frequency estimates based on the simulated data were then weighted with those based on the observed data (9 or 10 years in duration). Carpenter (1980) used and published the weighted estimates.

For this study, each of the 8 stations was evaluated and a determination was made as to whether to use the Carpenter (1980) frequency estimates or those based just on the observed data. The analysis of the short-term observed record at some stations was complicated by the major flood event of August 1967 that occurred during the short systematic record. The following conclusions were made based on engineering judgment:

- Puncheon Branch at Dover, DE (station 01483720) – use the observed record
- Murderkill River Trib near Felton, DE (station 01484002) – use the observed record and consider the August 1967 flood the highest in 40 years

- Pratt Branch near Felton, DE (station 01484050) – use the observed record and consider the August 1967 flood the highest in 40 years
- Andrews Branch near Delmar, MD (station 01486100) – use the weighted estimates as published by Carpenter (1980)
- Toms Dam Branch near Greenwood, DE (station 01486980) – use the observed record
- Meadow Branch near Delmar, DE (station 01487900) - use the weighted estimates as published by Carpenter (1980)
- Meredith Branch near Sandtown, DE (01490600) - use the weighted estimates as published by Carpenter (1980)
- Sangston Prong near Whiteleysburg, DE (station 01491010) – use the observed record and consider the August 1967 flood as the highest in 30 years

There were a few stations where the annual peak flows demonstrated an upward trend when plotted versus time. An example is given in Figure A3.2 for Stockley Branch at Stockley, Delaware (01484500). Because there were no significant land-use changes for these watersheds, the increase in annual peak flows was assumed to be due to climatic variability and the full period of record was used in the frequency analysis with no trend adjustments. Only a few stations in Eastern Coastal Plain Region exhibited this type of trend, so it is unlikely there is any regional change in climate.

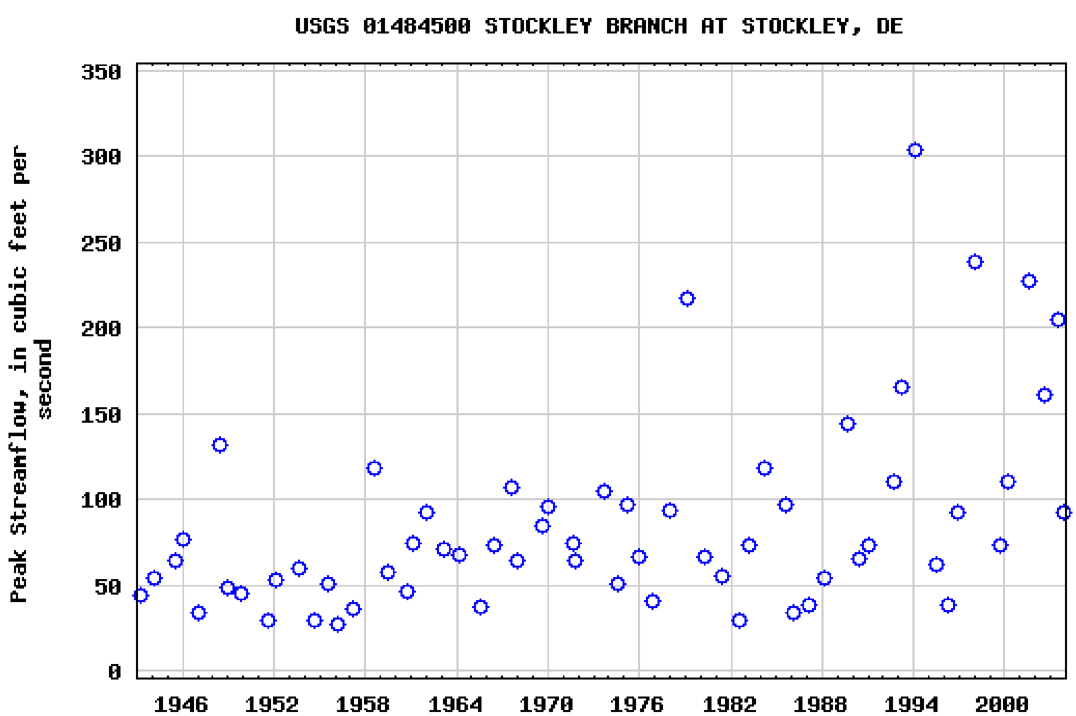


Figure A3.2. Annual peak data for Stockley Branch at Stockley, Delaware (01484500).

Regional Regression Analyses for the Eastern Coastal Plain Region

In the previous regional regression analysis documented by Moglen and others (2006), the significant explanatory variables for the Eastern Coastal Plain Region regression equations were drainage area in square miles, basin relief in feet and percentage of the watershed with A soils based on the STATSGO data. For the current analysis using the SSURGO soils data and the updated flood frequency estimates, the most significant explanatory variables are now drainage area in square miles, percentage of A Soils and land slope in ft/ft or percent or basin relief in feet. Land slope as defined by the SCS and mean basin slope as defined in Ries and Dillow (2006) are essentially the same and either one could be used in the regional regression equations. Both variables represent the mean of the slope grids in the watershed along the steepest direction of flow. In addition, basin relief also defines the steepness of the watershed and could be used in the regression equations in lieu of land slope as discussed later.

The regional regression analyses first included all 31 stations, 16 stations in Maryland and 15 in Delaware. The watershed characteristics and flood discharges are listed in Appendices 1 and 2, respectively. Three stations were outliers and were not used in the regression analysis:

- Sowbridge Branch near Milton, Delaware, station 01484300 (drainage area = 7.17 square miles, 22 years of record),
- Toms Dam Branch near Greenwood, Delaware, station 01486980 (drainage area = 6.44 square miles, 10 years of record),
- Beaverdam Branch at Matthews, Maryland, station 01492000 (drainage area = 5.49 square miles, 32 years of record).

Annual peak flows are very low for Sowbridge Branch and Toms Dam Branch with the highest annual peak flow of 134 cfs at either station for drainage areas of about 7 square miles. Sowbridge Branch has 50.7 percent of the watershed in A soils but even with A soils as an explanatory variable, the station is still an outlier. A major flood has not occurred at either station so it appears to be a time-sampling issue (record for Toms Branch is only 10 years). The flood frequency estimates at Beaverdam Branch are influenced by the large flood that occurred in September 1960 which is more than two times the next largest annual peak. This coupled with the fact that 33.5 percent of the watershed is in A soils make this station an outlier when A soils is an explanatory variable. The flood discharges are high for this station because of the large 1960 flood and the percent of A soils may not be properly defined. The final regression equations were based on 28 stations, excluding these three stations.

Some of the explanatory variables are correlated and this explains why certain variables are either statistically significant or not. If two explanatory variables are highly correlated, the variable that is most highly correlated with the flood discharges takes precedent. The correlations among several explanatory variables for the 28 stations used in the regional regression analysis are given in Table A3.1.

Table A3.1: Correlation structure for the logarithms of the explanatory variables for 28 stations used in the regression analysis

Variables	DA	S_A	S_D	LSLOPE	CSL	MBS	BR	FOR
Drainage Area (DA), mi^2	1.00	0.039	0.36	-0.15	-0.66	-0.16	0.41	0.16
A Soils (S_A), percent		1.00	-0.33	-0.008	0.08	-0.021	0.12	0.022
D Soils (S_D), percent			1.00	-0.67	-0.68	-0.67	-0.43	0.36
Land Slope (LSLOPE), ft/ft				1.00	0.72	0.999	0.72	-0.22
Channel Slope (CSL), ft/mi					1.00	0.73	0.32	-0.27
Mean Basin Slope (MBS), percent						1.00	0.72	-0.20
Basin Relief (BR), ft							1.00	0.006
Forest (FOR), percent								1.00

The strong correlations (> 0.65) given in Table A3.2 are as follows:

- Drainage area and channel slope are inversely correlated,
- Percent D soils is inversely correlated with land slope, channel slope, mean basin slope and basin relief,
- Land slope is directly correlated with channel slope and basin relief and is essentially the same variable as mean basin slope (correlation = 0.999),
- Channel slope is directly correlated with mean basin slope,
- Mean basin slope is directly correlated with basin relief.

As shown in Table A3.2, percent A soils is not highly correlated with any other explanatory variable and is therefore explaining variability in the flood discharges not explained by other variables. Even though drainage area and channel slope are highly correlated, channel slope is still a significant variable in the regression analyses when used in conjunction with drainage area. However, the exponent on drainage area, the most significant variable, is close to 1.0 for certain frequencies and this is not rational so channel slope was not used in the final regression equations.

Percent D soils has a high inverse correlation with land slope, channel slope and mean basin slope. Therefore, percent D soils was not statistically significant in the regression analysis because all the slope parameters were statistically significant and reduced the significance of percent D soils.

As noted above, land slope and mean basin slope, although computed slightly different, are essentially the same variable. Both were highly significant in the regression analysis. Land slope was chosen because of its use in other hydrologic regions in Maryland. Land slope and basin relief are also highly correlated (0.72) and so both variables are essentially accounting for the same variation in the flood discharges. Basin relief was used in the regression equations for the Eastern Coastal Plain for the previous study as documented in Moglen and others (2006) and the Hydrology Panel report (2006) Appendix 3. Therefore, two sets of regression equations are provided herein based on drainage area, A soils and land slope (slightly more accurate) and based on drainage area, A soils and basin relief (for comparison to the existing Fixed Region equations).

Regression equations based on land slope

The following equations are based on 28 stations in Maryland and Delaware with drainage area (DA) ranging from 0.91 to 113.7 square miles, percent A soils (S_A) ranging from 0.0 to 78.8 percent, and land slope (LSLOPE) ranging from 0.00250 to 0.0160 ft/ft. All variables are statistically significant at the 5-percent level of significance except LSLOPE for flood discharges less than the 5-year event but LSLOPE is included in the regression equations for consistency. The equations, standard error of estimate (SE) in percent and equivalent years (Eq. years) of record are as follows:

Equation	**SE (%)**	**Eq. years**	
$Q_{1.25} = 41.53\ DA^{0.815}\ (SA+1)^{-0.139}\ LSLOPE^{0.115}$	32.4	4.6	(1)
$Q_{1.50} = 78.75\ DA^{0.824}\ (SA+1)^{-0.144}\ LSLOPE^{0.194}$	32.3	4.1	(2)
$Q_{2} = 134.0\ DA^{0.836}\ (SA+1)^{-0.158}\ LSLOPE^{0.249}$	32.8	4.4	(3)
$Q_{5} = 477.5\ DA^{0.847}\ (SA+1)^{-0.184}\ LSLOPE^{0.385}$	35.1	7.0	(4)
$Q_{10} = 924.3\ DA^{0.844}\ (SA+1)^{-0.196}\ LSLOPE^{0.445}$	36.7	9.7	(5)
$Q_{25} = 1860.4\ DA^{0.834}\ (SA+1)^{-0.212}\ LSLOPE^{0.499}$	39.3	13	(6)
$Q_{50} = 2941.5\ DA^{0.824}\ (SA+1)^{-0.222}\ LSLOPE^{0.531}$	41.6	15	(7)
$Q_{100} = 4432.9\ DA^{0.812}\ (SA+1)^{-0.230}\ LSLOPE^{0.557}$	44.2	17	(8)
$Q_{200} = 6586.3\ DA^{0.800}\ (SA+1)^{-0.237}\ LSLOPE^{0.582}$	47.2	18	(9)
$Q_{500} = 10,587\ DA^{0.783}\ (SA+1)^{-0.247}\ LSLOPE^{0.610}$	51.6	19	(10)

The 100-year estimates from Equation 8 above are compared to the corresponding gaging station estimates in Figure A3.3. The equal yield line is drawn as a frame of reference. The 100-year estimates seem to be evenly distributed about the equal yield line.

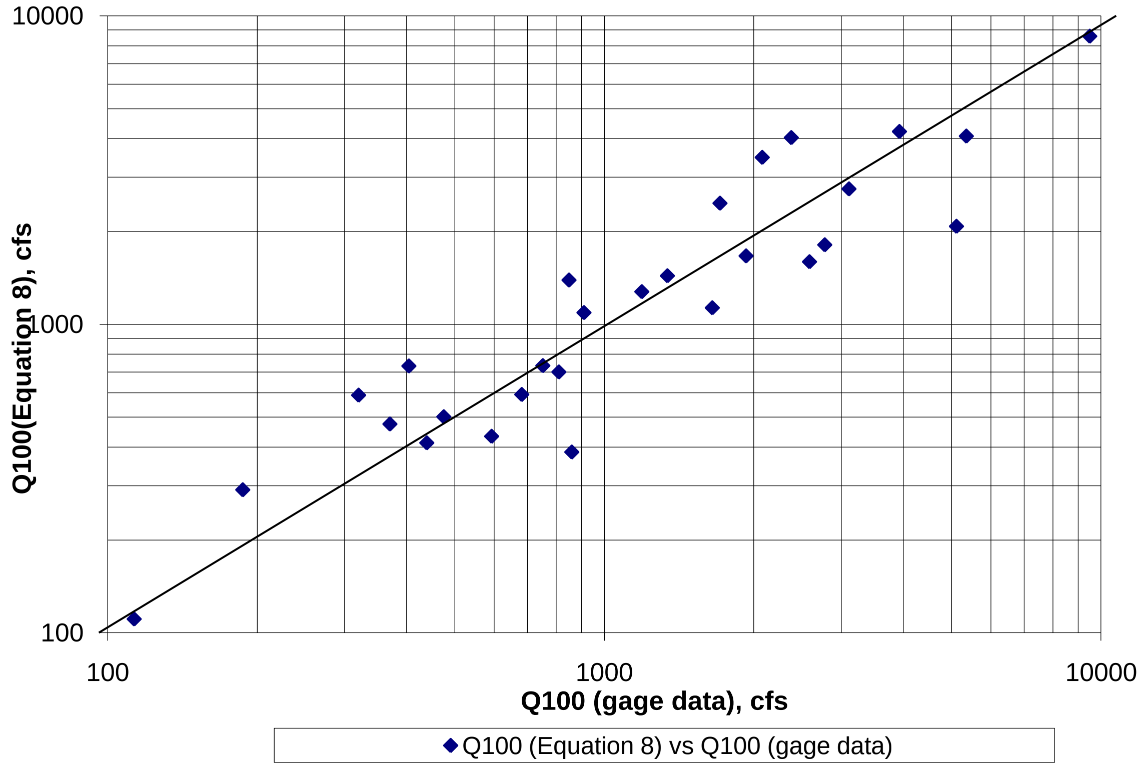


Figure A3.3. Comparison of the 100-year estimates based on Equation 8 in this report and gaging station data.

Estimates from the existing 100-year equation in Moglen and others (2006) and Appendix 3 of the Hydrology Panel report were compared to estimates from Equation 8 given earlier in this report. The comparisons are shown in Figure A3.4. The existing 100-year equation is based on drainage area, basin relief and percentage of A soils based on STATSGO data. As shown in Figure 4, the existing equation and Equation 8 give about the same 100-year estimate on average. The best fit line has a slope close to 1.0. The variation about the best fit line is primarily due to differences in SSURGO and STATSGO data for some of the gaging stations.

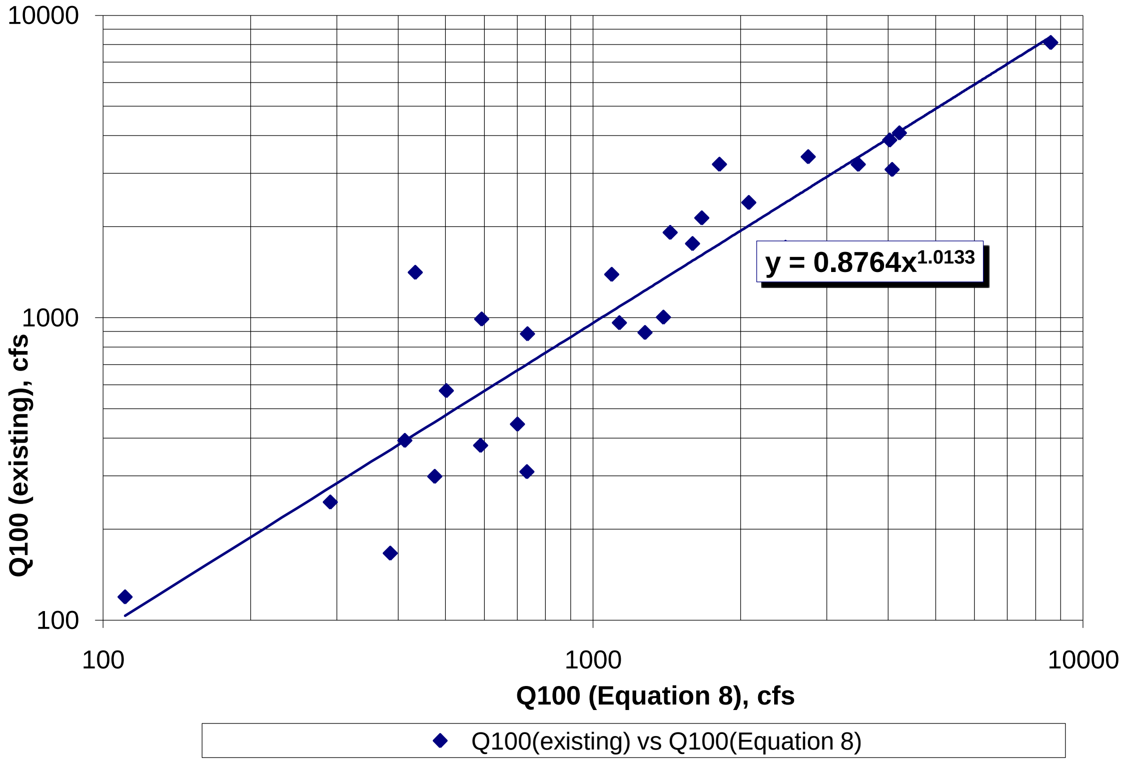


Figure A3.4. Comparison of 100-year estimates for the existing 100-year equation in Moglen and others (2006) and Equation 8 in this report.

Comparison to USGS Scientific Investigations Report 2006-5146

The USGS published Scientific Investigations Report (SIR) 2006-5146 titled "Magnitude and Frequency of Floods on Nontidal Streams in Delaware" in 2006 that provides regression equations for Delaware streams. The Coastal Plain Region equations are based on drainage area, percentage A soils (STATSGO soils), and mean basin slope. A comparison was made between the 100-year flood discharge estimated by the USGS Coastal Plain Region equation and estimates from Equation 8 in this report.

Figure A3.5 compares the USGS 100-year estimates to corresponding estimates from Equation 8 given earlier in this report. Equation 8 gives higher 100-year estimates across the range of flows shown in Figure A3.5. The difference ranges from a few percent at the low discharges to about 30 percent for the larger discharges.

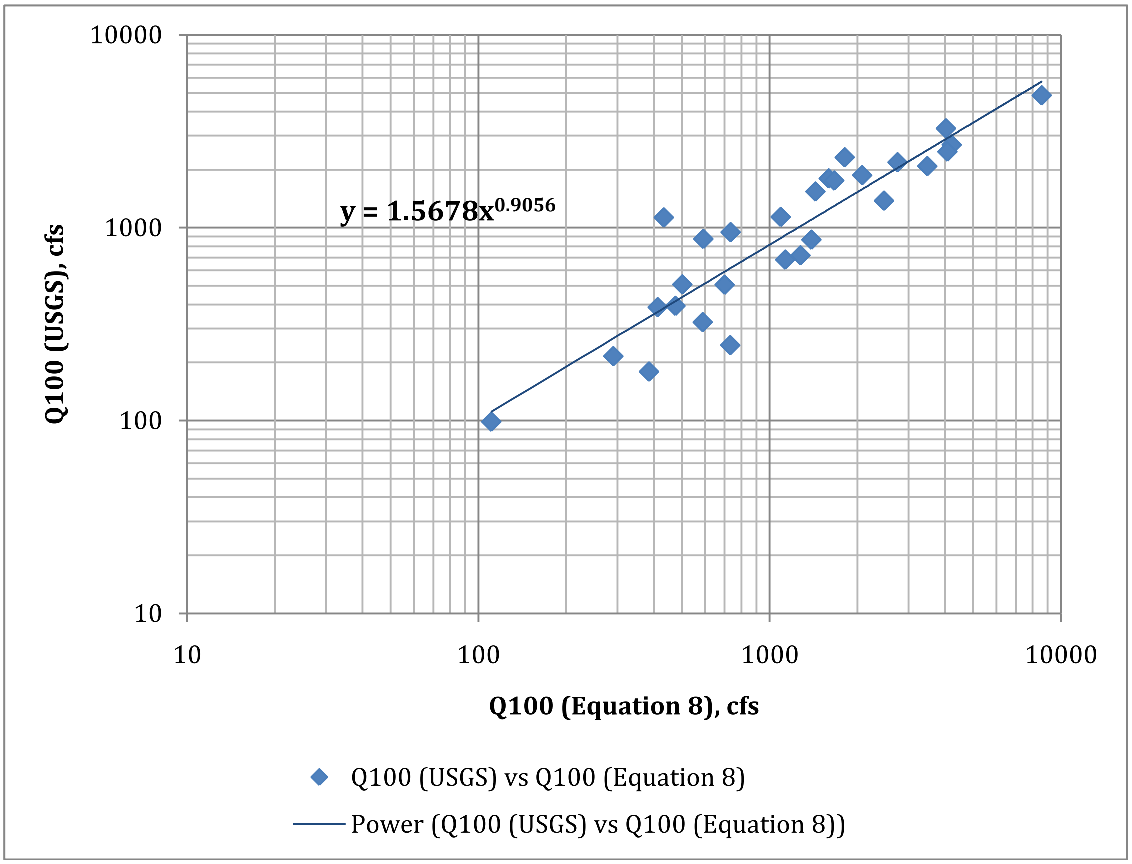


Figure A3. 5. Comparison of 100-year discharges estimated from the USGS equation in SIR 2006-5146 and Equation 8 in this report.

Summary Comments for the Eastern Coastal Plain Region

The regression equations for the Eastern Coastal Plains were revised using updated annual peak data for 28 gaging stations in Maryland and Delaware and SSURGO soils data. However, of the 28 stations used in the regression analysis, only 13 stations had updated annual peak data since 1999. The three variables found to be most significant were drainage area, percentage A soils and land slope. Comparisons of 100-year estimates from Equation 8 to estimates from the existing 100-year equation (Moglen and others, 2006; Hydrology Panel, 2006) indicate that, on average, the two equations give similar estimates. There is significant variation for individual stations due to the variation in SSURGO and STATSGO soils data. A comparison with USGS SIR 2006-5146 indicates that Equation 8 provides 100-year estimates that range from a few percent to about 30 percent more than the USGS estimates. This is partially related to the different values of regional skew that were used by USGS (0.204) and in this study (0.45).

Table A3.2. Listing of gaging stations in the Eastern Coastal Plain Region.

		Gage Name	Start year	End Year	Yrs. Record
USGS	1483200	BLACKBIRD CREEK AT BLACKBIRD, DE	1952	2006	54
USGS	1483500	LEIPSIC RIVER NEAR CHESWOLD, DE	1943	1975	33
USGS	1483720	PUNCHEON BRANCH AT DOVER, DE	1966	1975	10
USGS	1484000	MURDERKILL RIVER NEAR FELTON, DE	1932	1999	31
USGS	1484002	MURDERKILL RIVER TR NEAR FELTON, DE	1966	1975	10
USGS	1484050	PRATT BRANCH NEAR FELTON, DE	1905	1975	10
USGS	1484100	BEAVERDAM BRANCH AT HOUSTON, DE	1958	2006	49
USGS	1488500	MARSHYHOPE CREEK NEAR ADAMSVILLE, DE	1935	2006	60
USGS	1490600	MEREDITH BRANCH NEAR SANDTOWN, DE	1966	1975	10
USGS	1491010	SANGSTON PRONG NEAR WHITELEYSBURG, DE	1966	1975	10
USGS	1484300*	SOWBRIDGE BRANCH NEAR MILTON, DE	1957	1978	22
USGS	1484500	STOCKLEY BRANCH AT STOCKLEY, DE	1943	2003	62
USGS	1486980*	TOMS DAM BRANCH NEAR GREENWOOD, DE	1966	1975	10
USGS	1487000	NANTICOKE RIVER NEAR BRIDGEVILLE, DE	1935	2006	64
USGS	1487900	MEADOW BRANCH NEAR DELMAR, DE	1967	1975	9
USGS	1489000	FAULKNER BRANCH AT FEDERALSBURG, MD	1950	1991	42
USGS	1490800	OLDTOWN BRANCH AT GOLDSBORO, MD	1967	1976	10
USGS	1491000	CHOPTANK RIVER NEAR GREENSBORO, MD	1948	2006	59
USGS	1491050	SPRING BRANCH NEAR GREENSBORO, MD	1967	1976	10
USGS	1490000	CHICAMACOMICO RIVER NEAR SALEM, MD	1951	2006	34
USGS	1492050	GRAVEL RUN AT BEULAH, MD	1966	1975	11
USGS	1493500	MORGAN CREEK NEAR KENNEDYVILLE, MD	1951	2006	55
USGS	1492500	SALLIE HARRIS CREEK NEAR CARMICHAEL, MD	1952	2006	36
USGS	1493000	UNICORN BRANCH NEAR MILLINGTON, MD	1948	2005	56
USGS	1494000	SOUTHEAST CREEK AT CHURCH HILL, MD	1952	1965	14
USGS	1486000	MANOKIN BRANCH NEAR PRINCESS ANNE, MD	1951	2006	53
USGS	1492000*	BEAVERDAM BRANCH AT MATTHEWS, MD	1950	1981	32
USGS	1492550	MILL CREEK NEAR SKIPTON, MD	1966	1976	11
USGS	1486100	ANDREWS BRANCH NEAR DELMAR, MD	1967	1976	10
USGS	1485000	POCOMOKE RIVER NEAR WILLARDS, MD	1950	2006	57
USGS	1485500	NASSAWANGO CREEK NEAR SNOW HILL, MD	1950	2006	57

***** Not used in the regression analysis

Update of Regression Equations for the Western Coastal Plain

Previous Investigations in the Western Coastal Plain Region

The Fixed Region regression equations that are currently (2010) being used for bridge design in Maryland are documented in Moglen and others (2006) and are available in GISHydro2000 (Moglen, 2007). These equations for the Western Coastal Plain Region are based on STATSGO soils data and frequency analyses based on annual peak data through 1999. These Fixed Region regression equations for the Western Coastal Plain Region are also summarized in "Application of Hydrologic Methods in Maryland", a report prepared by the Maryland Hydrology Panel (2006).

In June 2009, the Fixed Region regression equations for the Western Coastal Plain Region were updated by including additional years of flow record through 2008 and incorporating recently released SSURGO soils data. A slightly revised version of the SSURGO soils data became available in early 2010 and the regression equations were updated to utilize this new information. The flood frequency analyses were not updated and are still based on annual peak flow data through 2008.

Data Compilation for the Western Coastal Plain Region

The annual peak flow data for gaging stations in the Western Coastal Plain Region of Maryland were reviewed for suitability for regional analysis. Those stations with at least 10 years of annual peak flow data without regulation from flood-control structures were considered. Using these criteria, 26 stations were selected with record lengths ranging from 10 to 71 years. No gaging stations located in Virginia were used because there are no land use data comparable to Maryland stations. The stations are listed in Table 3 at the end of the Western Coastal Plain Region. Of the 26 stations, 22 were used previously in developing the Fixed Region regression equations (Moglen and others, 2006; Maryland Hydrology Panel, 2006). Three stations that were considered outliers in the 2006 analysis were considered again for this analysis and one new station was added (South Fork Jabez Branch at Millersville, 01589795). This latter station did not have sufficient record to be included in the 2006 analysis. Of the 26 stations considered for this regional analysis, 12 stations have additional peak flow data beyond 1999 and through the 2008 water year.

The following watershed characteristics were determined for the 26 gaging stations used in the current analysis using GISHydro2000 (Moglen, 2007).

14. Gage ID
15. Drainage area (as calculated using GISHydro) in square miles
16. USGS published drainage area in square miles
17. Impervious area: from Maryland Department of Planning land use 2002
18. A soils: SSURGO in percent
19. B soils: SSURGO in percent
20. C soils: SSURGO in percent

21. D soils: SSURGO in percent
22. Land Slope: consistent with SCS definition in ft/ft
23. Channel Slope (10/85) in feet/mile
24. Percent urban area: from Maryland Department of Planning land use 2002
25. Basin Relief (as defined by Dillow, 1996) in feet
26. Forest Cover: from Maryland Department of Planning land use 2002
27. Curve number based on SSURGO soils
28. Longest flow path in miles

Flood Frequency Analysis in the Western Coastal Plain Region

Annual peak data for the 12 stations with new annual peak data were retrieved from the USGS web site (http://water.usgs.gov/md/nwis/sw and Bulletin 17B (Interagency Advisory Committee on Water Data, 1982) frequency analyses were performed using station skew. Flood frequency analyses were first done with station skew to determine if a change is needed in the generalized (regional) skew for the Western Coastal Plain Region. In Moglen and others (2006), a generalized skew value of 0.55 with a standard error of 0.44 was adopted for the Western Coastal Plain Region as well as for the Piedmont, Blue Ridge and Appalachian Plateau Regions. An analysis of station skew based on the updated Bulletin 17B analyses for 21 long-term stations (stations with high and low outliers were not used) indicated that the mean skew is 0.52 with a standard error of 0.45. The median skew was 0.54. Because the new analysis was very consistent with the 2006 analysis that included the Piedmont, Blue Ridge and Appalachian Plateau Regions, the generalized skew of 0.55 and standard error of 0.44 as determined in the previous analysis (Moglen and others, 2006; Maryland Hydrology Panel, 2006) was used in developing the final frequency curves.

The final flood frequency estimates were determined by weighting the station skew and generalized skew of 0.55 using the U.S. Geological Survey (USGS) program PeakFQ (Flynn and others, 2006) that implements Bulletin 17B. Flood discharges were estimated for the 1.25-, 1.50-, 2-, 5-, 10-, 25-, 50-, 100-, 200- and 500-year events.

There was one small-stream station, Clark Run near Bel Alton (01660930), where rainfall-runoff modeling results were available from an earlier study by Carpenter (1980). In the Carpenter study, a rainfall-runoff model was calibrated based on short-term rainfall and runoff data and then long-term annual peaks (approximately 65 years) were simulated using long-term precipitation data at Baltimore, Maryland or Atlantic City, New Jersey. The frequency estimates based on the simulated data were then weighted with those based on the observed data (9 to 11 years in duration). Carpenter (1980) published the weighted estimates.

For this study, the flood discharges as determined by Carpenter (1980) were used for Clark Run near Bel Alton (01660930). These estimates were considered more reasonable than the estimates based on 11 years of data (1966-76).

Several of the gaged watersheds have undergone urbanization during the period of data of data collection. The annual time series were reviewed to determine if there were any visual trends in the data. There were only two stations that had a noticeable trend and they were: NE Branch Anacostia River at Riverdale (01649500) and NW Branch Anacostia River near Hyattsville (01651000). The annual peak data for station 01649500 are shown in Figure A3.6 and in Figure A3.7 for station 01651000.

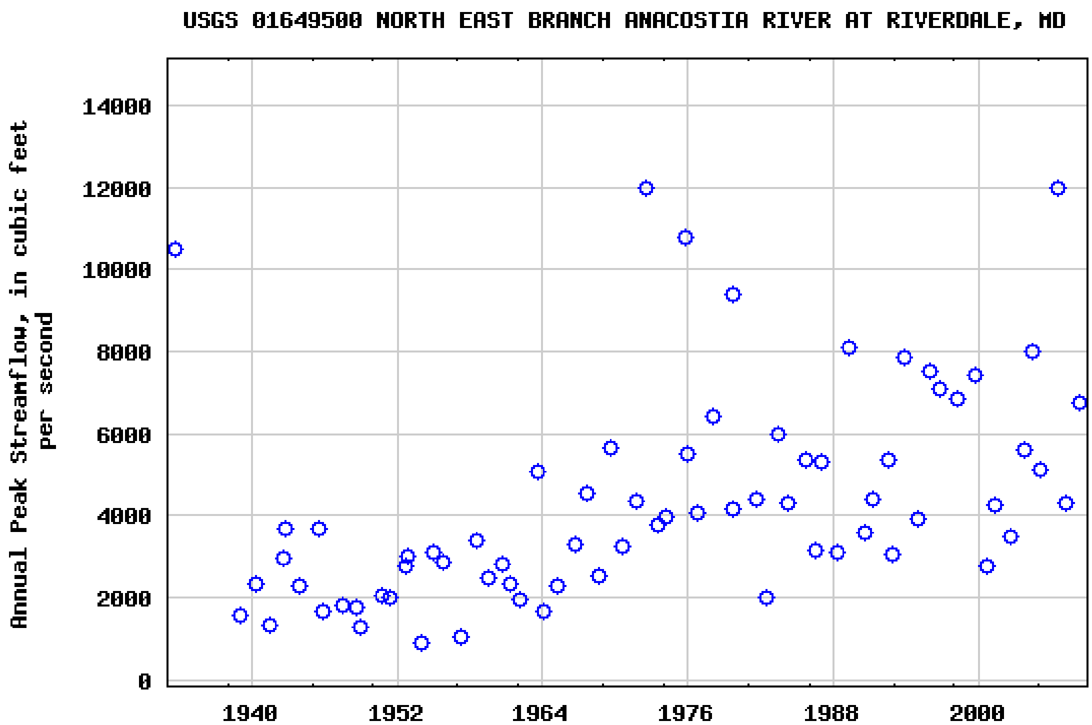


Figure A3.6. Annual peak data for NE Branch Anacostia River at Riverdale, Maryland (01649500).

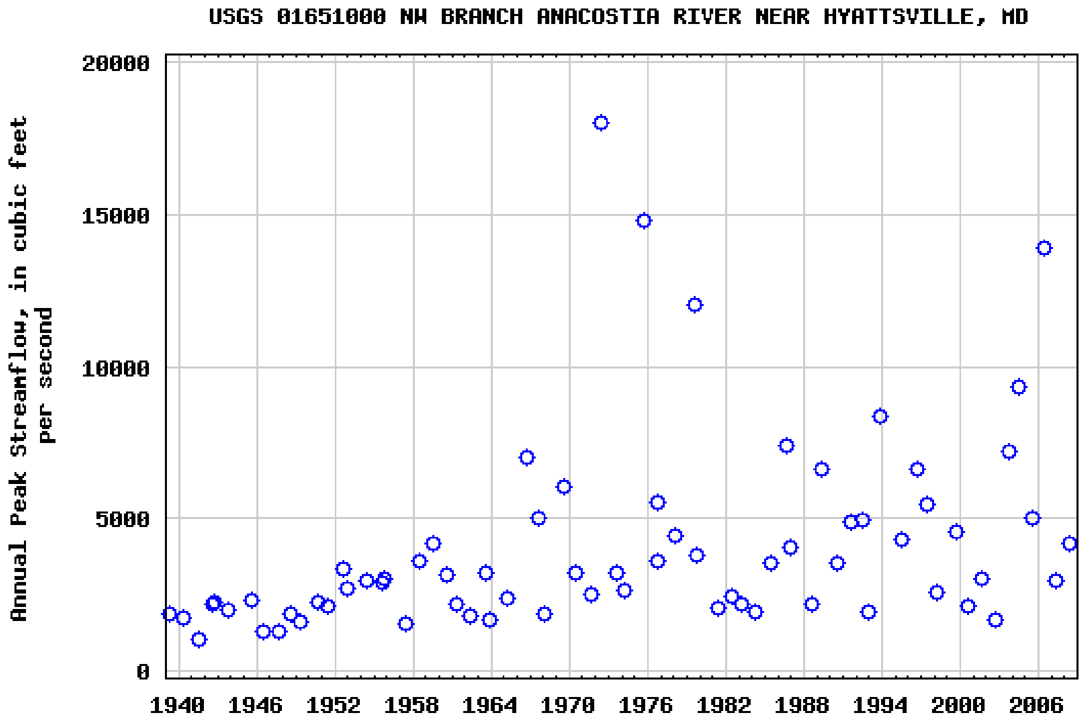


Figure A3.7. Annual peak data for NW Branch Anacostia River near Hyattsville, Maryland. (01651000).

As shown in Figures A3.6 and A3.7, there is an increase in annual peaks for both stations beginning in the mid 1960s. The frequency analysis for station 01649500 was performed on the period 1963 to 2008 and for station 01651000 the period chosen was 1966 to 2008. These periods were chosen in lieu of the full period of record to achieve a more homogeneous record. The frequency analyses for all other stations were based on the full period of record because there were no noticeable trends.

Figures A3.6 and A3.7 both illustrate three large floods that occurred in the 1970s. This was an active period for floods for this region of Maryland.

The frequency curve for one station, St. Clement Creek near Clements, Maryland (01661050), was determined graphically by drawing a smooth curve through the Weibull plotting positions. The frequency curve at this station had an S shape and could not be accurately characterized by the 3-parameter log-Pearson Type III distribution. An examination of the USGS topographic map indicated a very wide floodplain upstream of the gaging station and the flood data may be affected by natural storage in the floodplain.

Regional Regression Analyses for the Western Coastal Plain Region

In the previous regional regression analysis documented by Moglen and others (2006), the significant explanatory variables for the Western Coastal Plain Region regression equations were drainage area in square miles, impervious area for 1985 in percent and percentage of the watershed with D soils based on the STATSGO data. For the current analysis, neither the percentage D soils nor the percentage A soils, based on SSURGO data, were statistically significant. Therefore, the sum of the percentage of A and B soils and the sum of the percentage of C and D soils were evaluated as predictor variables.

Both combinations of variables (A+B and C+D) were statistically significant but, of course, not in the same equation since the two sums are highly correlated (-0.93). The sum of the percentage of C and D soils was chosen after many trial analyses because this sum provided a slightly lower standard error than the sum of the percentage of A and B soils and the sum of the percentage of C and D soils was more uniformly distributed across the 24 watersheds. The downside of using the sum of the percentage of C and D soils is that this variable is more correlated with impervious area, the third explanatory variable, than the sum of the percentage A and B soils. The objective any regression analysis is to choose explanatory variables that are as uncorrelated as possible.

Impervious area for the 1985, 1990 and 1997 land use conditions were available from Moglen and others (2006). The impervious area based on USGS 1970's land use data was also available but those data were not always consistent with subsequent land use data. In this study, impervious area was determined for 2002 land use conditions. The impervious area for a given watershed that was most indicative of the period of record for the peak flow data was determined. For example, if the peak flow data ended in the 1980s or before, impervious area for 1985 was used. The impervious area for 1985, as used in the 2006 analysis, was still the most appropriate data for 16 of the 24 stations in the regression analysis.

For the regression analysis the impervious area for 1985 and the impervious area most applicable to the period of record were evaluated. The impervious area most applicable to the period of record actually provided a slightly lower standard error but the exponent on impervious area did not change much from the 1.25-year event to the 500-year event, which is not reasonable. The impervious area for 1985 was chosen as the third explanatory variable because the range in exponent was more reasonable.

The impervious area for 1985 was used in developing the regression equations because this variable yielded the most reasonable regression equations. When applying the regression equations to an ungaged site, the analyst should use the most current estimate of impervious area.

The watershed characteristics and flood discharges are listed in Appendices 1 and 2, respectively.

Results of the Regression Analysis for the Western Coastal Plain Region

The following equations are based on 24 stations in the Western Coastal Plain region of Maryland with drainage area (DA) ranging from 0.41 to 349.6 square miles, impervious area ranging from 0.0 to 36.8 percent, and the sum of the percentage of C and D soils ranging from 13 to 74.7 percent. Two stations were deleted from the analysis because they were outliers: Sawmill Creek at Glen Burnie (01589500) and Dorsey Run near Jessup (01594400). Both stations had small annual peaks for their respective drainage areas and there are other factors effectively runoff in addition to the variables in the regression equations.

The equations and standard errors are given below. The flood discharges for various recurrence intervals x (Q_x), drainage area (DA), impervious area (IA) and the sum of the percentage of C and D soils (S_{CD}) were converted to logarithms base 10 and a linear regression analysis was performed. The equations were then converted to a power form and are given below. Drainage area (DA) and sum of percentage C and D soils (S_{CD}) are significant at the 5-percent level (p-level) for all recurrence intervals. Impervious area (IA) is statistically significant at the 10-percent level up to the 100-year event (Q_{100}). For Q_{200} and Q_{500}, the p-level for IA is 0.1237 and 0.1763, respectively, but this variable was retained in the equations for consistency. The equations, standard error of estimate (SE) in percent, and equivalent years (Eq. years) of record are as follows:

Equation	**SE (%)**	**Eq. years**	
$Q_{1.25} = 5.18\ DA^{0.694}\ (IA+1)^{0.382}\ (S_{CD}+1)^{0.414}$	39.0	3.6	(11)
$Q_{1.50} = 6.73\ DA^{0.682}\ (IA+1)^{0.374}\ (S_{CD}+1)^{0.429}$	36.4	3.6	(12)
$Q_{2} = 7.61\ DA^{0.678}\ (IA+1)^{0.362}\ (S_{CD}+1)^{0.475}$	33.2	4.6	(13)
$Q_{5} = 10.5\ DA^{0.665}\ (IA+1)^{0.290}\ (S_{CD}+1)^{0.612}$	38.2	6.7	(14)
$Q_{10} = 13.1\ DA^{0.653}\ (IA+1)^{0.270}\ (S_{CD}+1)^{0.669}$	42.7	8.2	(15)
$Q_{25} = 17.5\ DA^{0.634}\ (IA+1)^{0.264}\ (S_{CD}+1)^{0.719}$	48.1	10	(16)
$Q_{50} = 21.2\ DA^{0.621}\ (IA+1)^{0.263}\ (S_{CD}+1)^{0.751}$	54.0	11	(17)
$Q_{100} = 25.6\ DA^{0.608}\ (IA+1)^{0.262}\ (S_{CD}+1)^{0.781}$	61.2	11	(18)
$Q_{200} = 30.5\ DA^{0.596}\ (IA+1)^{0.261}\ (S_{CD}+1)^{0.812}$	69.6	10	(19)
$Q_{500} = 37.9\ DA^{0.579}\ (IA+1)^{0.261}\ (S_{CD}+1)^{0.849}$	82.5	10	(20)

As noted earlier, impervious area for 1985 land use conditions was used to develop the regression equations but the analyst applying the equations at an ungaged site should use the most current value of impervious area.

The regression estimates for the 100-year discharges from Equation 18 are plotted versus the gaging station estimates in Figure A3.8. The equal yield or equal discharge line is shown as a point of reference. For the higher discharges, the data points are evenly distributed about the equal yield line. For the smaller discharges (and watersheds), there is a tendency for the data points to be on one side or the other of the equal yield line. On average, there does not appear to be a significant bias.

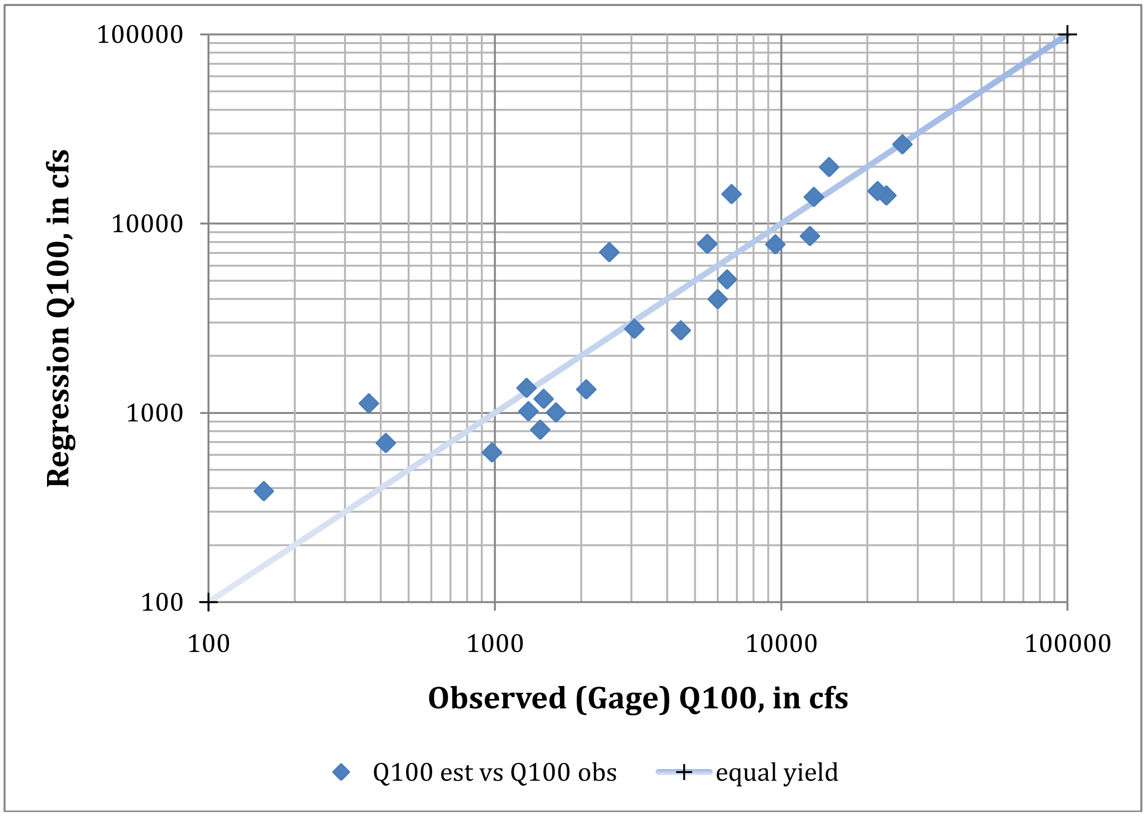


Figure A3.8. Regression estimates for the 100-year flood discharge from Equation 18 plotted versus the gaging station estimates for the Western Coastal Plain Region.

Estimates from the existing 100-year equation in Moglen and others (2006) and Appendix 3 of the Hydrology Panel report were compared to estimates from Equation 18 given earlier in this report. The comparisons are shown in Figure A3.9. The existing 100-year equation is based on drainage area, imoervious area and percentage of D soils based on STATSGO data. As shown in Figure A3.9, the existing equation gives estimates about 20 percent higher than Equation 18 for the smaller discharges (and watersheds) and about 20 percent less for the larger discharges (and watersheds). The variation about the best fit line is primarily due to differences in SSURGO and STATSGO data for some of the gaging stations.

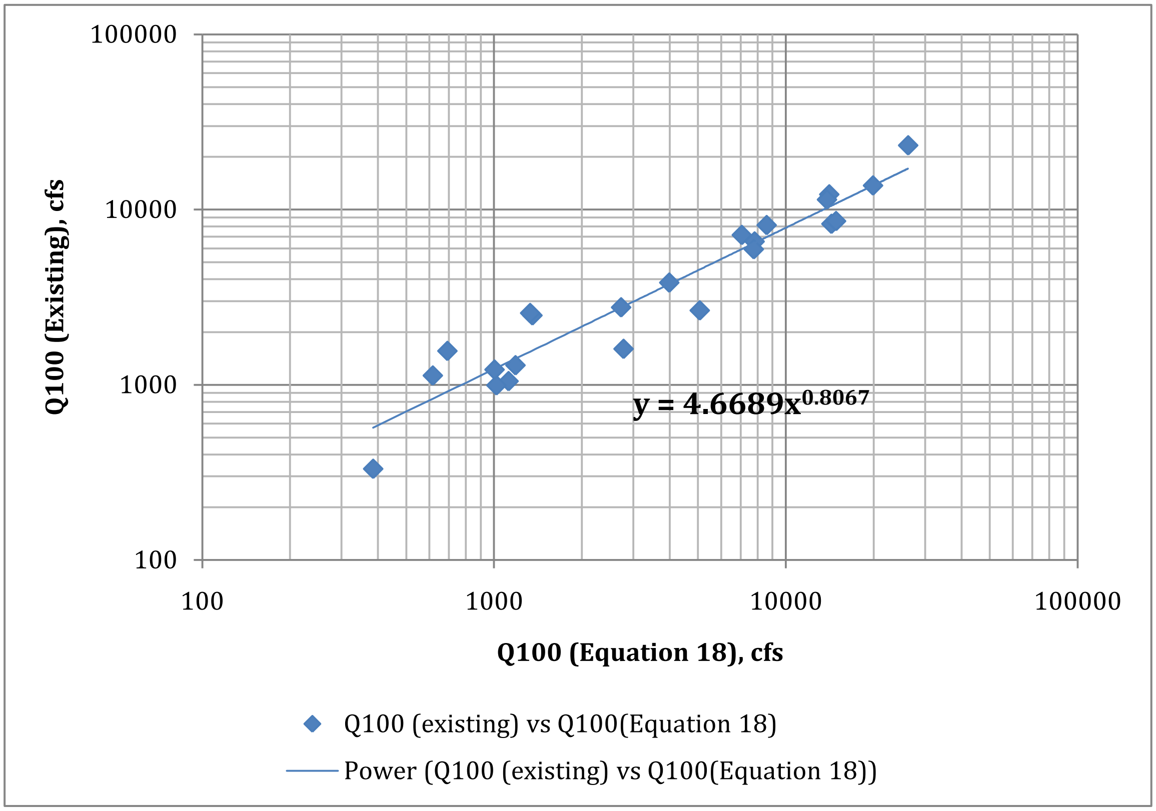


Figure A3.9. Comparison of 100-year estimates for the existing 100-year equation in Moglen and others (2006) and Equation 18 in this report.

Summary Comments for the Western Coastal Plain Region

The regression equations for the Western Coastal Plain Region were revised using updated annual peak data for 24 gaging stations in Maryland and SSURGO soils data. Of the 26 stations used in the regression analysis, only 12 stations had updated annual peak data since 1999. The final set of regression equations were based on drainage area, impervious area for 1985, and the sum of the percentages of C and D soils.

Impervious area was available for several time periods including 1985, 1990, 1997, and 2002. For the regression analysis, the impervious area for 1985 was considered to provide the most reasonable equations. For future application of the regression equations at ungaged sites, the current impervious area should be used in the equations.

Table A3.3: Listing of Gaging Stations used in Western Coastal Plain Analysis

STATION_NO	STATION_NAME	Period of Record	DRAIN_AREA
01594445	MILL BRANCH NEAR MITCHELLVILLE, MD	1967-76	1.39
01594670	HUNTING CREEK NEAR HUNTINGTOWN, MD	1989-98	9.3
01660930	CLARK RN NR BEL ALTON, MD	1966-76	11.2
01661430	GLEBE BRANCH AT VALLEY LEE, MD	1968-78	0.3
01594710	KILLPECK CREEK AT HUNTERSVILLE, MD	1986-97	3.3
01660900	WOLF DEN BRANCH NEAR CEDARVILLE, MD	1967-80	2.3
01594400*	DORSEY RUN NEAR JESSUP, MD	1949-68	11.9
01594600	COCKTOWN CREEK NEAR HUNTINGTOWN, MD	1958-76	3.9
01594500	WESTERN BRANCH NEAR LARGO, MD	1950-74	29.5
01661000	CHAPTICO CREEK AT CHAPTICO, MD	1948-72	10.5
01585400	BRIEN RUN AT STEMMERS RUN, MD	1959-87	1.9
01653500	HENSON CREEK AT OXON HILL, MD	1948-78	17.4
01590500	BACON RIDGE BRANCH AT CHESTERFIELD, MD	1944-90	7.0
01590000	NORTH RIVER NEAR ANNAPOLIS, MD	1932-73	8.9
01594800	ST LEONARD CREEK NEAR ST LEONARD, MD	1958-03	6.8
01594526	WESTERN BRANCH AT UPPER MARLBORO, MD	1985-08	89.1
01660920	ZEKIAH SWAMP RUN NEAR NEWTOWN, MD	1984-08	81.0
01594440	PATUXENT RIVER NEAR BOWIE, MD	1978-08	349.7
01589500*	SAWMILL CREEK AT GLEN BURNIE, MD	1933-08	4.9
01661050	ST CLEMENT CREEK NEAR CLEMENTS, MD	1969-08	18.2
01653600	PISCATAWAY CREEK AT PISCATAWAY, MD	1966-08	39.7
01589795	SOUTH FORK JABEZ BRANCH AT MILLERSVILLE	1990-08	1.0
01658000	MATTAWOMAN CREEK NEAR POMONKEY, MD	1950-08	55.8
01661500	ST MARYS RIVER AT GREAT MILLS, MD	1947-08	25.3
01649500	NE BRANCH ANACOSTIA RIVER AT RIVERDALE	1933-08	73.4
01651000	NW BRANCH ANACOSTIA RIVER NEAR HYATTSVILLE	1933-08	49.4

*Not used in the regional regression analysis

Update of Regression Equations for Rural Watersheds in the Piedmont and Blue Ridge Regions

Previous Investigations in the Piedmont and Blue Ridge Regions

Dillow (1996) and Moglen and others (2006) defined separate sets of regression equations for the Piedmont and Blue Ridge Regions (Figure 1). In both analyses, it was assumed that the area of carbonate/limestone rock was confined to the Blue Ridge Region as defined by Dillow (1996). Recent investigations by the Maryland Hydrology Panel have determined that the carbonate rock extends eastward into the Piedmont Region. Therefore for this current analysis, gaging stations in the Piedmont and Blue Ridge Regions are used in the same analysis. No gaging stations located in Pennsylvania were used because there are no land use data comparable to that available for Maryland stations.

Separate regression equations were defined for the Piedmont Region for rural and urban watersheds by Moglen and others (2006). The urban watersheds were those with 10 percent or greater impervious area during the period of annual peak flow data. It was not possible to get reasonable equations by combining the rural and urban watersheds in the same analysis. For this current analysis, the rural watersheds in the Piedmont Region were combined with rural watersheds in the Blue Ridge Region. The urban equations for the Piedmont Region were not updated in the current analysis.

The Fixed Region regression equations for rural watersheds in the Piedmont Region (see Figure A3.1) as documented in Moglen and others (2006) and the Maryland Hydrology Panel (2006) were based on drainage area and percentage of forest cover. These equations were based on 34 gaging stations.

The Fixed Region regression equations for the Blue Ridge Region (see Figure A3.1) as documented by Moglen and others (2006) were based on 20 gaging stations. The explanatory variables were drainage area and percentage of the watershed underlain with carbonate/limestone rock. The percentage of carbonate/limestone rock was determined from the carbonate rock map in Dillow (1996).

The blue areas shown in Figure A3.10 are the areas of carbonate rock as defined by Dillow (1996). However, as shown in Figure A3.10, there are sinkholes and carbonate/limestone rock in areas outside of the blue area previously used to define percentage carbonate rock. The area impacted by sinkholes and carbonate rock extends into Carroll County in the Piedmont Region. A new carbonate rock map was developed and it is shown in Figure A3.11.

Regression Analyses for the Piedmont and Blue Ridge Regions

In an effort to better quantify the effect of limestone and carbonate rock on flood discharges in Maryland, the number of sinkholes per square kilometer was defined. The locations of the sinkholes are shown in Figure A3.10. The sinkholes per square kilometer (density) were estimated by based on data from:

- Karst points in Pennsylvania as provided by Stuart Reese and William Kochanov with the Pennsylvania Department of Conservation and Natural Resources,
- Sinkholes in Carroll County as provided by Tom DeVillbis with the Carroll County Planning Department,
- Sinkholes in Frederick Valley as compiled by Dave Brezinski with the Maryland Geological Survey (published data),
- Sinkholes in Hagerstown Valley as compiled by Dave Brezinski with the Maryland Geological Survey (preliminary data),
- Maryland Geological Survey RI 73 (Duigon, 2001).

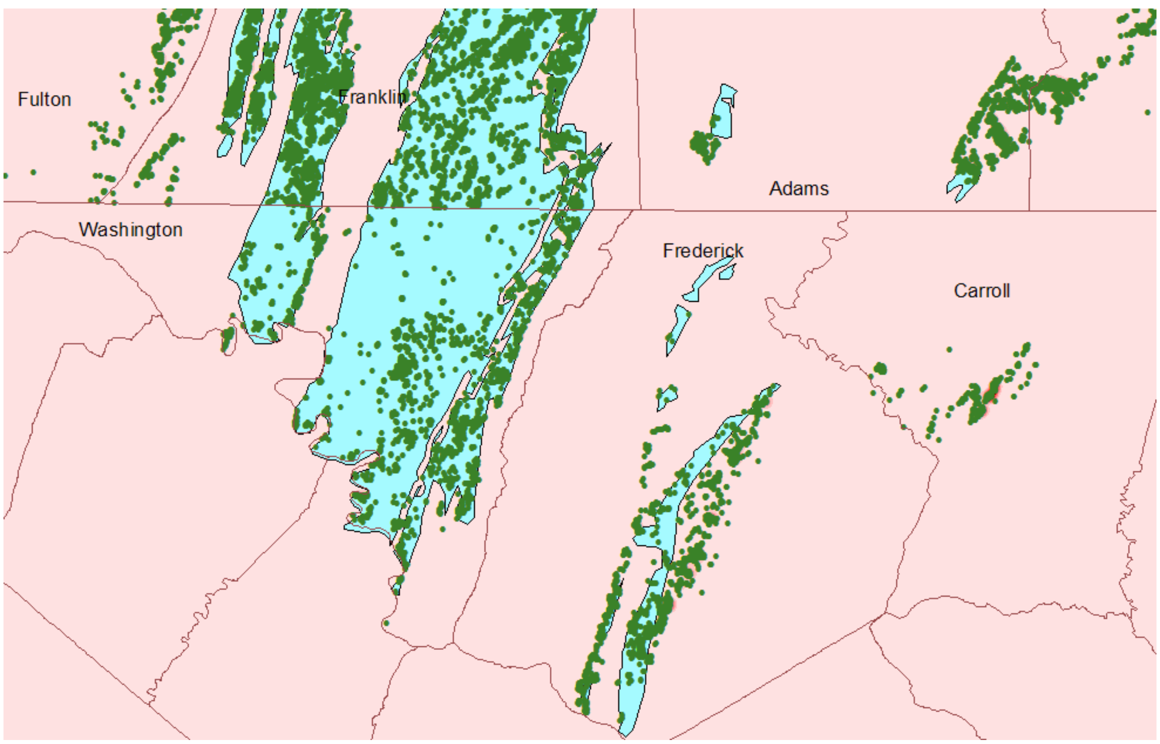


Figure A3.10. Distribution of carbonate/limestone rock (blue areas) from Dillow (1996) and location of sinkholes (green circles) in the Piedmont and Blue Ridge Regions of Maryland.

Regression analyses were performed using the percentage of carbonate rock and density of sinkholes to determine which variable provided the best predictions of flood discharges. These analyses indicated that the percentage carbonate rock provided slightly lower standard errors than the density of sinkholes. The percentage of carbonate/limestone rock was selected as the best variable to characterize the karst features for watersheds in the Piedmont and Blue Ridge Regions. The percentage of carbonate rock was estimated from the map shown in Figure A3.11.

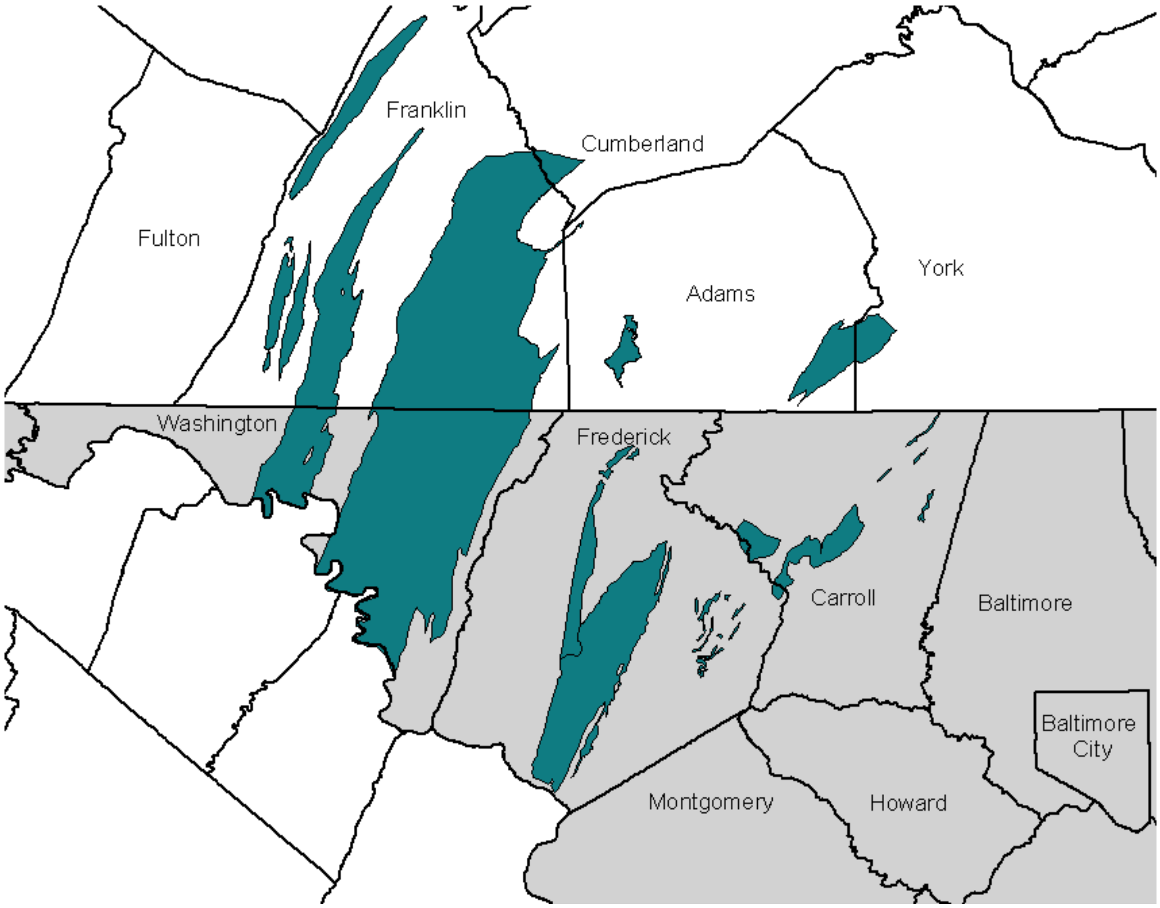


Figure A3.11. Distribution of underlying carbonate/limestone rock in the Piedmont and Blue Ridge Regions of Maryland.

The regression analysis for the combined Piedmont and Blue Ridge Regions was based on 54 rural gaging stations. The flood frequency curves were not updated for this analysis and the flood discharges previously determined by Moglen and others (2006) were used for this analysis. Therefore, these flood discharges are based on annual peak data through 1999. The watershed characteristics and flood discharges are listed in Appendices 1 and 2, respectively.

Of the 54 stations used in the regression analysis, only 14 stations in Maryland had percentage of carbonate rock greater than zero. The percentage of carbonate/limestone rock (LIME) ranged from zero to 99.35 percent for Marsh Run at Grimes, Maryland (01617800). Even with LIME as an explanatory variable, station 01617800 was an extreme outlier. This station was deleted from the analysis because it was an influential observation with too much impact on the regression equations. There were four other stations with more than 60 percent of the watershed underlain with carbonate rock. In the final regression analysis based on 53 stations, the percentage of carbonate/limestone rock (LIME) ranged from zero to 81.72 percent and drainage area (DA) ranged from 0.11 to 820 square miles.

There are no gaging stations in the Blue Ridge Region that have nonzero values of percentage carbonate rock and impervious area greater than 10 percent. Station 01640000, Little Pipe Creek at Avondale, Maryland, is a watershed with 76.53 percent carbonate/limestone rock with impervious of 6.9 percent in 1985 and 15.4 percent in 1997. The period of record at this station ended in 1979 so this station was used in the rural analysis because the impervious area was less than 10 percent. There are no regression equations for urban watersheds in the Blue Ridge Region. For watersheds in the Blue Ridge Region with impervious area greater than 10 percent and significant carbonate/limestone rock, the analyst will need to develop some innovative approach for estimating the flood discharges.

The percentage of forest cover was previously significant in the Piedmont Region rural regression equations (Moglen and others, 2006). For the 53 stations used in the current analysis, forest cover is significant at the 5-percent level for the 10-year flood and less and significant at the 10-percent level for the 25-year flood. Forest cover has a correlation of 0.34 with drainage area and that is possibly why it is not statistically significant across all recurrence intervals. Even though forest cover is not statistically above the 25-year flood, it was retained in the analysis because it significantly reduced the standard errors for the 10-year flood and less. Forest cover for 1985 land use conditions was used to develop the regression equations because it was most representative of the period of annual peak flow data. Forest cover ranged from 2.7 to 100 percent for the 53 stations used in the analysis.

Channel slope and basin relief are highly correlated with drainage area with correlation coefficients of -0.83 and 0.71, respectively, and these variables are not statistically significant.

The regression equations and standard errors are given below. The flood discharges for various recurrence intervals x (Q_x), drainage area (DA) in square miles, the percentage of carbonate/limestone rock (LIME), and forest cover (FOR) were converted to logarithms base 10 and a linear regression analysis was performed. The equations were then converted to a power form as shown below. Drainage area (DA) and percentage of carbonate/limestone rock (LIME) were significant at the 5-percent level of significance. The significance of forest cover (FOR) is discussed above. The equations, the standard error of estimate (SE) in percent, and the equivalent years (Eq. years) of record are as follows:

Equation	**SE (%)**	**Eq. years**	
$Q_{1.25} = 287.1\ DA^{0.774}\ (LIME+1)^{-0.118}\ (FOR+1)^{-0.418}$	42.1	2.8	(21)
$Q_{1.50} = 327.3\ DA^{0.758}\ (LIME+1)^{-0.121}\ (FOR+1)^{-0.358}$	37.6	3.1	(22)
$Q_{2} = 396.9\ DA^{0.743}\ (LIME+1)^{-0.124}\ (FOR+1)^{-0.332}$	35.6	3.7	(23)
$Q_{5} = 592.5\ DA^{0.705}\ (LIME+1)^{-0.133}\ (FOR+1)^{-0.237}$	31.4	9.0	(24)
$Q_{10} = 751.1\ DA^{0.682}\ (LIME+1)^{-0.138}\ (FOR+1)^{-0.183}$	30.9	14	(25)
$Q_{25} = 996.0\ DA^{0.655}\ (LIME+1)^{-0.145}\ (FOR+1)^{-0.122}$	32.2	20	(26)
$Q_{50} = 1{,}218.8\ DA^{0.635}\ (LIME+1)^{-0.150}\ (FOR+1)^{-0.082}$	34.5	23	(27)
$Q_{100} = 1{,}471.1\ DA^{0.617}\ (LIME+1)^{-0.154}\ (FOR+1)^{-0.045}$	37.5	24	(28)
$Q_{200} = 1{,}760.7\ DA^{0.600}\ (LIME+1)^{-0.159}\ (FOR+1)^{-0.009}$	41.0	25	(29)
$Q_{500} = 2{,}215.4\ DA^{0.577}\ (LIME+1)^{-0165}\ (FOR+1)^{0.035}$	46.3	25	(30)

Summary Comments for the Piedmont and Blue Ridge Regions

The rural gaging stations were combined for the Blue Ridge and Piedmont Regions because carbonate/limestone rock is present in both regions. A rural gaging station is defined as one where the percentage of impervious area is less than 10 percent for the period of annual peak flow data. All the gaging stations in the Blue Ridge Region have less than 10 percent impervious area for the period of annual peak flow data.

The regression equations for the combined regions were based on 53 stations with peak flow data through 1999. The final regression equations were based on drainage area, percentage of carbonate/limestone rock and percentage of forest cover in the watershed. A new carbonate rock map was developed by the Hydrology Panel. There are no regression equations applicable to watersheds with significant carbonate/limestone rock and impervious areas greater than 10 percent because there are no gaging stations with these attributes.

Regression Equations for Urban Watersheds in the Piedmont Region

The regression equations for urban watersheds in the Piedmont Region were not updated in the current analysis. The equations listed below were taken from Moglen and others (2006). The equations are also given in Appendix 3 of the Hydrology Panel Report (2006). Annual peak flow data through 1999 were used to define the flood discharges (Q_x). For the 16 watersheds used to derive the Piedmont urban equations, drainage area (DA) ranges from 0.49 to 102.05 square miles and impervious area ranges from 10 to 37.5 percent. As with the regression equations for the Western Coastal Plain Region, the equations below were determined using impervious area for 1985 land use conditions but analysts should use the most current impervious area when applying the equations at an ungaged location. The equations, standard error of estimate (SE) in percent, and equivalent years (Eq. years) of record are as follows:

	SE (%)	**Eq. years**	
$Q_{1.25} = 17.85\ DA^{0.652}\ (IA+1)^{0.635}$	41.7	3.3	(31)
$Q_{1.50} = 24.66\ DA^{0.648}\ (IA+1)^{0.631}$	36.9	3.8	(32)
$Q_2 = 37.01\ DA^{0.635}\ (IA+1)^{0.588}$	35.1	4.5	(33)
$Q_5 = 94.76\ DA^{0.624}\ (IA+1)^{0.499}$	28.5	13	(34)
$Q_{10} = 169.2\ DA^{0.622}\ (IA+1)^{0.435}$	26.2	24	(35)
$Q_{25} = 341.0\ DA^{0.619}\ (IA+1)^{0.349}$	26.0	38	(36)
$Q_{50} = 562.4\ DA^{0.619}\ (IA+1)^{0.284}$	27.7	44	(37)
$Q_{100} = 898.3\ DA^{0.619}\ (IA+1)^{0.222}$	30.7	45	(38)
$Q_{200} = 1413\ DA^{0.621}\ (IA+1)^{0.160}$	34.8	44	(39)
$Q_{500} = 2529\ DA^{0.623}\ (IA+1)^{0.079}$	41.2	40	(40)

Regression Equations for the Appalachian Plateau

The regression equations for watersheds in the Appalachian Plateau were not updated in the current analysis. The equations listed below were taken from Moglen and others (2006). The equations are also given in Appendix 3 of the Hydrology Panel Report (2006). Annual peak flow data through 1999 were used to define the flood discharges (Q_x). For the 23 stations used to derive the Appalachian Plateau equations, drainage area (DA) ranging from 0.52 to 293.7 square miles and land slope (LSLOPE) ranging from 0.06632 to 0.22653 ft/ft. One station, 03076505, was an outlier and eliminated from the regression analysis. Basin relief, channel slope, and basin shape have relatively high correlations with drainage area (0.78, 0.77, and 0.62, respectively) and were not statistically significant in the regression equations. The equations, standard error of estimate (SE) in percent, and equivalent years (Eq. years) of record are as follows:

	SE (%)	**Eq. years**	
$Q_{1.25} = 70.25\ DA^{0.837}\ LSLOPE^{0.327}$	23.6	5.7	(41)
$Q_{1.50} = 87.42\ DA^{0.837}\ LSLOPE^{0.321}$	21.9	5.9	(42)
$Q_2 = 101.41\ DA^{0.834}\ LSLOPE^{0.300}$	20.7	7.1	(43)
$Q_5 = 179.13\ DA^{0.826}\ LSLOPE^{0.314}$	21.6	12	(44)
$Q_{10} = 255.75\ DA^{0.821}\ LSLOPE^{0.340}$	24.2	14	(45)
$Q_{25} = 404.22\ DA^{0.812}\ LSLOPE^{0.393}$	29.1	15	(46)
$Q_{50} = 559.80\ DA^{0.806}\ LSLOPE^{0.435}$	33.1	16	(47)
$Q_{100} = 766.28\ DA^{0.799}\ LSLOPE^{0.478}$	37.4	15	(48)
$Q_{200} = 1046.9\ DA^{0.793}\ LSLOPE^{0.525}$	41.8	15	(49)
$Q_{500} = 1565.0\ DA^{0.784}\ LSLOPE^{0.589}$	48.0	15	(50)

References

Carpenter, D.H., 1980, *Technique for Estimating Magnitude and Frequency of Floods in Maryland*: USGS Water-Resources Investigations Open-File Report 80-1016, U.S. Geological Survey, Towson, MD.

Dillow, J.J.A., 1996, *Technique for Estimating Magnitude and Frequency of Peak Flows in Maryland*: USGS Water-Resources Investigations Report 95-4154, U.S. Geological Survey, Baltimore, MD.

Duigon, M.T., 2001, *Karst Hydrogeology of the Hagerstown Valley*, Maryland: RI 73, Maryland Geological Survey, 128 p.

Flynn, K.M., Kirby, W.H., and Hummel, P.R., 2006, *User's Manual for Program PeakFQ, Annual Flood-Frequency Analysis Using Bulletin 17B Guidelines*: Chapter 4 of Book 4, Section B, Techniques and Methods 4-B4, U.S. Geological Survey, Reston, VA.

Hardison, C.H., 1971, *Prediction error of regression estimates of streamflow characteristics at ungaged sites*: U.S. Geological Survey Professional Paper 750-C, pp. C228-C236.

Interagency Advisory Committee on Water Data, 1982, *Guidelines For Determining Flood Flow Frequency*: Bulletin 17B of the Hydrology Subcommittee, U.S. Geological Survey, Reston, VA.

Maryland Hydrology Panel report, 2006, *Application of Hydrologic Methods in Maryland*: A report prepared by the Maryland Hydrology Panel convened by the Maryland State Highway Administration and the Maryland Department of the Environment, http://www.gishydro.umd.edu/panel.htm, August 2006, 293 p.

Moglen, G. E., Thomas, W.O., Jr., and Cuneo, C. G., 2006, *Evaluation of Alternative Statistical Methods for Estimating Frequency of Peak Flows in Maryland*: Final Report SP907C4B, University of Maryland, College Park, MD.

Moglen, G.E., 2007, *Introduction to GISHydro2000*: Training Manual, November 2007, http://www.gishydro.umd.edu, University of Maryland, College Park, Maryland.

Ries, K.G., III, and Dillow, J.J.A., 2006, *Magnitude and Frequency of Floods on Nontidal Streams in Delaware*: USGS Scientific Investigations Report 2006-5146, U.S. Geological Survey, Baltimore, MD.

Stedinger, J.R., Vogel, R.M., and Foufoula-Georgia, E., 1993, Chapter 18 *Frequency analysis of extreme events*: in Handbook of Hydrology, David Maidment, Editor in Chief, McGraw-Hill, Inc.

APPENDIX 4
REGRESSION EQUATIONS FOR THE ESTIMATION OF BANKFULL CROSS-SECTION AREA, DEPTH AND WIDTH AS A FUNCTION OF UPSTREAM DRAINAGE AREA

Background

One method of estimating the time of concentration of a watershed is to estimate the travel time through the hydraulic flow path. An estimation of the time required for a particle of water to travel through the channel network is one element in the hydraulic flow path approach. This channel travel time is usually estimated by computing the velocity with the Manning equation under bankfull conditions.

Often, it is not feasible to send a crew into the field to make the measurements needed to define the bankfull depth, width and area. When field surveys are not practical, the Panel recommends use of the regression equations that estimate the bankfull depth, area and width as a function of the upstream drainage area. The US Fish and Wildlife Service (FWS) and the Maryland State Highway Administration, in cooperation with the US Geological Survey, developed the three sets of equations presented in this appendix.

A. The FWS Equations

A-1 Equations for Piedmont Hydrologic Region

Reference: McCandless, Tamara L., and Everett, Richard A., Maryland Stream Survey: Bankfull Discharge and Channel Characteristics of Streams in the Piedmont Hydrologic Region, US Fish and Wildlife Service, Chesapeake Bay Field Office, CBFO-S02-01, 2002

Measurements were made at 23 sites having drainage areas between 1.47 sq. mi. and 102.00 sq. mi. The equations are:

$$\text{Cross-sectional Area} = 17.42DA^{0.73}$$
$$\text{Width} = 14.78DA^{0.39}$$
$$\text{Depth} = 1.18DA^{0.34}$$

where DA is the upstream drainage area in square miles. McCandless and Everett's Figure 17 illustrates the quality of the agreements.

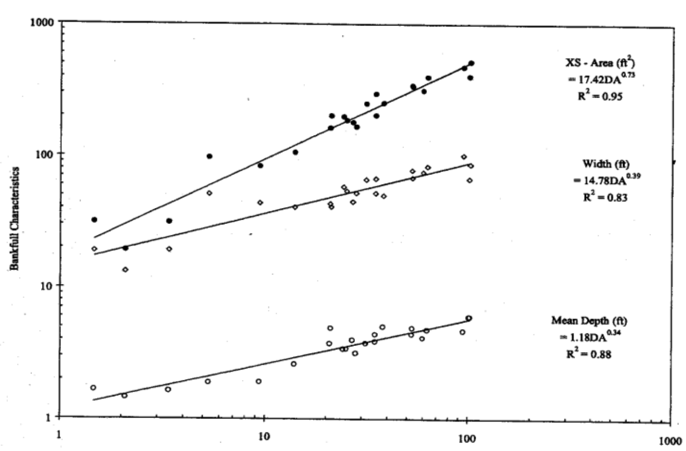


Figure 17. Bankfull channel dimensions as a function of drainage area for Maryland Piedmont survey sites (n = 23).

A-2 Equations for Allegheny Plateau and the Valley and Ridge Hydrologic Regions

Reference: McCandless, Tamara L., Maryland Stream Survey: Bankfull Discharge and Channel Characteristics of Streams in the Allegheny Plateau and Valley and Ridge Hydrologic Region, US Fish and Wildlife Service, Chesapeake Bay Field Office, CBFO-S03-01, 2003

Measurements were made at 14 sites having drainage areas between 0.2 sq. mi. and 73.1 sq. mi. The equations are:

$$\text{Cross-sectional Area} = 13.17DA^{0.75}$$
$$\text{Width} = 13.87DA^{0.44}$$
$$\text{Depth} = 0.95DA^{0.31}$$

where DA is the upstream drainage area in square miles. McCandless' Figure 13 illustrates the quality of the agreements.

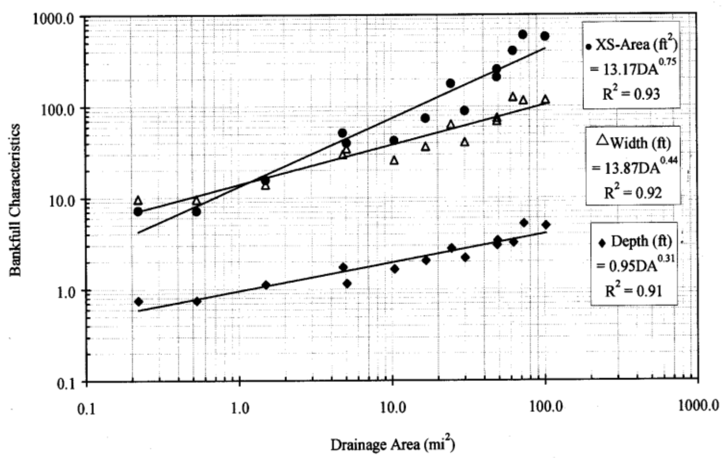


Figure 13. Bankfull channel dimensions as a function of drainage area for AP/VR survey sites (n = 14).

A-3 Equations for the Coastal Plain Hydrologic Region

Reference: McCandless, Tamara L., Maryland Stream Survey: Bankfull Discharge and Channel Characteristics of Streams in the Coastal Plain Hydrologic Region, US Fish and Wildlife Service, Chesapeake Bay Field Office, CBFO-S03-02, 2003

Measurements were made at 14 sites having drainage areas between 0.3 sq. mi. and 113 sq. mi. The equations are:

$$\text{Cross-sectional Area} = 10.34DA^{0.70}$$
$$\text{Width} = 10.30DA^{0.38}$$
$$\text{Depth} = 1.01DA^{0.32}$$

where DA is the upstream drainage area in square miles. McCandless' Figure 12 illustrates the quality of the agreements.

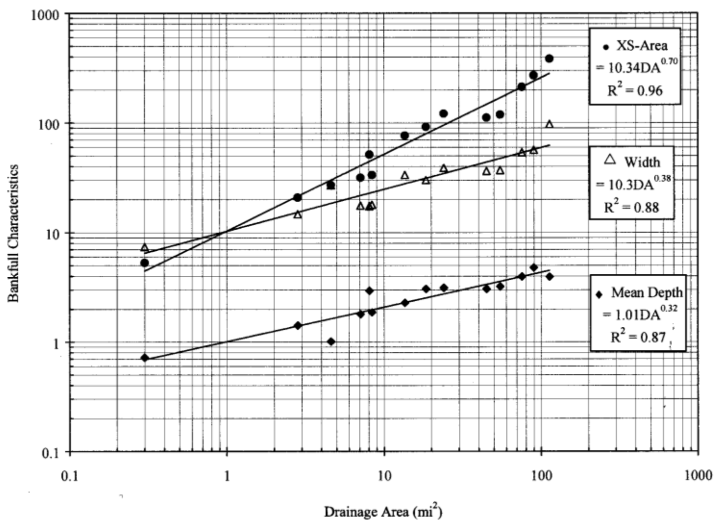


Figure 12. Bankfull channel dimensions as a function of drainage area for Coastal Plain survey sites (n = 14).

B. Manual Use of the FWS Equations

B-1 Determining the Time of Concentration

The engineer will need to identify the channel portion of the longest flow path. The engineer should then determine the drainage area at the upstream and downstream extremes of the flow path. We will denote these areas as DA_u and DA_d, respectively. The geometric mean of these two values is determined as:

$$\overline{DA} = \exp\left[\frac{\ln(DA_u) + \ln(DA_d)}{2}\right] \qquad \text{(Appendix 4-1)}$$

The geometric mean of the upstream and downstream drainage areas is then substituted into the FWS channel geometry equations to determine a bankfull width and depth for this mean drainage area. The width and depth are then combined with the channel roughness and slope to determine a bankfull velocity. The channel length of the longest flow path is then divided by the bankfull velocity to determine the travel time associated with the channel portion of the time of concentration.

Example: Determine the channel portion of travel time for a 2000 foot long channel with a slope of 0.0015 ft/ft in the Maryland Piedmont physiographic province. The drainage area at the upstream end of the channel is 5.0 square miles. At the downstream end, the drainage area is 10.0 square miles. Use a channel roughness, n=0.05.

Solution: First, determine the geometric mean drainage area:

$$\overline{DA} = \exp\left[\frac{\ln(5) + \ln(10)}{2}\right] = 7.07\,\text{mi}^2$$

using this value, the bankfull channel width and depth in the Piedmont are calculated:

$$w = 14.78(7.07)^{0.39} = 31.69 \text{ feet}$$

$$d = 1.18(7.07)^{0.34} = 2.29 \text{ feet}$$

Now use Manning's equation to determine the bankfull velocity:

$$v = \frac{1.49}{0.05}\left[\frac{31.69 \cdot 2.29}{2(2.29)+31.69}\right]^{2/3}(0.0015)^{1/2} = 1.83 \text{ ft/s}$$

The channel portion of the travel time is then:

$$t_{channel} = \frac{l}{v} = \frac{2000}{1.83} = 1093 \text{ sec} = 18.2 \text{ minutes}$$

This travel time would be added to the overland and swale portions of the travel time along the longest flow path to determine the overall t_c value.

B-2 Determining the Rating Curve for Reach Routing

As in the case of determining the time of concentration, t_c, the engineer will need to know the upstream and downstream drainage areas for the reach being studied. The engineer will additionally need the reach slope, roughness values for in-bank and out-of-bank flow, and cross-section geometry for the out-of-bank portion of the flow presumably determined from a topographic map. As in the t_c calculations, the engineer must determine the geometric mean drainage area and use this to determine the bankfull channel geometry – idealizing the channel as a rectangular section with bankfull width and depth determined from the FWS equations for the appropriate region using the geometric mean drainage area. (Note: Alternatively, the engineer may choose to simply use the drainage area from the location of the selected cross-section to determine the bankfull width and depth from the FWS equations.) This channel portion of the cross-section is then superimposed on the cross-section from the topographic map with the channel cross-section replacing the topographic map measurements at the lowest observed elevation from the topographic map. That is, the topographic map is assumed to indicate only the elevation of the top-of-bank, so the rectangular cross-section is "carved" into the cross-section such that the channel incises a depth, *d*, into the topographically-derived cross-section.

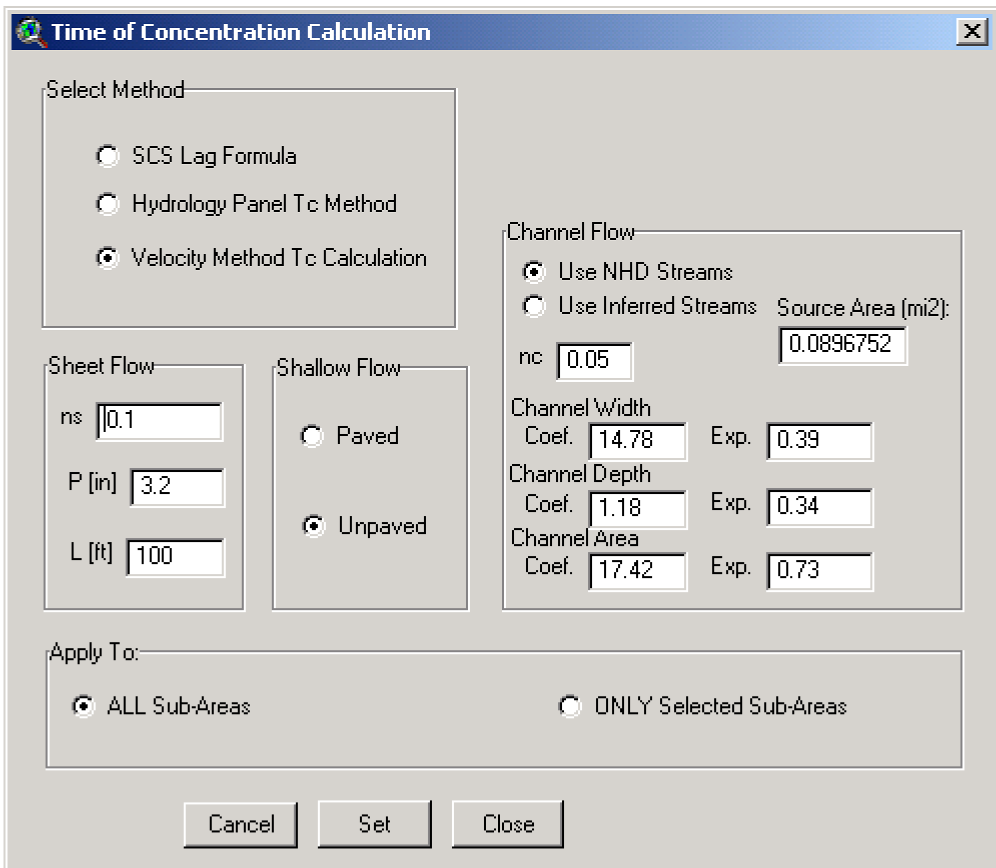
Once this cross-section is determined, the engineer need only choose an appropriate set of stages over which to apply Manning's equation to determine channel velocity and ultimately discharge. For each selected stage, the derived discharge and cross-sectional area ("End Area") should be recorded.

C. Using the FWS Equations within GISHydro2000

The FWS channel geometry equations have an influence on two different elements of the TR-20 input file: the time of concentration calculation and the rating curve for reach routing. Additionally, the way these equations are to be used will likely differ depending on whether GISHydro2000 is being used to generate the TR-20 input file, or whether the input file is being developed manually.

C-1 Determining the Time of Concentration

GISHydro2000 allows for the calculation of the time of concentration, t_c, using three different methods: the SCS lag equation, the Hydrology Panel equation, and the velocity method. The velocity method is the recommended method for t_c calculation. The figure below shows the time of concentration dialog box. If the user selects the velocity method



then the "Channel Flow" portion of the dialog directly reflects how the FWS equations' influence the t_c calculation. GISHydro2000 detects the physiographic province(s) in which the watershed is located and performs an area-weighted calculation to determine the coefficients and exponents of the width, depth, and cross-sectional area channel geometry equations. (The coefficients shown in the illustrated dialog box correspond to the Piedmont province.) Once all parameters have been set, GISHydro2000 proceeds in the calculation of velocity on a pixel-by-pixel bases all along the longest flow path. The channel portion of the longest flow path is indicated by either the minimum source area (the inferred streams option) or by the upstream extent of the 1:100,000 NHD (National Hydrography Dataset) produced by the USGS. Normal depth at bankfull conditions is assumed and thus the local slope, channel roughness, and channel geometry may be used in Manning's equation to determine a velocity. Note that the channel geometry changes slightly on a pixel-by-pixel basis since the drainage area increases in a known way along the flow path. The local area is thus used to determine the local channel bankfull width, depth, and area. The incremental flow length associated with each pixel is also readily determined within the GIS. Dividing this incremental length by the local flow velocity gives an incremental travel time. By summing all incremental travel times for each pixel along the longest flow path the total travel time is calculated. The figure below shows a small portion of the calculations along a longest flow path within the Piedmont region. The reader should also note that the GIS is able to exhaustively make these incremental travel time calculations throughout the watershed so that the user does not need to specify the location of the longest flow path, this is determined internally by the GIS.

Attributes Of Longest Path Sub 0

Value	Count	Type	Mixed	Da	Slope	Width	Depth	Xarea	L_length	Tot_length	Vel	L_time	Tot_time
85	1	swale	No	2175	0.0100	-1.00	-1.00	-1.00	141.4	9577	1.60	0.025	1.502
86	1	swale	No	2185	0.0200	-1.00	-1.00	-1.00	141.4	9718	2.26	0.017	1.519
87	1	swale	No	2193	0.0200	-1.00	-1.00	-1.00	100.0	9818	2.26	0.012	1.531
88	1	swale	No	2196	0.0071	-1.00	-1.00	-1.00	100.0	9918	1.35	0.021	1.552
89	1	swale	No	2197	0.0200	-1.00	-1.00	-1.00	100.0	10018	2.26	0.012	1.564
90	1	swale	No	2198	0.0071	-1.00	-1.00	-1.00	141.4	10160	1.35	0.029	1.594
91	1	channel	No	7475	0.0071	21.71	1.65	35.79	141.4	10301	3.18	0.012	1.606
92	1	channel	No	7657	0.0200	21.92	1.66	36.42	100.0	10401	5.38	0.005	1.611
93	1	channel	No	7682	0.0071	21.95	1.67	36.51	141.4	10543	3.20	0.012	1.623
94	1	channel	No	7699	0.0400	21.96	1.67	36.57	141.4	10684	7.62	0.005	1.628
95	1	channel	No	7710	0.0400	21.98	1.67	36.61	141.4	10825	7.62	0.005	1.634
96	1	channel	No	7722	0.0300	21.99	1.67	36.65	100.0	10925	6.60	0.004	1.638
97	1	channel	No	7738	0.0071	22.01	1.67	36.70	141.4	11067	3.21	0.012	1.650
98	1	channel	No	7790	0.0071	22.07	1.67	36.88	141.4	11208	3.21	0.012	1.662

C-2 Determining the Rating Curve for reach Routing

GISHydro2000 uses the FWS equation to develop the rating curve for each routing reach within the watershed. The user indicates the location of the cross-section within the GISHydro2000 interface by draWing a line perpendicular to the flow path at a representative location along the routing reach. A cross-section editor dialog box appears as shown below. The GIS automatically determines the drainage area at the location of the cross-section. This area is used with the region-appropriate FWS equations to infer the in-bank portion of the channel geometry. The out-of-bank portion of the geometry is determined directly from the DEM. Combining the in-bank and out-of-bank portions of the cross-section and applying Manning's equation with the normal depth assumption at various depths spanning the likely range of flow conditions allows for the generation of a stage-discharge-end area table which is used directly as input to TR-20.

APPENDIX 5
EXAMPLES OF CALIBRATION OF WINTR-20 TO THE REGIONAL REGRESSION EQUATIONS

OVERIVIEW

The example presented is produced to illustrate how a study may be developed and how an existing development condition WinTR-20 model and calibration window are formed and how the model may be adjusted to the window. Although the ultimate development condition is required by regulation for the design discharges, the existing condition WinTR-20 model is the one which must be calibrated. This is the case because the regression equations are developed from USGS gage data. This data represents flows resulting from landuse conditions which are currently present or have been present in the past. This example presents a study up to the point where the existing condition WinTR-20 model has been calibrated. The design discharges are then developed from replacing the existing development curve number with the ultimate condition curve number and making any possible required changes to the time of concentration. In the past, GISHydro2000 was the primary tool. It was used to develop input parameters and calculate regression equations and calibration limits as well as create TR-20 input parameters, form and run the model. The platform which GISHydro2000 runs on, ArcView 3, is no longer supported by ESRI and there is a need to move to the ArcGIS platform. This move is ongoing and will result in the GISHydroNXT application. The study using GISHydroNXT is shown here. GISHydroNXT can be found and downloaded from the GISHydro website which is located at:

http://www.gishydro.umd.edu/

This revision of the Hydrology Panel Report required use of WinTR-20 which can be downloaded at

http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/WinTR20.html.

For those users who rely on the web server to run GISHydro2000, they may form a TR-20 model and use the functionality provided in WinTR-20 'Convert Old Data' to open and run the file.

PROJECT DESCRIPTION

The hydrology study is needed to compute ultimate development discharges for use in the hydraulic model to be performed when determining the type, size and location for the structure to replace SHA Bridge Number 1006200. The study, report and computed discharges will be submitted to Maryland Department of Environment (MDE) for their review and approval as part of obtaining a waterway construction permit for the project. This structure was built in 1932 and needs to be replaced due to its age and structural condition. The structure carries MD 140, Main Street, over Flat Run in Frederick County, Maryland (Figure A5-1).

MD 140 is classified as a Rural Minor Arterial by the Maryland Functional Classification System; the design storm for this roadway should be the 50-year event. The hydrology study will develop discharges for the 2-, 10-, 25-, 50- and 100-year storm events. The study should focus on calibrating discharges to the 50-year and 100-year storm events since the 50-year is the design storm and the 100-year is the base flood used to analyze floodplain impacts.

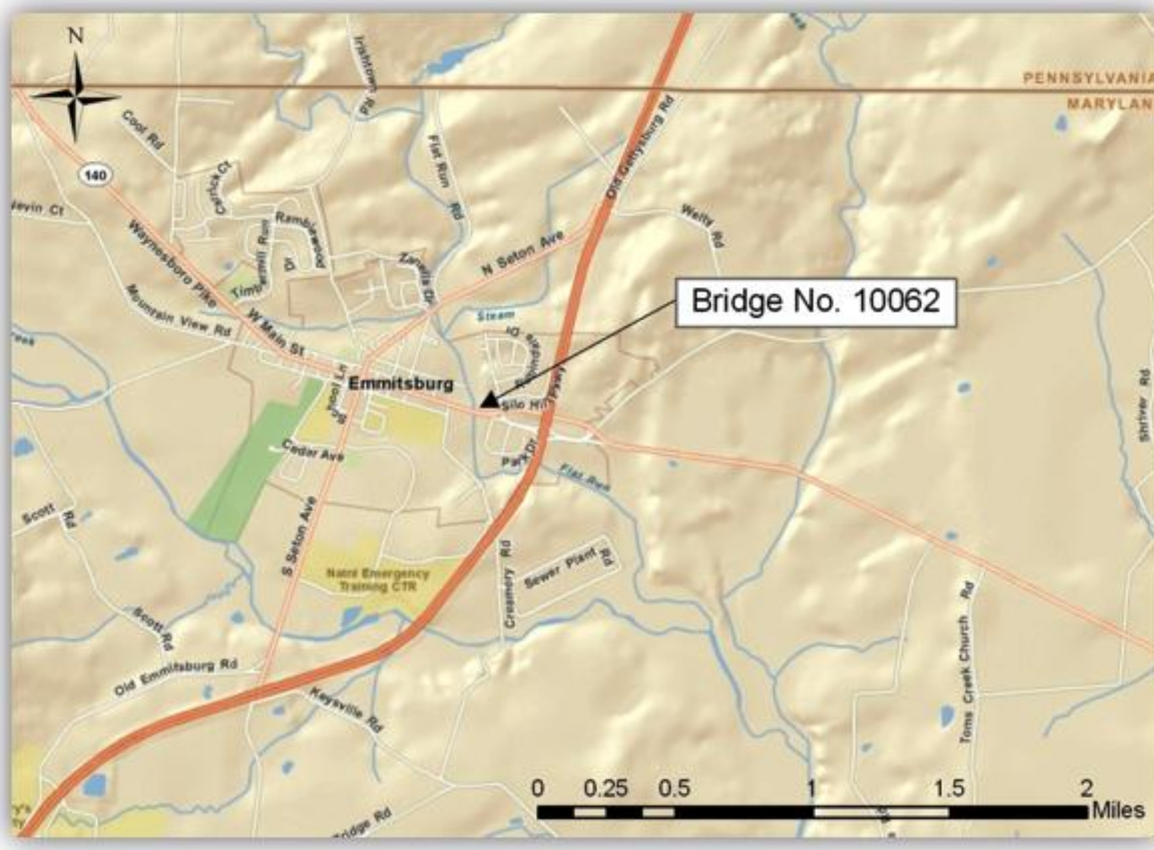


Figure A5-1. Location of the MD 140 bridge site over Flat Run in Frederick County, MD.

Watershed Description

The 10.8 square mile watershed lies entirely in the Blue Ridge Region but is contained in both Maryland and Pennsylvania. The watershed is characterized by mostly cropland with some urban and forested land use. There are no U. S. Geological Survey gages in the watershed.

Study Description

The design flows will be based on a WinTR-20 hydrology model using ultimate development with the land use to be derived from zoning maps. This example develops and calibrates the existing condition WinTR-20 model to be within the Fixed Region Regression Equation estimate and the upper 67 percent confidence limit of the Tasker program.

Step 1 – Watershed Delineation and Conceptual Approach

The first task is to delineate the watershed and develop a conceptual modeling approach. GISHydroNXT was used to delineate the watershed (Figure A5-2). SSURGO soils and the NLUD 2001 land use databases were used in this analysis. The Maryland Office of Planning 2002 land use data cannot be used for this analysis because the drainage area extends outside of the Maryland boundary. The NLUD 2001 data should be checked to ensure it adequately represents the land use. These data were developed from satellite imagery and can overestimate the amount of tree cover.

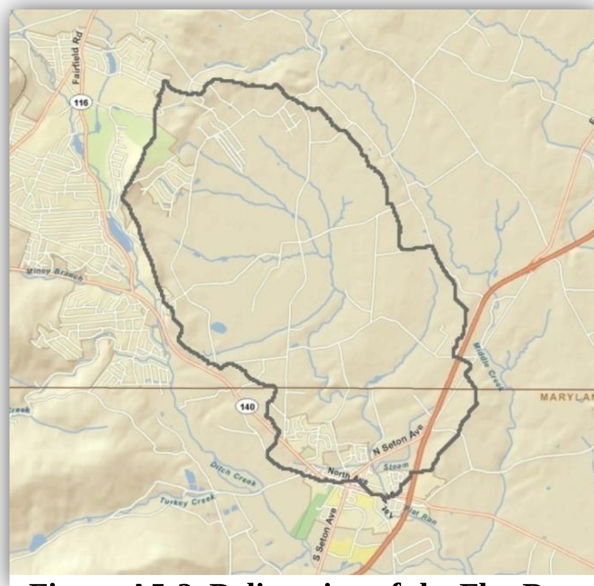


Figure A5-2. Delineation of the Flat Run watershed.

Select the outlet to delineate the drainage area and then compute the basin statistics. The conceptual approach to modeling the watershed should be developed. This particular watershed has a semi-elongated shape and is comprised of one main stem which forms in the upper third of the watershed from three contributing tributaries . There are no structures on the main stem which would provide significant storage such as dams or railroad crossings. There are also no crossings within the watershed where additional design discharges may be needed. For these reasons, a single area approach should first be considered.

The NLUD 2001 land use data were checked using aerial photos. Several locations were investigated and the data visually appears to represent the land use data in most cases. Figure A5-3 shows the land use categories made semi- transparent with the aerial photography shown underneath. In the map below, the aqua blue color represents land use Value 22 or low intensity residential. The limits, in most areas, appear to be reasonable.

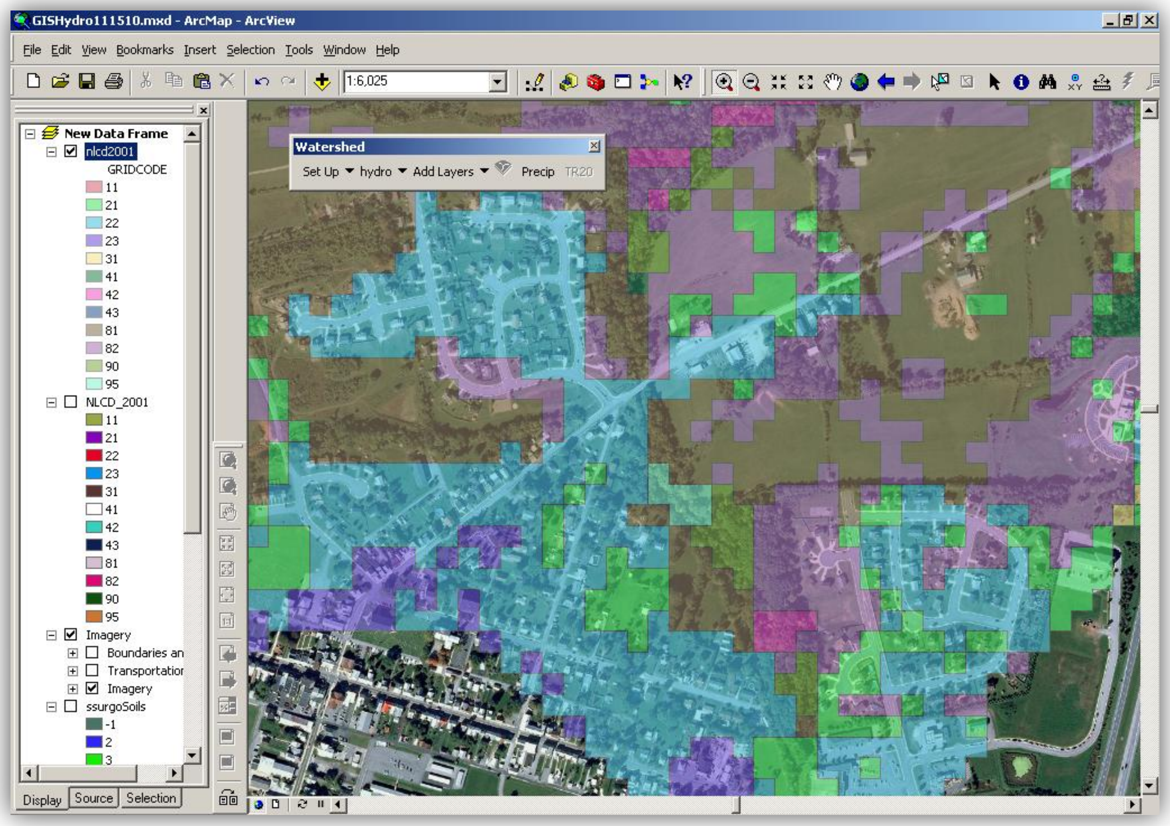


Figure A5-3. Distribution of land use data from the NLUD 2001 database.

Step 2 – Compute the Fixed Region Regression Equations and Tasker Limits

Use GISHydroNXT to compute the appropriate flood discharges using the Fixed Region Regression Equations for the Blue Ridge Region and compute the Tasker limits.

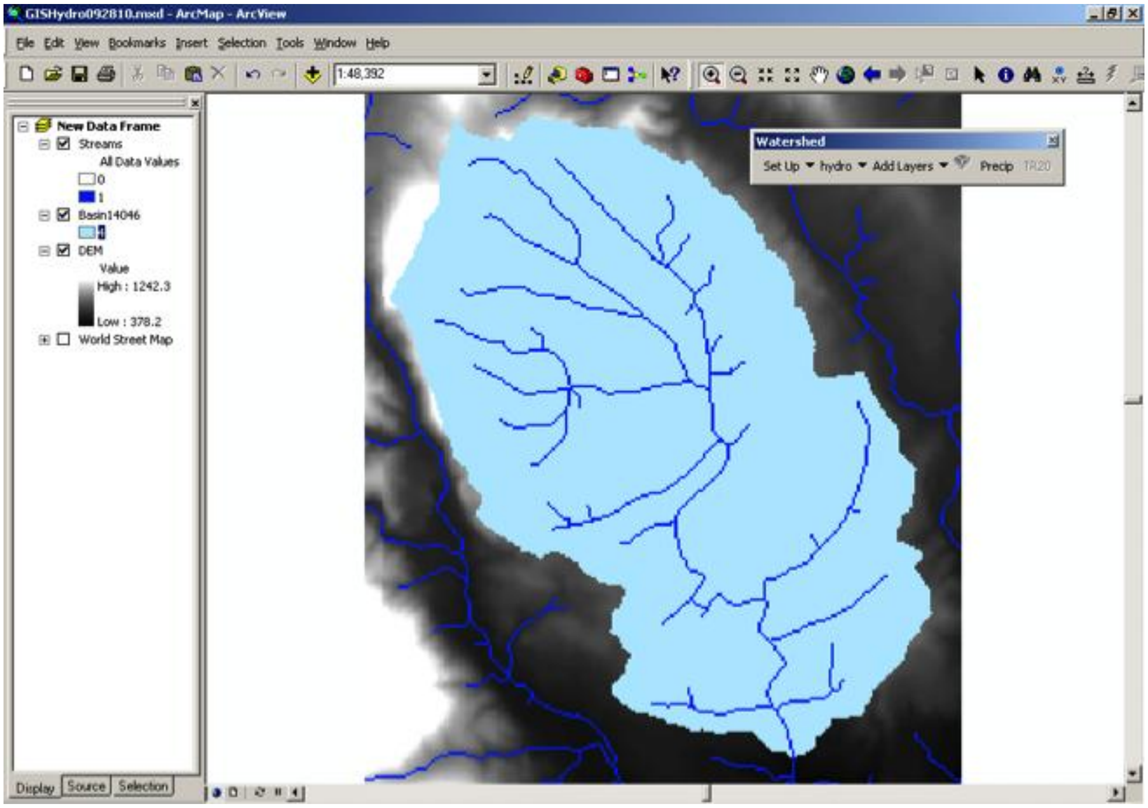


Figure A5-4. Flat Run watershed upstream of MD 140 in Frederick County, MD.

Step 3 – Develop the Time of Concentration

The time of concentration should be calculated manually using the TR55 velocity method approach after estimating the location of the longest hydraulic flow path. The total time of concentration is the sum of sheet, shallow concentrated and channel flow segments.

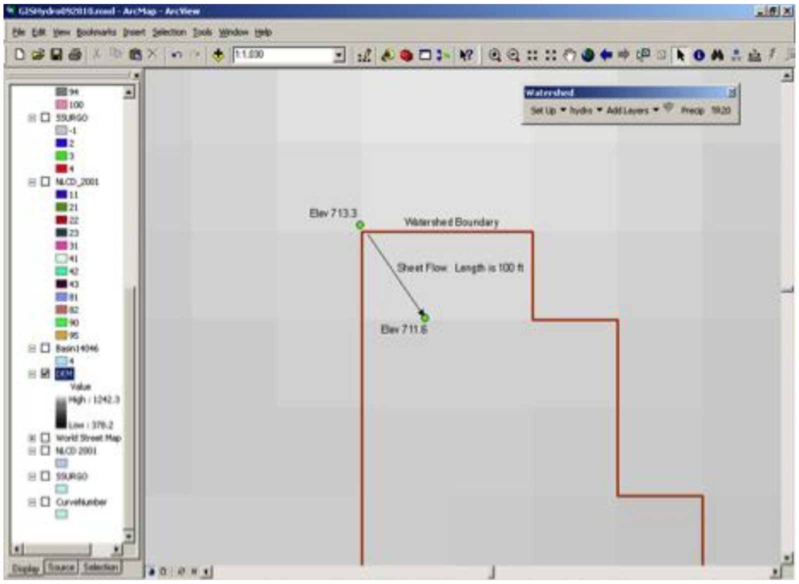


Figure A5-5. Flow lines for Sheet Flow.

<u>Sheet Flow</u>
From the most hydraulically distant point, determine the length and slope of the flow lines. The elevation values are developed from the digital elevation model (DEM) included with GISHydroNXT (Figure A5-5).

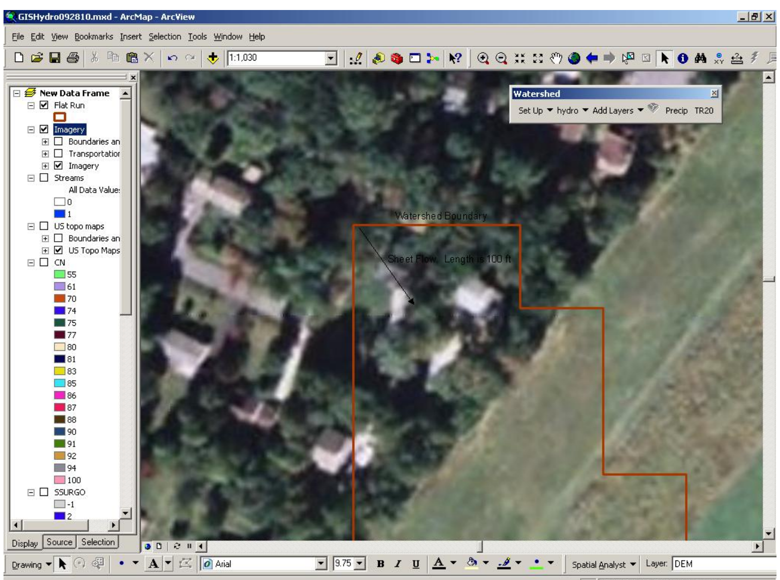


Figure A5-6: Aerial photograph showing the Sheet Flow reach.

The surface cover for the sheet flow can be determined from aerial photographs such as the one shown in Figure A5-6, which shows residential grass and light tree cover. This should also be field verified. The layer file shown can be viewed using adding GIS data from online services through the following link:

http://www.arcgis.com/home/item.html?id=a5fef63517cd4a099b437e55713d3d54.

Computation of the Sheet Flow travel time is given in calculation sheet A5-1.

Shallow Concentrated Flow

Obtain the slope and distance from the end of the sheet flow to the beginning of the channel as shown in Figure A5-7. Determine whether this is paved or unpaved. The beginning of the channel for this example appears to be a pond. This should be field verified and checked. The seamless USGS Quad map layer can be viewed using adding GIS data from online services through the following link:

http://www.arcgis.com/home/item.html?id=9608ff2e65224ef29c7337f47108b8a5.

Computation of the Shallow Concentrated Flow travel time is given in calculation sheet A5-1.

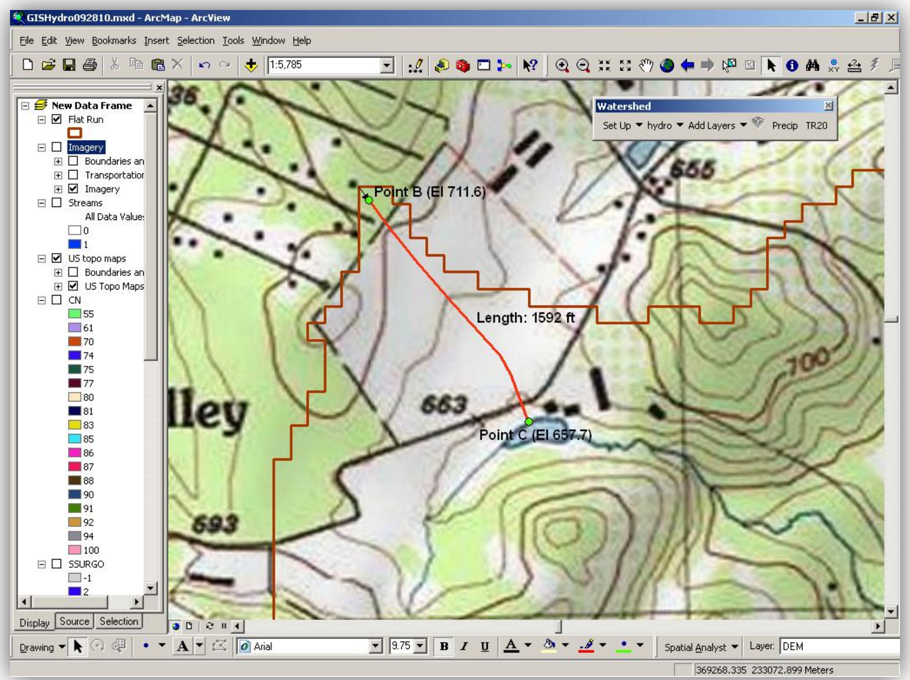


Figure A5-7. Location of the Shallow Concentrated Flow reach.

Channel Flow

The channel flow segment was broken into two reaches because of the difference in drainage areas and the enlargement of the channel between these reaches. The channel will be significantly larger and deeper between Points D and E than between Points C and D (Figure A5-8). The U.S. Fish & Wildlife Service (USFWS) Report *Maryland Stream Survey: Bankfull Discharge and Channel Characteristics of Streams in the Alleghany Plateau and the Valley and Ridge Hydrologic Regions*, CBFO-S03-01, dated May 2003, is used to estimate the channel dimensions for this project. These equations can be found in Appendix 4 of the September 2010

Hydrology Panel report. Two cross-sections are needed: between Points C and D and between Points D and E. The sections should be located close to the midpoint of each reach, their locations are shown on Figure A%-8. The contributing drainage area to both cross-sections is needed. GISHydroNXT is used to delineate the contributing area to the mid-point of each reach. The drainage area contributing to Reach C-D is 0.9 square miles and to Reach D-E is 7.4 square miles. The locations of the cross sections are shown in Figure A5-8. Figure 13 of the USFWS report is used to estimate channel characteristics which are reported in the attached spreadsheet. The travel times used to calculate the Channel Flow time of concentration are also reported in calculation sheet A5-1.

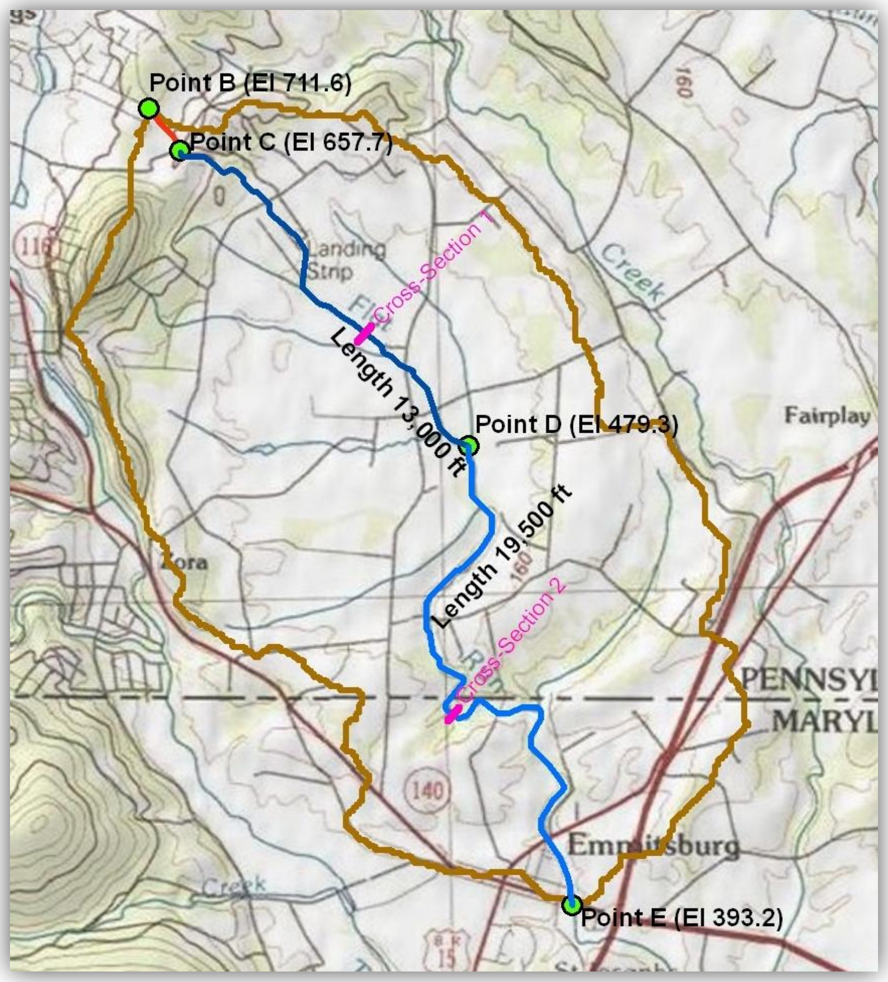


Figure A5-8. Location of channel reaches for determining the Channel Flow travel times.

One of the values requiring the most judgment in estimating the time of concentration is the selection of the Manning's Roughness Coefficient. In this calculation, the roughness coefficient must account for all losses including minor losses such as changes in channel cross-section, local obstructions and gradient changes. The value should be larger than what may be appropriate for a straight uniform channel. The recommended 0.05 base value is used for this example.

Using these base values a total time of concentration was computed as 3.82 hours. This value should be compared to the W.O. Thomas, Jr. Equation estimate and the SCS Lag Equation estimate which are reported in the basin statistics file. These values are 5.1 hours and 4.5 hours, respectively. The time of concentration based on time times may be underestimated based on this comparison.

Time of Concentration				
Project: MD 140 over Flat Run	By: J. Knaub		Date: 12/22/10	
Location: Frederick County	Checked:		Date:	
Notes: Undivided Watershed. This calculation is performed for and example project to be included in the SHA/MDE hydrology panel report. No calibration has been performed.				
Sheet Flow (Aplicable to T_c only)				
Segment I.D.	A-B			
1. Surface Description (See Table)......................	Grass/Light Woods			
2. Manning's roughness coefficient (See Table)...	0.3			
3. Flow Length, L (total L≤ 300 ft)...... ....ft	100			
4. Two-year 24-hr rainfall, P_2.............................in	3.15			
5.Land Slope, s...ft/ft	0.017	=(713.3-711.6)/100		
6. $T_t = \frac{0.007\,(nL)^{0.8}}{P_2^{0.5}\,s^{0.4}}$ compute T_t.......hr	0.31			0.31
Shallow Concentrated Flow				
Segment I.D.	B-C			
7. Surface Description (Paved or Unpaved)...........	Unpaved			
8. Flow Length, L...ft	1590			
9.Land Slope, s...ft/ft	0.034	=(711.6-657.7)/1590		
10.Average Velocity, V................................ft/s	3.0			
11. $T_t = \frac{L}{3600\ V}$ compute T_t.......hr	0.15			0.15
Channel Flow				
Segment I.D.	C-D	D-E		
12. Watershed area, a ....mi^2	0.9	7.4		
13. Cross sectional flow area, ...ft^2	12.2	59.1		
14. Width, ...ft	13.2	33.5		
15. Depth, ...ft	0.9	1.8		
13. Wetted perimeter, P_w....................................ft	15.1	37.0		
14. Hydraulic radius,r ...... $r = \frac{a}{P_w}$ ....ft	0.8	1.6		
15.Channel Slope, s.......................................ft/ft	0.0137	0.0044		
16. Manning's roughness coefficient (See Table)...	0.05	0.05		
17 $v = \frac{1.49\,r^{\frac{2}{3}}\,s^{\frac{1}{2}}}{n}$ Compute V.......ft/s	3.0	2.7		
18. Flow Length, L...ft	13000	19500		
19. $T_t = \frac{L}{3600\ V}$ compute T_t.......hr	1.19	2.01		3.20
20. Watershed or Subarea T_c or T_t (add T_t in steps 6, 11, and 19)............................Hr=				**3.65**

Calculation Sheet A5-1: Time of concentration computation using TR-55 method.

Step 4 – Determine the Rainfall Data and Build the WinTR-20 Model

Use GISHydroNXT to develop the rainfall depths for various storm duration and frequencies. The values for this example are shown in Figure A5-9. GISHydroNXT develops these data from the NOAA Atlas 14 publication.

GISHydroNXT will build the WinTR-20 model for each storm event to evaluate. The program asks for a time of concentration value, the engineer should enter the TR-55 velocity method value computed manually.

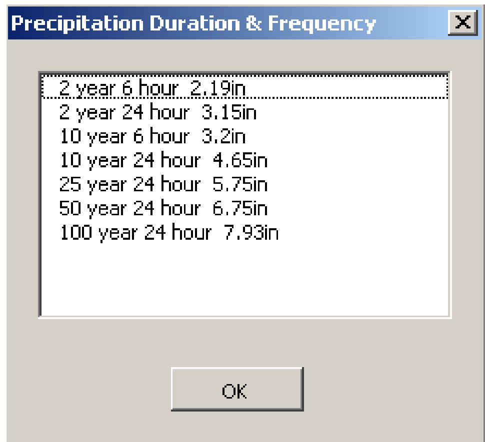


Figure A5-9. Rainfall depths from NOAA Atlas 14.

Step 5 – Run WinTR-20

Open WinTR-20 and open the input file created by GISHydroNXT. Save the file and run to compute discharges.

Step 6 – Evaluate Results

Figure A5-10 shows the results of the WinTR-20 model as compared to the regression equation and upper 67-percent Tasker Limit.

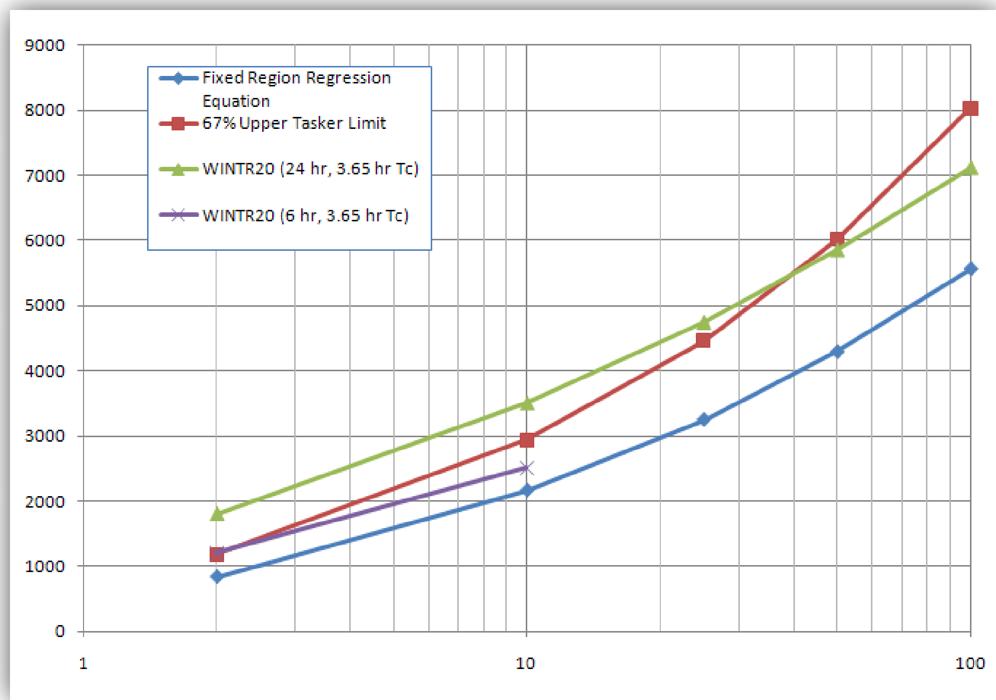


Figure A5-10. Comparison of Win TR-20 flood discharges without calibration to the Fixed Region regression estimates.

Table A5-1

Return Period	Discharge			
	Fixed Region Eqn	Upper 67% Tasker Limit	WINTR20 (24 hr, Tc=3.65 hrs)	WINTR20 (6 hr, Tc=3.65)
2	833	1180	1806	1201
10	2160	2940	3502	2512
25	3240	4460	4740	- - -
50	4280	6020	5852	- - -
100	5560	8030	7117	- - -

Figure A5-10 and Table A5-1 show that the 50-year and 100-year storm events are within the Fixed Region Regression Equation and the upper 67-percent limit of the Tasker Program. The 24-hour storm event flows for the 2-year, 10-year and 25-year are above the 67-percent Tasker limit. It is appropriate to use the 6-hour storm duration for the 2-year and 10-year events since the time of concentration is less than 6 hours. The 25-year event falls slightly above the upper 67-percent limit of the Tasker Program. This implies the TR-20 model should be calibrated. A separate reason to calibrate is that the computed time of concentration is shorter than both predictions from the Lag Equation and the W.O. Thomas Jr. Equation. It is reasonable and appropriate to calibrate this model. A longer time of concentration would affect all flows – decreasing the peak flow values.

One common and reasonable adjustment is to investigate the reach lengths. Figure A5-11 shows the computed reach length on top of an aerial photo with the stream thalweg shown in red. This depiction shows that digitizing a blue line from the 24,000 scale USGS Quad map effectively shortens the true reach length. A 10 percent increase in the reach lengths for the channel flow portion is appropriate and should be done to more accurately reflect the true lengths. The time of concentration is recalculated in calculation sheet A5-2 as 4.14 hours. This time of concentration is more in line with the values estimated by the Lag time and Thomas equations.

Time of Concentration				
Project: MD 140 over Flat Run	By: J. Knaub		Date: 12/22/10	
Location: Frederick County	Checked:		Date:	
Notes: Undivided Watershed. This calculation is performed for and example project to be included in the SHA/MDE hydrology panel report. Calibrated by increasing reach length by 10%				
Sheet Flow (Aplicable to T_c only)				
Segment I.D.	A-B			
1. Surface Description (See Table)….................	Grass/Light Woods			
2. Manning's roughness coefficient (See Table)…	0.3			
3. Flow Length, L (total L≤ 300 ft)…… ....ft	100			
4. Two-year 24-hr rainfall, P_2………….....…........in	3.15			
5.Land Slope, s……………………………….......ft/ft	0.017	=(713.3-711.6)/100		
6. $T_t = \frac{0.007\,(nL)^{0.8}}{P_2^{0.5}\,s^{0.4}}$ compute T_t…….hr	0.31			0.31
Shallow Concentrated Flow				
Segment I.D.	B-C			
7. Surface Description (Paved or Unpaved)……….	Unpaved			
8. Flow Length, L……………………..........…….ft	1590			
9.Land Slope, s……………………...…………ft/ft	0.034	=(711.6-657.7)/1590		
10.Average Velocity, V……………………………ft/s	3.0			
11. $T_t = \frac{L}{3600\ V}$ compute T_t…….hr	0.15			0.15
Channel Flow				
Segment I.D.	C-D	D-E		
12. Watershed area, a ……………….............….mi²	0.9	7.4		
13. Cross sectional flow area, .. …………………ft²	12.2	59.1		
14. Width, . ……………...…………………...………ft	13.2	33.5		
15. Depth, ………………………………..…………ft	0.9	1.8		
13. Wetted perimeter, P_w…………..…………………..ft	15.1	37.0		
14. Hydraulic radius,r …… $r = \frac{a}{P_w}$ ....ft	0.8	1.6		
15.Channel Slope, s……………..…………………ft/ft	***0.0125***	***0.004***	**Recalculated**	
16. Manning's roughness coefficient (See Table)…	0.05	0.05		
17 $v = \frac{1.49\,r^{\frac{2}{3}}\,s^{\frac{1}{2}}}{n}$ Compute V…....ft/s	2.9	2.6		
18. Flow Length, L……………………….....……….ft	***14300***	***21450***	**Increased by 10%**	
19. $T_t = \frac{L}{3600\ V}$ compute T_t…….hr	1.38	2.30		3.68
20. Watershed or Subarea T_c or T_t (add T_t in steps 6, 11, and 19)……………………….Hr=				**4.14**

Calculation Sheet A5-2: Time of Concentration with 10% increase in reach lengths.

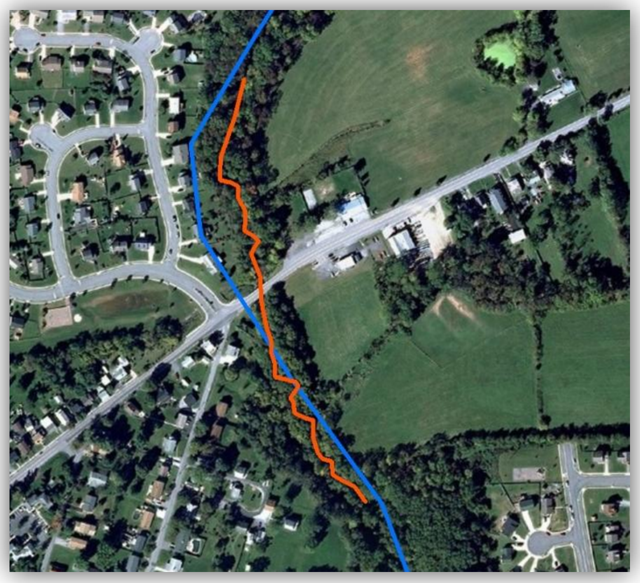


Figure A5-11. Comparison of computed reach length (blue) to the stream thalweg (red) from an aerial photo.

The computed discharges are in Figure A5-12 with the 2-year and 10-year storms computed using both the 6-hour and 24-hour storm durations. The 2-year and 10-year storm events, computed using 4.14 hours for the time of concentration and the 6-hour storm duration, both fall within the calibration window. The larger storm events are computed using the 24-hour storm duration and lie within the calibration window.

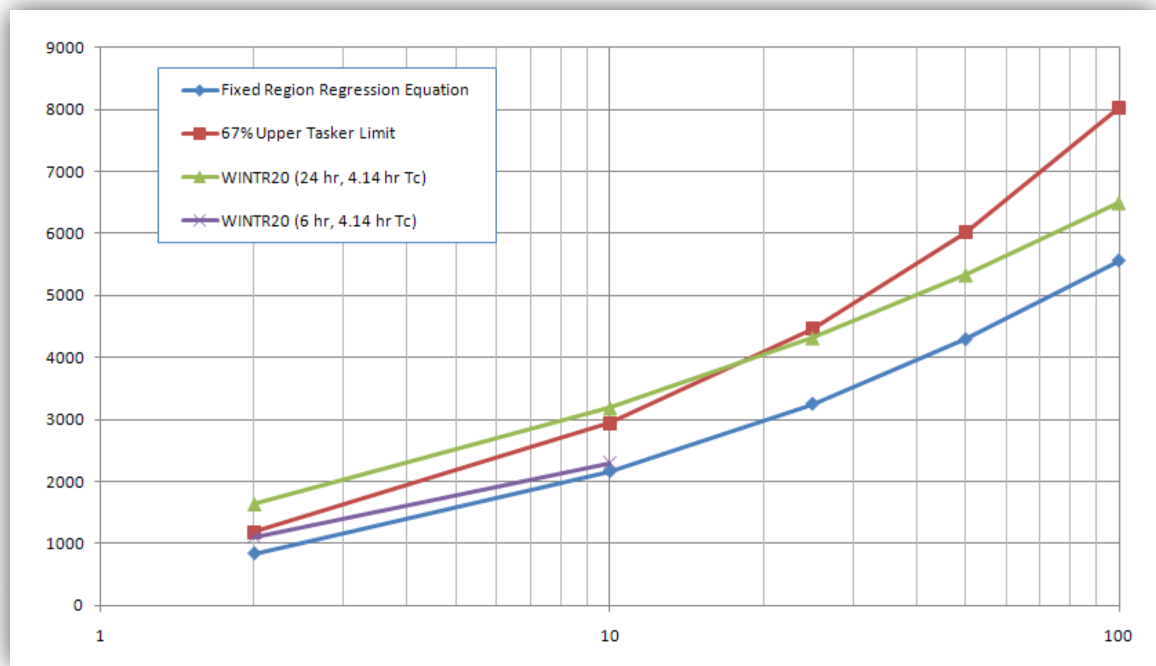


Figure A5-12. Comparison of Win TR-20 flood discharges from a calibrated model to the Fixed Region regression estimates.

Table A5-2

Return Period	Discharge			
	Fixed Region Eqn	Upper 67% Tasker Limit	WINTR20 (24 hr, Tc=4.14 hrs)	WINTR20 (6 hr, Tc=4.14)
2	833	1180	1636	1103
10	2160	2940	3182	2297
25	3240	4460	4313	- - -
50	4280	6020	5330	- - -
100	5560	8030	6494	- - -

The final calibrated existing condition WinTR-20 model will be reported using the adjusted time of concentration value of 4.14 hours and the 6-hour storm duration for the 2- and 10-year storms and the 24-hour storm duration for the 25-, 50- and 100-year storm events. The results are shown in Figure A5-13 and Table A5-3. All storms fall within the calibration limits.

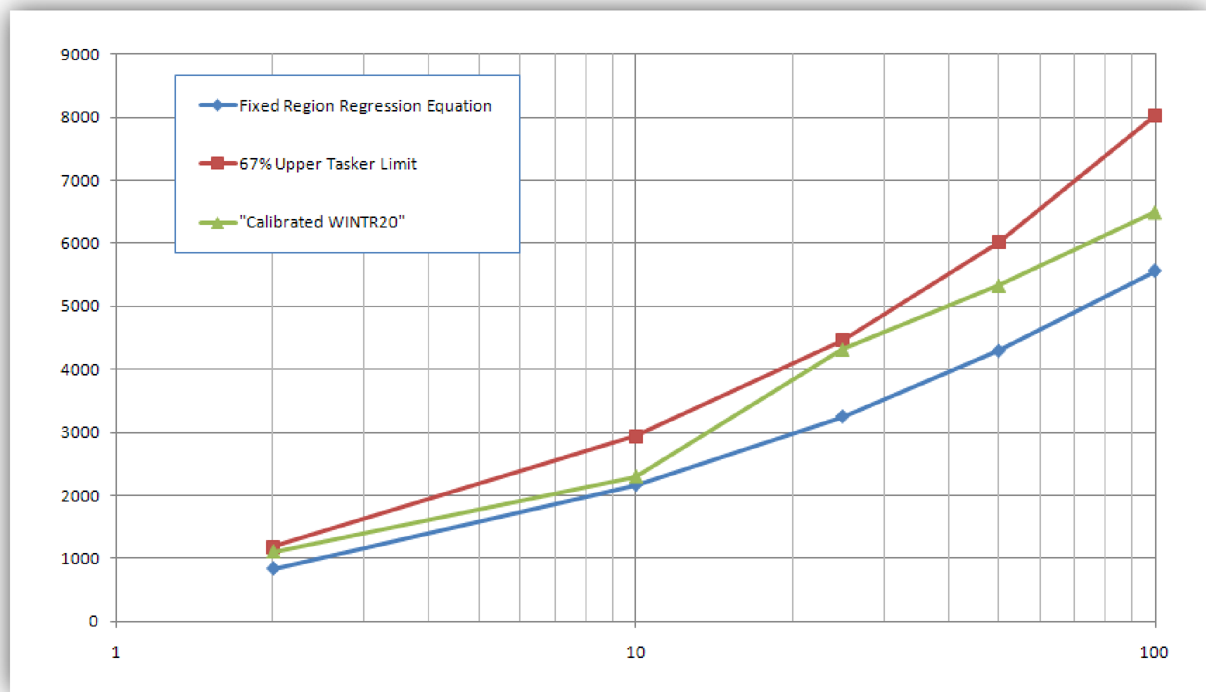


Figure A5-13. Final calibrated Win TR-20 flood discharges as compared to the Fixed Region regression estimates.

Table A5-3. Calibrated Win TR-20 model (6- and 24-hour storm durations)

Return Period	Discharge		
	Fixed Region Eqn	Upper 67% Tasker Limit	WINTR20 (Tc=4.14 hrs)
2	833	1180	1103
10	2160	2940	2297
25	3240	4460	4313
50	4280	6020	5330
100	5560	8030	6494

Step 7 – Form the Ultimate Condition WinTR-20 Model

The final step to complete a study is to modify the calibrated existing condition WinTR-20 model to reflect the ultimate development condition. This example illustrates how to calibrate an existing condition WinTR-20 model. Chapter 4 of the September 2010 Hydrology Panel report provides instructions on how to perform this final step.

<u>GISHydroNXT Basin Statistics</u>

```
Hydro Extension Version Date: June 30, 2010
Analysis Data:10/29/2010

Data Selected:
DEM Coverage: DEMTOT
Land Use Coverage: NLUD_2001
Soil Coverage: SSURGO
Hydrologic Condition
Outlet Easting:    372642(MD Stateplane, NAD 1983)
Outlet Nothing:    226076(MD Stateplane, NAD 1983)
Findings:
Region(s)Blue Ridge and Great Valley
Drainage Area:  10.80square miles
Channel Slope:  29.0431ft/mile
Land Slope:  0.0466ft/ft
Longest Flow Path:  7.12mi
BasinRelief: 129.19ft
Time of Concentration:  4.46hr  [from SCS Lag Equation * 1.67
Time of Concentration:  5.1hr  [W.O. Thomas, Jr. Equation]
Average CN:   79.87
%Impervious  1.49%
%Forest Cover  21.00%
%Limestone.00%
%Storage0.00%
%A Soils:  0.00
%B Soils:  31.45
%C Soils:  54.57
%D Soils:  14.00
2-Year, 24-hour Prec: 3.15inches
```

Thomas Discharges and Tasker Limits

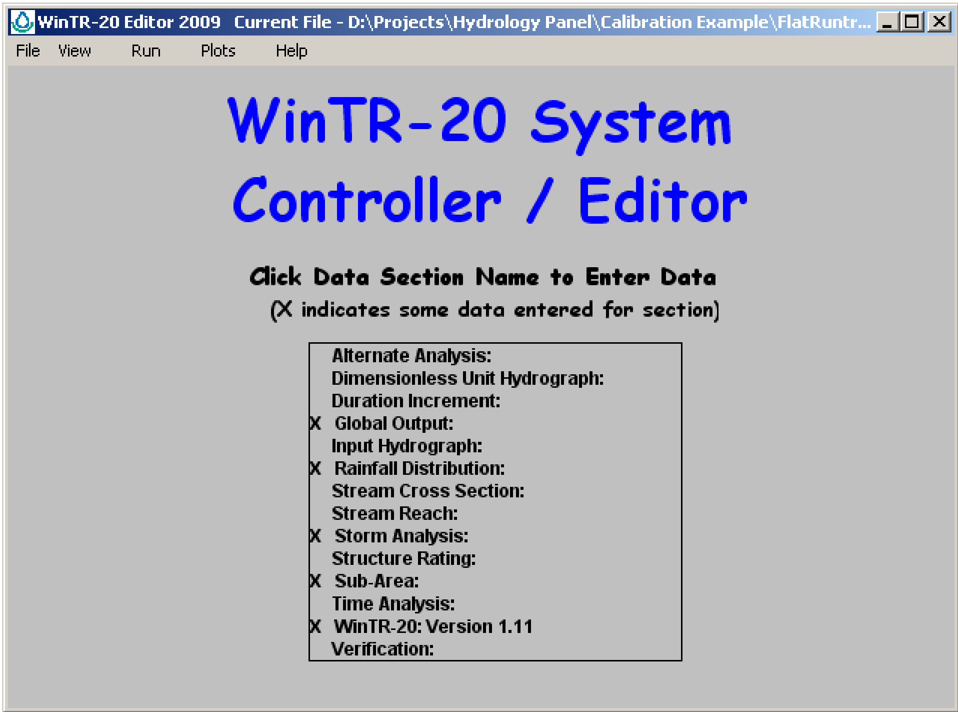
Flood frequency estimates for
MD 140 over Flat Run
REGION: Blue Ridge & Piedmont Rural
area= 10.80:lime = 0.00:forest = 21.00 :skew= 0.53

Return Period	Discharge (cfs)	Standard Error of Prediction (percent)	Equivalent Years of Record	Standard Error of Prediction (logs)
1.25	498.	42.8	2.74	0.1780
1.50	656.	38.2	3.03	0.1603
2.00	833.	36.2	3.62	0.1523
5.00	1520.	31.9	8.71	0.1351
10.00	2160.	31.3	13.67	0.1329
25.00	3240.	32.8	19.28	0.1387
50.00	4280.	35.0	22.05	0.1477
100.00	5560.	38.1	23.53	0.1598
200.00	7130.	41.6	24.19	0.1736
500.00	9750.	47.0	24.20	0.1939

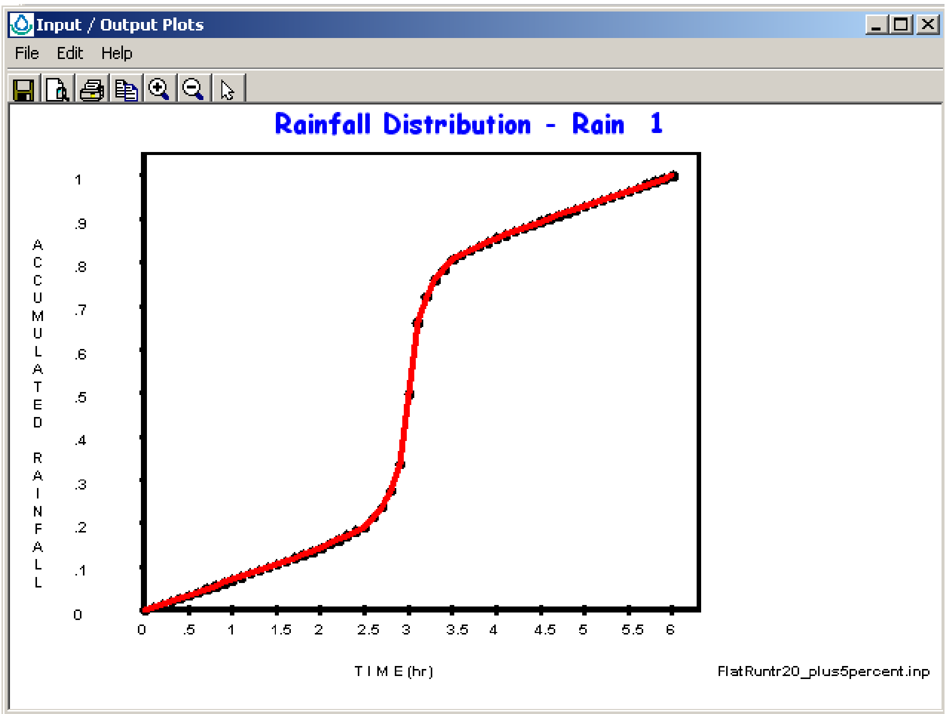
P R E D I C T I O N   I N T E R V A L S

Return	50 PERCENT		67 PERCENT		90 PERCENT		95 PERCENT	
Period	lower	upper	lower	upper	lower	upper	lower	upper
1.25	377.	657.	330.	750.	251.	987.	219.	1130.
1.50	511.	843.	454.	949.	354.	1220.	314.	1370.
2.00	656.	1060.	586.	1180.	463.	1500.	413.	1680.
5.00	1230.	1880.	1120.	2080.	905.	2560.	817.	2840.
10.00	1760.	2660.	1590.	2940.	1300.	3610.	1170.	3990.
25.00	2610.	4030.	2350.	4460.	1900.	5530.	1710.	6140.
50.00	3400.	5390.	3050.	6020.	2430.	7560.	2170.	8450.
100.00	4330.	7140.	3850.	8030.	3010.	10300.	2660.	11600.
200.00	5430.	9350.	4780.	10600.	3650.	13900.	3200.	15900.
500.00	7200.	13200.	6240.	15200.	4620.	20600.	3990.	23800.

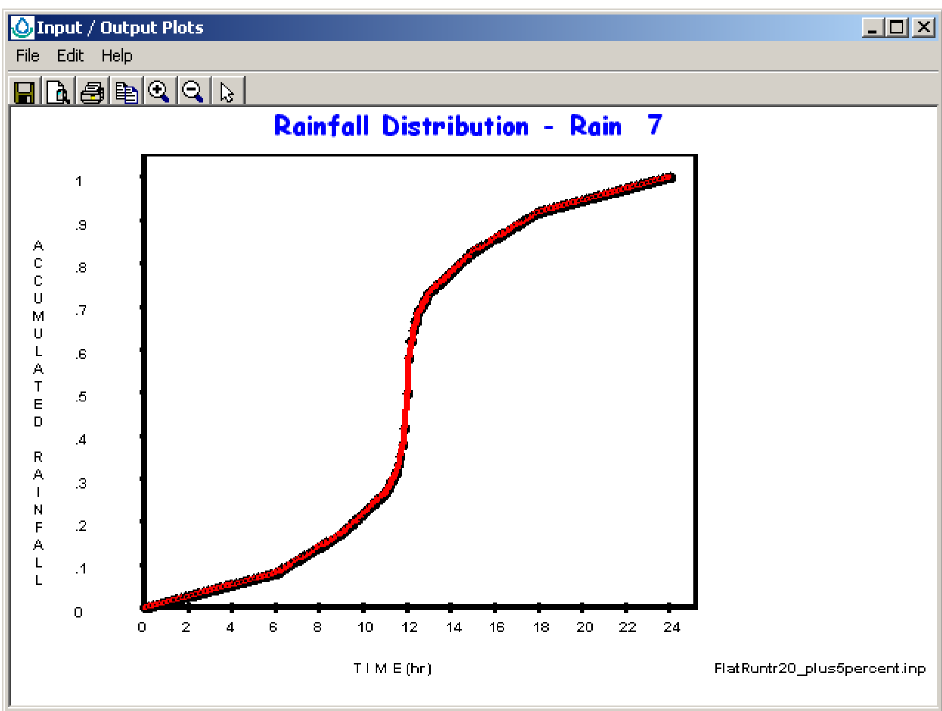
WinTR-20 Model Development Process

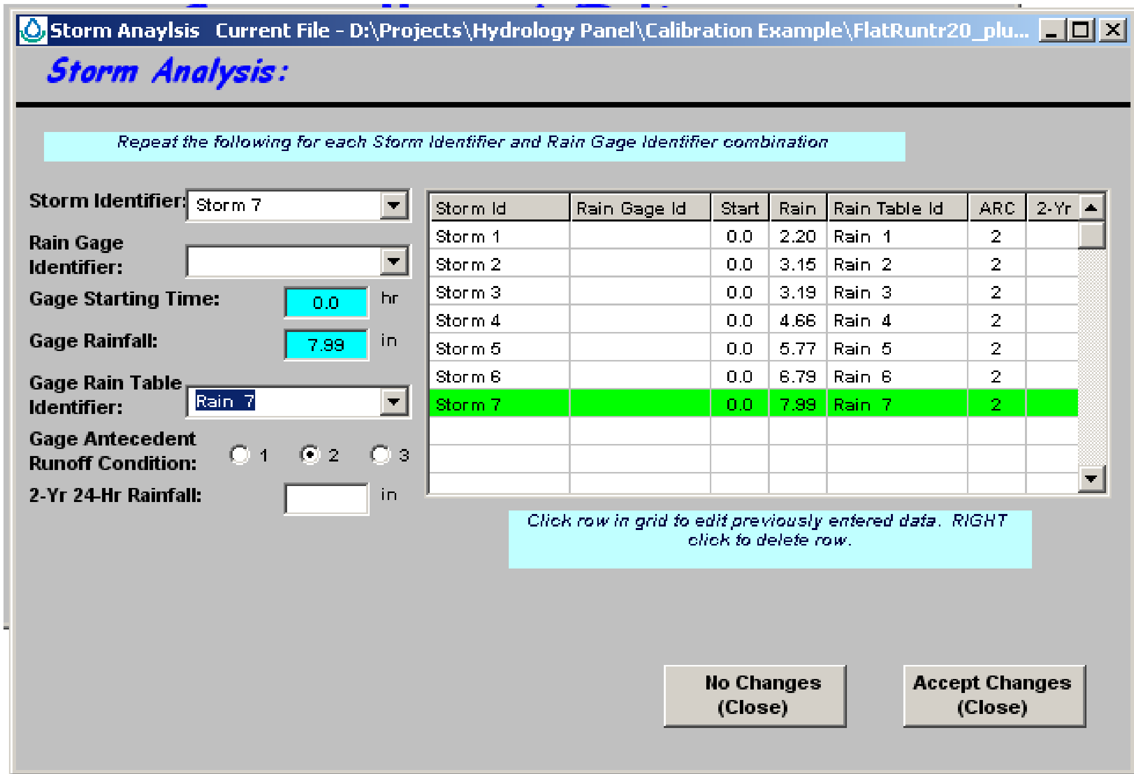


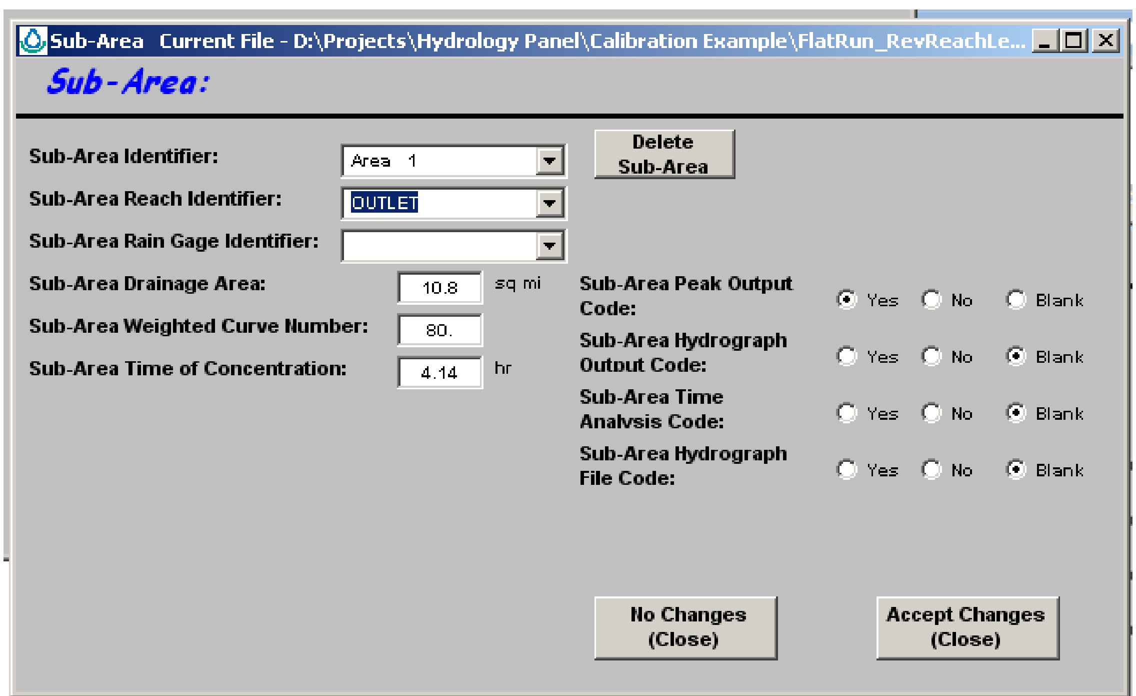
Example 6-hour Rainfall Distribution



Example 24-hour Rainfall Distribution




Storm Anaylsis Current File - D:\Projects\Hydrology Panel\Calibration Example\FlatRuntr20_plu...
Storm Analysis:
Repeat the following for each Storm Identifier and Rain Gage Identifier combination
Storm Identifier: Storm 7
Rain Gage Identifier:
Gage Starting Time: 0.0 hr
Gage Rainfall: 7.99 in
Gage Rain Table Identifier: Rain 7
Gage Antecedent Runoff Condition: 1 2 3
2-Yr 24-Hr Rainfall: in
Storm Id | Rain Gage Id | Start | Rain | Rain Table Id | ARC | 2-Yr
Storm 1 | | 0.0 | 2.20 | Rain 1 | 2 |
Storm 2 | | 0.0 | 3.15 | Rain 2 | 2 |
Storm 3 | | 0.0 | 3.19 | Rain 3 | 2 |
Storm 4 | | 0.0 | 4.66 | Rain 4 | 2 |
Storm 5 | | 0.0 | 5.77 | Rain 5 | 2 |
Storm 6 | | 0.0 | 6.79 | Rain 6 | 2 |
Storm 7 | | 0.0 | 7.99 | Rain 7 | 2 |
Click row in grid to edit previously entered data. RIGHT click to delete row.
No Changes (Close)
Accept Changes (Close)


Sub-Area Current File - D:\Projects\Hydrology Panel\Calibration Example\FlatRun_RevReachLe...
Sub-Area:
Sub-Area Identifier: Area 1
Delete Sub-Area
Sub-Area Reach Identifier: OUTLET
Sub-Area Rain Gage Identifier:
Sub-Area Drainage Area: 10.8 sq mi
Sub-Area Weighted Curve Number: 80.
Sub-Area Time of Concentration: 4.14 hr
Sub-Area Peak Output Code: Yes No Blank
Sub-Area Hydrograph Output Code: Yes No Blank
Sub-Area Time Analysis Code: Yes No Blank
Sub-Area Hydrograph File Code: Yes No Blank
No Changes (Close)
Accept Changes (Close)

WinTR-20 Output

```
WinTR-20 Printed Page File      Beginning of Input Data List
D:\Projects\Hydrology Panel\Calibration Example\FlatRun_RevReachLengthpls10.inp

WinTR-20: Version 1.11                   0         0                   0
MD140 over Flat Run
Single area TR-20 analysis

SUB-AREA:
          Area   1  OUTLET              10.8      80.       4.14      Y Y



STORM ANALYSIS:
          Storm 1             0.0       2.20      Rain  1   2
          Storm 2             0.0       3.15      Rain  2   2
          Storm 3             0.0       3.19      Rain  3   2
          Storm 4             0.0       4.66      Rain  4   2
          Storm 5             0.0       5.77      Rain  5   2
          Storm 6             0.0       6.79      Rain  6   2
          Storm 7             0.0       7.99      Rain  7   2




RAINFALL DISTRIBUTION:
          Rain  1             0.10000
                    0.0       0.00710   0.01420   0.02120   0.02830
                    0.03540   0.04250   0.04960   0.05660   0.06370
                    0.07080   0.07790   0.08500   0.09200   0.09910
                    0.10620   0.11360   0.12100   0.12840   0.13580
                    0.14320   0.15290   0.16270   0.17250   0.18220
                    0.19200   0.21550   0.23910   0.27680   0.33670
                    0.50000   0.66330   0.72320   0.76090   0.78450
                    0.80800   0.81780   0.82750   0.83730   0.84710
                    0.85680   0.86420   0.87160   0.87900   0.88640
                    0.89380   0.90090   0.90800   0.91500   0.92210
                    0.92920   0.93630   0.94340   0.95040   0.95750
                    0.96460   0.97170   0.97880   0.98580   0.99290
                    1.00000
          Rain  2             0.10000
                    0.0       0.00110   0.00220   0.00330   0.00440
                    0.00550   0.00660   0.00770   0.00880   0.00990
                    0.01100   0.01210   0.01320   0.01420   0.01530
                    0.01640   0.01750   0.01860   0.01970   0.02080
                    0.02190   0.02300   0.02410   0.02520   0.02630
                    0.02740   0.02850   0.02960   0.03070   0.03180
                    0.03290   0.03400   0.03510   0.03620   0.03730
                    0.03840   0.03950   0.04050   0.04160   0.04270
                    0.04380   0.04490   0.04600   0.04710   0.04820
                    0.04930   0.05040   0.05150   0.05260   0.05370
                    0.05480   0.05590   0.05700   0.05810   0.05920
                    0.06030   0.06140   0.06250   0.06360   0.06470
                    0.06580   0.06860   0.07140   0.07430   0.07710
                    0.08000   0.08280   0.08560   0.08850   0.09130
                    0.09420   0.09700   0.09980   0.10270   0.10550
                    0.10840   0.11120   0.11400   0.11690   0.11970
                    0.12260   0.12540   0.12820   0.13110   0.13390
                    0.13680   0.13960   0.14240   0.14530   0.14810
                    0.15100   0.15590   0.16090   0.16580   0.17070
                    0.17570   0.18060   0.18560   0.19050   0.19540
```

```
          0.20040   0.20530   0.21030   0.21520   0.22020
          0.22510   0.23030   0.23540   0.24060   0.24580
          0.25090   0.25770   0.26460   0.27140   0.27820
          0.28500   0.30140   0.31790   0.34420   0.38600
          0.50000   0.61400   0.65580   0.68210   0.69860
          0.71500   0.72180   0.72860   0.73540   0.74230
          0.74910   0.75420   0.75940   0.76460   0.76970
          0.77490   0.77980   0.78480   0.78970   0.79470
          0.79960   0.80460   0.80950   0.81440   0.81940
          0.82430   0.82930   0.83420   0.83910   0.84410
          0.84900   0.85190   0.85470   0.85760   0.86040
          0.86320   0.86610   0.86890   0.87180   0.87460
          0.87740   0.88030   0.88310   0.88600   0.88880
          0.89160   0.89450   0.89730   0.90020   0.90300
          0.90580   0.90870   0.91150   0.91440   0.91720
          0.92000   0.92290   0.92570   0.92860   0.93140
          0.93420   0.93530   0.93640   0.93750   0.93860
          0.93970   0.94080   0.94190   0.94300   0.94410
          0.94520   0.94630   0.94740   0.94850   0.94960
          0.95070   0.95180   0.95290   0.95400   0.95510
          0.95620   0.95730   0.95840   0.95950   0.96050
          0.96160   0.96270   0.96380   0.96490   0.96600
          0.96710   0.96820   0.96930   0.97040   0.97150
          0.97260   0.97370   0.97480   0.97590   0.97700
          0.97810   0.97920   0.98030   0.98140   0.98250
          0.98360   0.98470   0.98580   0.98680   0.98790
          0.98900   0.99010   0.99120   0.99230   0.99340
          0.99450   0.99560   0.99670   0.99780   0.99890
          1.00000
Rain  3             0.10000
          0.0       0.00680   0.01350   0.02030   0.02710
          0.03380   0.04060   0.04740   0.05410   0.06090
          0.06760   0.07440   0.08120   0.08790   0.09470
          0.10150   0.10860   0.11580   0.12290   0.13010
          0.13720   0.14830   0.15940   0.17050   0.18170
          0.19280   0.21980   0.24690   0.28820   0.32000
          0.50000   0.68000   0.71180   0.75310   0.78020
          0.80720   0.81830   0.82950   0.84060   0.85170
          0.86280   0.86990   0.87710   0.88420   0.89140
          0.89850   0.90530   0.91210   0.91880   0.92560
          0.93240   0.93910   0.94590   0.95260   0.95940
          0.96620   0.97290   0.97970   0.98650   0.99320
          1.00000
Rain  4             0.10000
          0.0       0.00120   0.00240   0.00360   0.00480
          0.00600   0.00720   0.00840   0.00960   0.01080
          0.01200   0.01320   0.01450   0.01570   0.01690
          0.01810   0.01930   0.02050   0.02170   0.02290
          0.02410   0.02530   0.02650   0.02770   0.02890
          0.03010   0.03130   0.03250   0.03370   0.03490
          0.03610   0.03730   0.03850   0.03970   0.04090
          0.04220   0.04340   0.04460   0.04580   0.04700
          0.04820   0.04940   0.05060   0.05180   0.05300
          0.05420   0.05540   0.05660   0.05780   0.05900
          0.06020   0.06140   0.06260   0.06380   0.06500
          0.06620   0.06740   0.06860   0.06990   0.07110
          0.07230   0.07510   0.07800   0.08080   0.08370
          0.08650   0.08940   0.09220   0.09510   0.09790
          0.10080   0.10360   0.10650   0.10930   0.11220
          0.11500   0.11790   0.12070   0.12360   0.12640
          0.12930   0.13210   0.13500   0.13780   0.14070
          0.14350   0.14640   0.14920   0.15210   0.15490
          0.15780   0.16240   0.16700   0.17170   0.17630
```

	0.18090	0.18550	0.19020	0.19480	0.19940
	0.20410	0.20870	0.21330	0.21800	0.22260
	0.22720	0.23210	0.23700	0.24190	0.24680
	0.25170	0.25930	0.26690	0.27450	0.28210
	0.28970	0.30820	0.32670	0.35500	0.37680
	0.50000	0.62320	0.64500	0.67330	0.69180
	0.71030	0.71790	0.72550	0.73310	0.74070
	0.74830	0.75320	0.75810	0.76300	0.76790
	0.77280	0.77740	0.78200	0.78670	0.79130
	0.79590	0.80060	0.80520	0.80980	0.81450
	0.81910	0.82370	0.82830	0.83300	0.83760
	0.84220	0.84510	0.84790	0.85080	0.85360
	0.85650	0.85930	0.86220	0.86500	0.86790
	0.87070	0.87360	0.87640	0.87930	0.88210
	0.88500	0.88780	0.89070	0.89350	0.89640
	0.89920	0.90210	0.90490	0.90780	0.91060
	0.91350	0.91630	0.91920	0.92200	0.92490
	0.92770	0.92890	0.93010	0.93140	0.93260
	0.93380	0.93500	0.93620	0.93740	0.93860
	0.93980	0.94100	0.94220	0.94340	0.94460
	0.94580	0.94700	0.94820	0.94940	0.95060
	0.95180	0.95300	0.95420	0.95540	0.95660
	0.95780	0.95910	0.96030	0.96150	0.96270
	0.96390	0.96510	0.96630	0.96750	0.96870
	0.96990	0.97110	0.97230	0.97350	0.97470
	0.97590	0.97710	0.97830	0.97950	0.98070
	0.98190	0.98310	0.98430	0.98550	0.98680
	0.98800	0.98920	0.99040	0.99160	0.99280
	0.99400	0.99520	0.99640	0.99760	0.99880
	1.00000				
Rain 5		0.10000			
	0.0	0.00130	0.00250	0.00380	0.00510
	0.00640	0.00760	0.00890	0.01020	0.01140
	0.01270	0.01400	0.01520	0.01650	0.01780
	0.01910	0.02030	0.02160	0.02290	0.02410
	0.02540	0.02670	0.02790	0.02920	0.03050
	0.03180	0.03300	0.03430	0.03560	0.03680
	0.03810	0.03940	0.04060	0.04190	0.04320
	0.04450	0.04570	0.04700	0.04830	0.04950
	0.05080	0.05210	0.05340	0.05460	0.05590
	0.05720	0.05840	0.05970	0.06100	0.06220
	0.06350	0.06480	0.06610	0.06730	0.06860
	0.06990	0.07110	0.07240	0.07370	0.07490
	0.07620	0.07910	0.08200	0.08500	0.08790
	0.09080	0.09370	0.09660	0.09950	0.10240
	0.10530	0.10820	0.11110	0.11410	0.11700
	0.11990	0.12280	0.12570	0.12860	0.13150
	0.13440	0.13730	0.14030	0.14320	0.14610
	0.14900	0.15190	0.15480	0.15770	0.16060
	0.16350	0.16820	0.17280	0.17740	0.18200
	0.18670	0.19130	0.19590	0.20050	0.20510
	0.20980	0.21440	0.21900	0.22360	0.22820
	0.23290	0.23760	0.24240	0.24710	0.25190
	0.25660	0.26490	0.27320	0.28150	0.28980
	0.29820	0.31720	0.33620	0.36440	0.40520
	0.50000	0.59480	0.63560	0.66380	0.68280
	0.70180	0.71020	0.71850	0.72680	0.73510
	0.74340	0.74810	0.75290	0.75760	0.76240
	0.76710	0.77180	0.77640	0.78100	0.78560
	0.79020	0.79490	0.79950	0.80410	0.80870
	0.81330	0.81800	0.82260	0.82720	0.83180
	0.83650	0.83940	0.84230	0.84520	0.84810
	0.85100	0.85390	0.85680	0.85970	0.86270

	0.86560	0.86850	0.87140	0.87430	0.87720
	0.88010	0.88300	0.88590	0.88890	0.89180
	0.89470	0.89760	0.90050	0.90340	0.90630
	0.90920	0.91210	0.91500	0.91800	0.92090
	0.92380	0.92510	0.92630	0.92760	0.92890
	0.93010	0.93140	0.93270	0.93390	0.93520
	0.93650	0.93780	0.93900	0.94030	0.94160
	0.94280	0.94410	0.94540	0.94660	0.94790
	0.94920	0.95050	0.95170	0.95300	0.95430
	0.95550	0.95680	0.95810	0.95940	0.96060
	0.96190	0.96320	0.96440	0.96570	0.96700
	0.96820	0.96950	0.97080	0.97210	0.97330
	0.97460	0.97590	0.97710	0.97840	0.97970
	0.98090	0.98220	0.98350	0.98480	0.98600
	0.98730	0.98860	0.98980	0.99110	0.99240
	0.99360	0.99490	0.99620	0.99750	0.99870
	1.00000				
Rain 6		0.10000			
	0.0	0.00130	0.00260	0.00390	0.00530
	0.00660	0.00790	0.00920	0.01050	0.01180
	0.01310	0.01440	0.01580	0.01710	0.01840
	0.01970	0.02100	0.02230	0.02360	0.02500
	0.02630	0.02760	0.02890	0.03020	0.03150
	0.03280	0.03410	0.03550	0.03680	0.03810
	0.03940	0.04070	0.04200	0.04330	0.04470
	0.04600	0.04730	0.04860	0.04990	0.05120
	0.05250	0.05380	0.05520	0.05650	0.05780
	0.05910	0.06040	0.06170	0.06300	0.06430
	0.06570	0.06700	0.06830	0.06960	0.07090
	0.07220	0.07350	0.07490	0.07620	0.07750
	0.07880	0.08180	0.08480	0.08770	0.09070
	0.09370	0.09670	0.09970	0.10270	0.10560
	0.10860	0.11160	0.11460	0.11760	0.12060
	0.12350	0.12650	0.12950	0.13250	0.13550
	0.13840	0.14140	0.14440	0.14740	0.15040
	0.15340	0.15630	0.15930	0.16230	0.16530
	0.16830	0.17300	0.17760	0.18230	0.18700
	0.19170	0.19640	0.20100	0.20570	0.21040
	0.21510	0.21970	0.22440	0.22910	0.23380
	0.23850	0.24310	0.24770	0.25240	0.25700
	0.26160	0.27060	0.27950	0.28840	0.29740
	0.30630	0.32550	0.34480	0.37260	0.41170
	0.50000	0.58830	0.62740	0.65520	0.67450
	0.69370	0.70260	0.71160	0.72050	0.72940
	0.73840	0.74300	0.74760	0.75230	0.75690
	0.76150	0.76620	0.77090	0.77560	0.78030
	0.78490	0.78960	0.79430	0.79900	0.80360
	0.80830	0.81300	0.81770	0.82240	0.82700
	0.83170	0.83470	0.83770	0.84070	0.84370
	0.84660	0.84960	0.85260	0.85560	0.85860
	0.86160	0.86450	0.86750	0.87050	0.87350
	0.87650	0.87940	0.88240	0.88540	0.88840
	0.89140	0.89440	0.89730	0.90030	0.90330
	0.90630	0.90930	0.91230	0.91520	0.91820
	0.92120	0.92250	0.92380	0.92510	0.92650
	0.92780	0.92910	0.93040	0.93170	0.93300
	0.93430	0.93570	0.93700	0.93830	0.93960
	0.94090	0.94220	0.94350	0.94480	0.94620
	0.94750	0.94880	0.95010	0.95140	0.95270
	0.95400	0.95530	0.95670	0.95800	0.95930
	0.96060	0.96190	0.96320	0.96450	0.96590
	0.96720	0.96850	0.96980	0.97110	0.97240
	0.97370	0.97500	0.97640	0.97770	0.97900

```
                    0.98030    0.98160    0.98290    0.98420    0.98560
                    0.98690    0.98820    0.98950    0.99080    0.99210
                    0.99340    0.99470    0.99610    0.99740    0.99870
                    1.00000
          Rain  7              0.10000
                    0.0        0.00140    0.00270    0.00410    0.00540
                    0.00680    0.00810    0.00950    0.01080    0.01220
                    0.01350    0.01490    0.01620    0.01760    0.01890
                    0.02030    0.02160    0.02300    0.02440    0.02570
                    0.02710    0.02840    0.02980    0.03110    0.03250
                    0.03380    0.03520    0.03650    0.03790    0.03920
                    0.04060    0.04190    0.04330    0.04470    0.04600
                    0.04740    0.04870    0.05010    0.05140    0.05280
                    0.05410    0.05550    0.05680    0.05820    0.05950
                    0.06090    0.06220    0.06360    0.06490    0.06630
                    0.06770    0.06900    0.07040    0.07170    0.07310
                    0.07440    0.07580    0.07710    0.07850    0.07980
                    0.08120    0.08420    0.08730    0.09040    0.09340
                    0.09650    0.09950    0.10260    0.10570    0.10870
                    0.11180    0.11490    0.11790    0.12100    0.12400
                    0.12710    0.13020    0.13320    0.13630    0.13930
                    0.14240    0.14550    0.14850    0.15160    0.15460
                    0.15770    0.16080    0.16380    0.16690    0.16990
                    0.17300    0.17780    0.18250    0.18730    0.19210
                    0.19690    0.20160    0.20640    0.21120    0.21600
                    0.22070    0.22550    0.23030    0.23510    0.23980
                    0.24460    0.24920    0.25370    0.25830    0.26290
                    0.26750    0.27700    0.28660    0.29610    0.30570
                    0.31520    0.33440    0.35360    0.38070    0.41820
                    0.50000    0.58180    0.61930    0.64640    0.66560
                    0.68480    0.69430    0.70390    0.71340    0.72300
                    0.73250    0.73710    0.74170    0.74630    0.75080
                    0.75540    0.76020    0.76490    0.76970    0.77450
                    0.77930    0.78400    0.78880    0.79360    0.79840
                    0.80310    0.80790    0.81270    0.81750    0.82220
                    0.82700    0.83010    0.83310    0.83620    0.83920
                    0.84230    0.84540    0.84840    0.85150    0.85450
                    0.85760    0.86070    0.86370    0.86680    0.86980
                    0.87290    0.87600    0.87900    0.88210    0.88510
                    0.88820    0.89130    0.89430    0.89740    0.90050
                    0.90350    0.90660    0.90960    0.91270    0.91580
                    0.91880    0.92020    0.92150    0.92290    0.92420
                    0.92560    0.92690    0.92830    0.92960    0.93100
                    0.93230    0.93370    0.93510    0.93640    0.93780
                    0.93910    0.94050    0.94180    0.94320    0.94450
                    0.94590    0.94720    0.94860    0.94990    0.95130
                    0.95260    0.95400    0.95530    0.95670    0.95810
                    0.95940    0.96080    0.96210    0.96350    0.96480
                    0.96620    0.96750    0.96890    0.97020    0.97160
                    0.97290    0.97430    0.97560    0.97700    0.97840
                    0.97970    0.98110    0.98240    0.98380    0.98510
                    0.98650    0.98780    0.98920    0.99050    0.99190
                    0.99320    0.99460    0.99590    0.99730    0.99860
                    1.00000

GLOBAL OUTPUT:
                               0.100      NNNNN      NNNNNN
```

WinTR-20 Printed Page File   End of Input Data List

MD140 over Flat Run
Single area TR-20 analysis

Name of printed page file:
D:\Projects\Hydrology Panel\Calibration Example\FlatRun_RevReachLengthpls10.out

STORM Storm 1

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Area 1	10.800		0.688		6.05	1103.3	102.16
OUTLET	10.800		0.688		6.05	1103.3	102.16

STORM Storm 2

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Area 1	10.800		1.364		14.91	1635.7	151.46
OUTLET	10.800		1.364		14.91	1635.7	151.46

STORM Storm 3

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Area 1	10.800		1.394		5.84	2297.0	212.69
OUTLET	10.800		1.394		5.84	2297.0	212.69

STORM Storm 4

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Area 1	10.800		2.598		14.81	3182.4	294.67
OUTLET	10.800		2.598		14.81	3182.4	294.67

STORM Storm 5

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Area 1	10.800		3.574		14.72	4313.1	399.36
OUTLET	10.800		3.574		14.72	4313.1	399.36

STORM Storm 6

MD140 over Flat Run
Single area TR-20 analysis

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Area 1	10.800		4.501		14.76	5329.9	493.51
OUTLET	10.800		4.501		14.76	5329.9	493.51

STORM Storm 7

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Area 1	10.800		5.616		14.56	6494.2	601.32
OUTLET	10.800		5.616		14.56	6494.2	601.32

MD140 over Flat Run
Single area TR-20 analysis

Area or Reach Identifier	Drainage Area (sq mi)	Alternate	Peak Flow by Storm: Storm 1 (cfs)	Storm 2 (cfs)	Storm 3 (cfs)	Storm 4 (cfs)	Storm 5 (cfs)
Area 1	10.800		1103.3	1635.7	2297.0	3182.4	4313.1
OUTLET	10.800		1103.3	1635.7	2297.0	3182.4	4313.1

Area or Reach Identifier	Drainage Area (sq mi)	Alternate	Peak Flow by Storm: Storm 6 (cfs)	Storm 7 (cfs)	(cfs)	(cfs)	(cfs)
Area 1	10.800		5329.9	6494.2			
OUTLET	10.800		5329.9	6494.2			

APPENDIX 6
REGRESSION EQUATIONS FOR ESTIMATING THE TIME OF CONCENTRATION

REGRESSION EQUATION FOR ESTIMATING THE TIME OF CONCENTRATION

Time of concentration (T_c) can be defined from an observed rainfall hyetograph and the resulting discharge hydrograph. T_c is estimated as the time between the end of rainfall excess and the first inflection point on the recession of the runoff hydrograph. The T_c values were computed from rainfall-runoff data compiled by the Dillow (1998) as part of a flood hydrograph study for the Maryland State Highway Administration.

Dillow (1998) compiled data for 278 rainfall-runoff events at 81 gaging stations in Maryland. Not all of the 278 events were suitable in defining T_c for our study. For some rainfall-runoff events, it was not possible to detect an inflection point on the recession of the hydrograph. On average, about three events were used in determining the average T_c for a watershed. For three gaging stations, there were no rainfall-runoff events suitable for determining T_c. Therefore, data for 78 gaging stations are used in developing a regression equation for estimating T_c for ungaged watersheds. The average T_c values and watershed characteristics are given in Table A6.1.

Stepwise regression analysis is used to relate the average T_c value at 78 gaging stations to the watershed characteristics given in Table A6.1. The watershed characteristics used in this analysis were taken from Dillow (1998). Some of the watershed characteristics that are highly correlated with T_c are also highly correlated with each other. For example, drainage area has a correlation coefficient of 0.98 with channel length. Since these two variables are highly correlated, both variables are not significant in the regression analysis because they are essentially explaining the same variation in T_c. The regression equation based on channel length has a slightly lower standard error than the one with drainage area and so channel length is used in the final equation. Channel length also is a better predictor of travel time for a variety of watershed shapes.

Using Dillow's approach (1998), qualitative variables are used in the regression analysis to identify gaging stations in different hydrologic regions in Maryland. Dillow (1998) determined that there are three hydrologic regions for estimating flood hydrographs for Maryland streams: Appalachian Plateau, Piedmont and Coastal Plain. These same regions are assumed applicable in our analysis and are shown in Figure A6.1. The qualitative-variable approach is superior to defining different regression equations for each geographic region because there are only 10 gaging stations in the Appalachian Plateau.

The qualitative variables AP and CP are used in the regression equation to account for variability in T_c not explained by the available explanatory variables. In Table A6.1, a CP value of 1 specifies the watershed is in the Coastal Plain Region, a AP value of 1 specifies the watershed is in the Appalachian Plateau and zero values for both CP and AP specify the watershed is in the Piedmont Region. The T_c values for watersheds in the Appalachian Plateau and Coastal Plains are larger than watersheds in the Piedmont for a given set of watershed characteristics (see Figure 4.2). The qualitative variables also account for regional differences in T_c related to watershed characteristics not available for analysis. Both AP and CP are highly significant in the regression analysis.

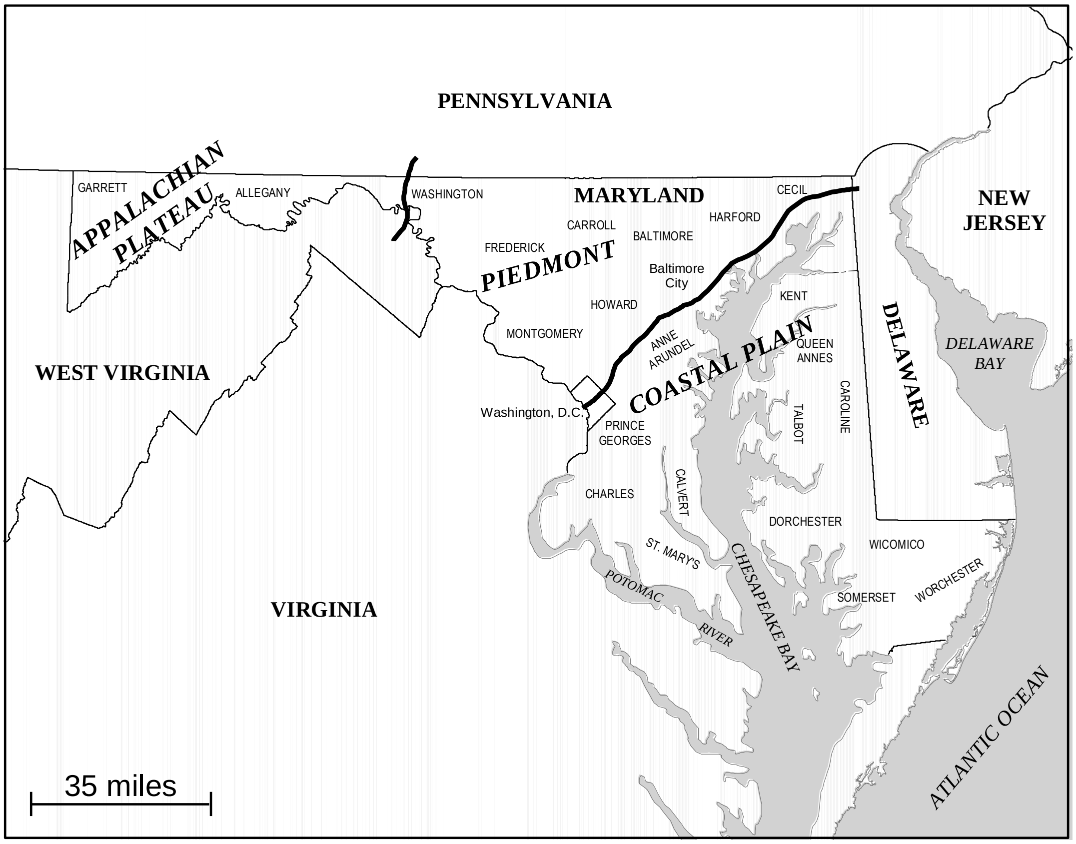


Figure A6.1. – Hydrologic regions in Maryland used in developing a regression equation for estimating the time of concentration for ungaged watersheds.

There is considerable variation in hydrology from the Coastal Plains of Maryland to the mountainous Appalachian Plateau. Therefore, several watershed characteristics are statistically significant in predicting T_c. In the folloWing equation, all explanatory variables are significant at the 5 percent level of significance. The coefficient of determination (R^2) is 0.888 percent implying the equation is explaining 88.8 percent of the variation in the observed value of T_c. The standard error of estimate is 30.0 percent.

$$T_c = 0.133\,(CL^{.475})\,(SL^{-.187})\,(101\text{-}FOR)^{-.144}\,(101\text{-}IA)^{.861}\,(ST+1)^{.154}\,(10^{.194AP})\,(10^{.366CP}) \qquad (1)$$

where

T_c = time of concentration in hours,
CL = channel length in miles,
SL = channel slope in feet per mile,

FOR = forest cover in percentage of the watershed,
IA = impervious area in percentage of the watershed,
ST = lakes and ponds in percentage of the watershed,
AP = 1 if the watershed is in the Appalachian Plateau, 0 otherwise,
CP = 1 if the watershed is in the Coastal Plain, 0 otherwise,
AP and CP = 0 for watersheds in the Piedmont Region.

Equation 1 was computed by transforming the T_c values and watershed characteristics to logarithms and then fitting a linear regression model to the transformed data. This transformation is somewhat standard in hydrologic analyses since the logarithmic transformation tends to stabilize the variance of the residuals, normalize the distribution of the residuals about the regression equation and linearize the equation.

The percentages of forest cover (FOR), impervious area (IA) and storage (ST) can be zero for a given watershed. Therefore, it is necessary to add constants to these variables prior to the logarithmic transformation or to subtract these variables from a constant to avoid taking the logarithm of zero. For our analysis, subtracting the percentages from 101 provided more reasonable estimates of the regression coefficients and slightly reduced the standard error of the regression equation.

Equation 1 can be used to estimate T_c for rural and urban watersheds in Maryland. The percentage of impervious area (IA) is a measure of the urbanization or development in the watershed. In addition, urban watersheds would have a reduced amount of forest cover.

The T_c values in Table A6.1 are generally longer than computed by SCS (1986) procedures for a given watershed area. One possible hypothesis is that this is related to size of the flood event used to determine T_c. In general, the recurrence intervals of peak discharges were less than a 2-yr event. There were only about 30 events across the 78 gaging stations where the peak discharge of the runoff hydrograph was a 5-yr event or greater. An evaluation of the T_c values as a function of recurrence interval revealed that the T_c values did not vary with recurrence interval in any consistent pattern. In some instances, the larger flood events had smaller T_c values and at other stations the converse was true. Therefore, it is not conclusive that the use of larger flood events would result in smaller T_c values

A comparison was also made between estimates of T_c computed from Equation 1 and procedures in SCS (1986) based on travel time. The travel times shown in Table A6.2 were computed by MSHA personnel as a combination of overland flow, shallow concentrated flow and channel flow (SCS, 1986). The times of concentration in Table A6.2 are plotted versus drainage area in Figure A6.2.

Table A6.2. A comparison of time of concentration (T_c) estimated from Equation 1 based on watershed characteristics to T_c values based on travel time.

Drainage area (mi^2)	Site or Location	Hydrologic Region	Regression T_c (hours)	Travel Time T_c (hours)
6.66	West Branch @ MD 165	Piedmont	3.4	3.0
25.70	Middle Creek @ MD 17	Piedmont	5.9	5.2
5.01	Mill Creek @ MD 7	Piedmont	4.4	4.3
43.73	Little Gunpowder Falls @ U.S. 1	Piedmont	7.9	9.0
3.16	Little Monacacy River @ MD 109	Piedmont	2.7	1.5
6.26	Blockston Branch @ MD 481	Coastal Plain	10.8	8.7
3.24	Middle Branch @ U.S. Route 113	Coastal Plain	9.1	7.2
6.05	Church Branch @ U.S. Route 113	Coastal Plain	11.0	10.6
1.61	Carey Branch @ U.S. Route 113	Coastal Plain	6.0	5.7
6.64	Birch Branch @ U.S. Route 113	Coastal Plain	11.0	7.6
143.5	Deer Creek @ MD 136	Piedmont	14.2	19.9
5.8	US 50 in Queen Anne's County	Coastal Plain	11.9	6.9
2.5	US 50 in Queen Anne's County	Coastal Plain	8.4	4.4
1.3	Meadow Branch @ MD 97	Piedmont	2.0	0.92
3.7	Upper Rock Creek @ ICC	Piedmont	3.0	2.1
3.77	North Branch @ MD 47	Appalachian	4.8	2.0
3.30	North Branch @ MD 47	Appalachian	4.0	1.4

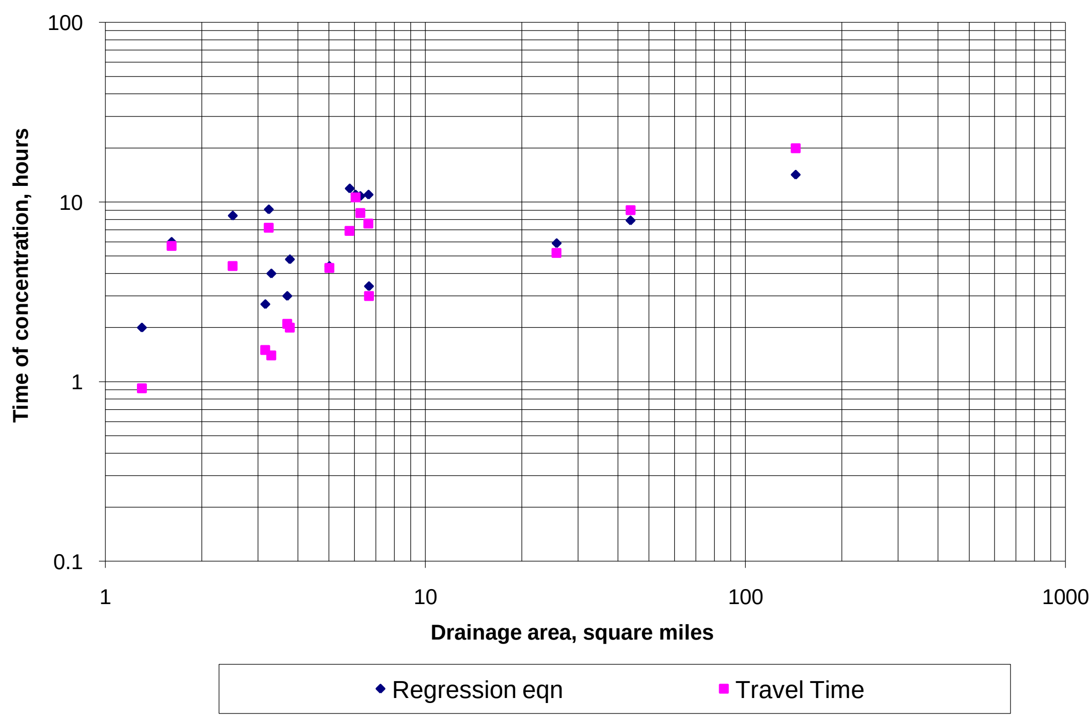


Figure A6.2. Comparison of time of concentration based on Equation 1 and the travel time method.

There is close agreement for T_c estimates for several of the sites shown in Table A6.2 and Figure A6.2, especially for the larger watersheds. When there are significant differences, the values based are travel times (also known as the segmental approach) are less than those from the regression equation. Based on this limited comparison, it appears that Equation 1 can be used to determine realistic bounds on T_c estimated by the travel time or segmental approach.

Any regression equation, such as Equation 1, should only be used at ungaged watersheds that have watershed characteristics within the range of those used to develop the equation. The upper and lower limits for the watershed characteristics are given in Table A6.3 for each hydrologic region to define the applicability of Equation 1. Therefore, Equation 1 should not be used for watersheds having characteristics outside the limits of those shown in Table A6.3.

Table A6.3. Upper and lower limits for watershed characteristics for the time of concentration regression equation for each hydrologic region.

Region	Variable	Upper limit	Lower limit
Appalachian Plateau	Drainage area (mi^2)	295	1.6
Appalachian Plateau	Channel length (mi)	40.8	2.1
Appalachian Plateau	Channel slope (ft/mi)	195	6.1
Appalachian Plateau	Storage (%)	3.2	0.0
Appalachian Plateau	Forest cover (%)	89	54
Appalachian Plateau	Impervious area (%)	1.25	0.0
Piedmont	Drainage area (mi^2)	494	2.1
Piedmont	Channel length (mi)	70	2.2
Piedmont	Channel slope (ft/mi)	336	11
Piedmont	Storage (%)	1.16	0.0
Piedmont	Forest cover (%)	92	2.0
Piedmont	Impervious area (%)	41	0.0
Coastal Plain	Drainage area (mi^2)	113	2.0
Coastal Plain	Channel length (mi)	18.3	2.0
Coastal Plain	Channel slope (ft/mi)	41.8	1.5
Coastal Plain	Storage (%)	26.0	0.0
Coastal Plain	Forest cover (%)	79	5.0
Coastal Plain	Impervious area (%)	35	0.0

In summary, Equation 1 is based on estimates of T_c computed from rainfall-runoff events at 78 gaging stations in Maryland. The computed values of TC tend to be larger than similar estimates based on SCS (1986) procedures. However, Equation 1 can be used to evaluate the reasonableness of T_c estimates from SCS (1986) procedures. Further research is needed to improve the estimation of T_c in Maryland that would ultimately provide for more accurate estimates of design discharges from hydrological models such as TR-20.

Table A6.1. Watershed characteristics and times of concentration for rural and urban watersheds used in developing the regression equations.

STANO is the station number
DA is the drainage area in square miles
SL is the channel slope in feet per mile
CL is channel length in miles
SIN is the channel sinuosity determined by dividing channel length by basin length
BL is the basin length in miles
ST is the percentage area of the drainage area covered by lakes, ponds and swamps
SH is the basin shape defined as channel length squared divided by drainage area
FOR is forest cover in percentage of the drainage area
IA is impervious area expressed as percentage of the drainage area
BDF is the basin development factor
LT is the lagtime in hours
AP = 1 if the watershed is in the Appalachian Plateau, CP = 1 if the watershed is in the Coastal Plains, CP and AP = 0 implies the watershed is in the Piedmont Region
T_c is the time of concentration in hours

STANO	DA	SL	CL	SIN	BL	ST	SH	FOR	IA	BDF	LT	AP	CP	T_c
01594930	8.23	26.4	4.4	1.14	3.86	0.000	1.81	86	0.00	0	7.50	1	0	6.38
01594934	1.55	161.9	2.1	1.07	1.95	0.000	2.45	82	0.00	0	6.43	1	0	4.00
01594936	1.91	130.9	2.7	1.16	2.33	0.000	2.84	87	0.00	0	6.62	1	0	6.00
01594950	2.30	194.6	2.7	1.24	2.18	0.000	2.07	89	0.00	0	6.74	1	0	5.00
01595000	73.0	30.5	16.5	1.30	12.70	0.186	2.21	78	0.49	0	12.27	1	0	11.50
01596500	49.1	65.1	19.0	1.41	13.44	0.066	3.68	80	0.06	0	13.97	1	0	9.75
03075500	134.	6.09	19.3	1.59	12.12	0.493	1.10	54	0.88	0	22.57	1	0	23.50
03076500	295.	22.2	40.8	1.45	28.11	3.180	2.68	66	0.24	0	25.10	1	0	29.25
03076600	48.9	65.6	15.3	1.89	8.11	0.000	1.35	62	1.25	0	16.47	1	0	11.25
03078000	62.5	28.2	19.5	1.61	12.13	1.005	2.35	75	0.66	0	16.88	1	0	19.58
01614500	494.	11.2	69.5	2.44	28.45	0.101	1.64	37	1.43	0	25.42	0	0	26.33
01617800	18.9	23.8	9.4	1.08	8.69	0.000	4.00	2	2.32	0	15.53	0	0	.
01619500	281.	10.8	49.9	1.55	32.26	0.123	3.70	30	2.67	0	24.66	0	0	27.12
01637500	66.9	47.5	23.3	1.50	15.50	0.000	3.59	38	1.01	0	8.98	0	0	7.62
01639000	173.	18.9	30.8	1.92	16.05	0.114	1.49	20	0.69	0	15.91	0	0	17.25
01639375	41.3	75.4	12.2	1.40	8.70	0.207	1.83	70	0.87	0	3.47	0	0	5.00
01639500	102.	13.5	26.9	1.43	18.75	0.000	3.45	14	0.13	0	11.80	0	0	8.50

STANO	DA	SL	CL	SIN	BL	ST	SH	FOR	IA	BDF	LT	AP	CP	T_c
01640965	2.14	336.4	2.2	1.12	1.96	0.000	1.80	92	0.00	0	1.78	0	0	1.88
01641000	18.4	145.2	9.7	1.57	6.18	0.373	2.08	80	1.93	1	5.11	0	0	5.44
01483700	31.9	4.66	12.3	1.38	8.89	11.927	2.48	21	4.46	2	27.41	0	1	32.92
01484000	13.6	6.26	5.9	1.01	5.87	0.626	2.53	34	0.33	0	21.04	0	1	20.85
01484500	5.24	4.87	4.4	1.19	3.70	0.000	2.61	39	3.24	0	12.82	0	1	14.88
01484548	13.6	4.39	7.9	1.22	6.48	26.055	3.09	33	1.13	0	24.28	0	1	31.75
01485000	60.5	1.49	14.6	1.18	12.42	18.396	2.55	25	0.08	0	28.58	0	1	37.00
01485500	44.9	3.56	12.2	1.11	10.98	1.326	2.69	79	0.30	0	37.21	0	1	41.75
01487000	75.4	3.23	13.7	1.20	11.44	0.000	1.74	40	0.85	0	20.80	0	1	23.25
01488500	44.8	2.65	11.7	1.17	10.00	0.000	2.23	39	0.14	0	12.99	0	1	15.08
01489000	8.50	7.65	5.3	1.46	3.64	0.000	1.87	24	0.00	0	5.78	0	1	8.44
01491000	113.	3.01	18.3	1.36	13.41	6.910	1.59	38	0.66	0	31.57	0	1	36.88
01493000	19.7	6.06	9.7	1.09	8.89	8.777	3.54	20	0.35	0	26.10	0	1	22.25
01493500	12.7	9.15	5.9	1.10	5.38	0.199	2.28	5	0.25	0	13.35	0	1	16.38
01483200	3.85	15.8	3.5	1.04	3.37	1.298	2.95	45	0.38	0	7.37	0	1	11.67
01484100	2.83	7.12	2.5	1.07	2.33	0.000	1.92	43	0.00	0	14.54	0	1	15.50
01486000	4.80	5.47	4.1	.	.	0.000	.	57	0.00	0	.	0	1	10.50
01590500	6.92	19.8	4.7	1.14	4.12	0.000	2.45	65	1.87	0	10.90	0	1	11.94
01594526	89.7	8.2	16.1	1.18	13.60	0.037	2.06	30	7.84	4	23.16	0	1	36.38
01594670	9.38	16.9	5.2	1.30	3.99	0.000	1.70	70	3.85	0	9.17	0	1	12.33
01653600	39.5	16.1	14.4	1.64	8.79	0.176	1.96	38	8.25	2	17.29	0	1	29.05
01660920	79.9	10.6	16.6	1.15	14.48	5.051	2.62	56	3.60	0	26.17	0	1	31.25
01661050	18.5	12.4	7.2	1.22	5.92	0.000	1.89	56	3.09	0	14.26	0	1	16.38
01594710	3.26	41.8	2.9	1.08	2.68	0.000	2.20	52	9.24	0	3.86	0	1	5.08
01661500	24.0	12.9	8.0	1.28	6.25	0.000	1.63	78	2.46	0	15.78	0	1	13.75
01583600	20.9	52.0	8.2	1.43	5.72	0.309	1.57	29	18.6	4	5.63	0	0	4.25
01585100	7.61	48.2	6.0	1.12	5.38	0.000	3.80	28	27.5	7	2.11	0	0	2.75

STANO	DA	SL	CL	SIN	BL	ST	SH	FOR	IA	BDF	LT	AP	CP	T_c
01585200	2.13	72.7	2.2	1.12	1.97	0.000	1.82	7	33.0	8	1.02	0	0	1.38
01585300	4.46	54.7	4.6	1.25	3.68	0.558	3.04	28	23.6	6	2.06	0	0	2.38
01585400	1.97	27.1	2.0	1.22	1.64	0.000	1.37	24	35.1	2	2.33	0	1	3.25
01589100	2.47	87.1	3.2	1.22	2.62	0.000	2.78	19	37.0	4	1.67	0	0	2.17
01589300	32.5	21.0	13.7	1.37	9.99	0.000	3.07	31	18.6	4	3.95	0	0	3.38
01589330	5.52	52.1	3.2	1.12	2.86	0.000	1.48	4	40.8	12	2.26	0	0	2.83
01589500	4.97	24.8	4.4	1.17	3.75	0.000	2.83	44	21.9	3	8.19	0	1	.
01589512	8.24	23.5	5.9	1.17	5.04	1.092	3.08	31	30.8	3	6.72	0	1	7.75
01593500	38.0	15.8	15.5	1.40	11.04	0.623	3.21	23	18.7	6	7.48	0	0	10.58
01645200	3.70	67.4	2.7	1.16	2.33	0.000	1.47	14	28.0	6	1.91	0	0	2.75
01649500	72.8	27.2	15.3	1.33	11.54	0.192	1.83	33	22.0	5	8.85	0	0	7.25
01651000	49.4	19.7	19.1	1.36	14.05	0.047	4.00	19	22.0	6	6.45	0	0	6.58
01495000	52.6	17.9	22.2	1.41	15.80	0.053	4.75	14	1.92	0	9.87	0	0	8.88
01496200	9.03	29.0	5.9	1.36	4.33	0.000	2.08	4	0.00	0	4.38	0	0	5.81
01580000	94.4	17.7	27.3	1.52	17.92	0.039	3.40	27	0.42	0	7.29	0	0	7.50
01581657	4.16	74.2	3.7	1.19	3.12	0.000	2.34	33	5.25	0	4.08	0	0	3.83
01581658	5.22	56.1	4.8	1.28	3.74	0.000	2.68	31	4.78	0	4.38	0	0	4.92
01581700	34.8	30.0	15.8	1.60	9.89	0.000	2.81	21	2.37	2	4.68	0	0	3.50
01582000	52.9	33.8	15.0	1.35	11.14	0.015	2.35	32	0.91	0	6.84	0	0	6.62
01583100	12.3	50.9	7.8	1.08	7.25	0.092	4.27	26	0.29	0	5.77	0	0	4.50
01583500	59.8	24.5	15.9	1.40	11.36	0.064	2.16	22	0.16	0	8.20	0	0	8.08
01584050	9.40	70.0	4.8	1.11	4.32	0.000	1.99	13	1.00	0	3.05	0	0	3.00
01585105	2.65	65.2	3.6	1.14	3.16	0.000	3.77	16	5.22	0	3.86	0	0	4.00
01585500	3.29	56.0	3.5	1.11	3.14	1.165	3.00	21	0.45	0	3.08	0	0	3.12
01586000	56.6	28.5	14.6	1.38	10.61	0.069	1.99	19	1.77	0	8.56	0	0	9.75
01586210	14.0	44.0	8.1	1.38	5.86	0.000	2.45	19	1.77	0	4.39	0	0	4.00
01586610	28.0	30.9	10.0	1.47	6.81	0.000	1.66	20	0.38	0	5.97	0	0	4.58

STANO	DA	SL	CL	SIN	BL	ST	SH	FOR	IA	BDF	LT	AP	CP	T_c
01589440	25.2	38.2	9.5	1.37	6.95	0.000	1.92	34	9.92	2	5.29	0	0	6.92
01591000	34.8	28.2	12.2	1.22	10.02	0.000	2.89	21	0.21	0	6.51	0	0	7.12
01591400	22.9	28.0	8.7	1.35	6.44	0.097	1.81	16	1.52	0	6.16	0	0	6.83
01591700	27.0	26.5	10.9	1.28	8.52	0.141	2.69	19	2.08	0	5.28	0	0	6.83
01593710	48.4	17.8	14.7	1.28	11.45	0.000	2.71	24	2.16	0	5.99	0	0	8.25
01594000	98.4	13.6	23.5	1.33	17.62	0.134	3.16	26	6.52	4	10.83	0	0	9.88
01641510	0.40	817.8	0.9	1.09	0.83	0.000	1.72	100	0.00	0	4.26	0	0	.
01643495	0.15	1000.	0.5	1.13	0.44	0.000	1.29	100	0.00	0	1.26	0	0	1.75
01643500	62.8	23.8	15.6	1.43	10.89	0.000	1.89	23	1.19	0	7.30	0	0	8.35
01645000	101.	14.0	21.2	1.56	13.61	0.120	1.83	25	3.15	4	10.88	0	0	4.31

APPENDIX 7
PARTIAL DURATION RAINFALL FREQUENCY DATA 6, 12, AND 24-HOUR TEMPORAL DISTRIBUTION

Development of the 24-hour storm distribution from NOAA Atlas 14 Data

Unique storm distributions are recommended for all locations and return periods when using NOAA Atlas 14 data. For ease of use on small projects, a set of locations in Maryland were selected which represent counties in Maryland. The average 100-year 24-hour rainfall for each county was calculated using GIS data. A point was selected within each county which had the average 100-year 24-hour rainfall. The complete partial duration data for each location was then downloaded from the NOAA 14 web site, http://hdsc.nws.noaa.gov/ . In Washington and Frederick counties, the 100-year 24-hour rainfall varied to a greater degree, so these two counties were divided into two regions so that two points were selected for these counties. These files along with a GIS layer with Maryland counties and the representative point locations may be downloaded from http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/WinTR20.html .

The WinTR-20 will import a partial duration text file downloaded from the NOAA 14 web site and develop storm distributions for each return period from 1-year to 500-years. Even though the 1000-year return period is included in the data, the WinTR-20 is not programmed to accept it.

The user of WinTR-20 has the choice to use the original NOAA Atlas 14 data or smoothed data to develop the 24-hour storm distribution. In developing the rainfall-frequency data, NOAA treated each duration independently. In some cases, this causes irregularities in rainfall intensity between durations which then creates irregularities in 24-hour storm distribution and resulting flood hydrograph.

For example, for a location in Howard County, Maryland, the 100-year 2-hour rainfall is 3.86 inches, the 100-year 3-hour rainfall is 4.20, and the 100-year 6-hour rainfall is 5.39. Between 2 and 3 hours the rainfall intensity is 0.34 inches per hour ((4.20 – 3.86)/ 1). Between 3 and 6 hours the rainfall intensity is 0.4 inches per hour ((5.39 – 4.20) / 3). The data shows the intensity actually increasing as the duration increases. As the duration increases, rainfall intensity should decrease. The smoothing algorithm in the WinTR-20 will smooth data from 5-minutes to 1-hour and from 1-hour to 24-hours while keeping the 1-hour rainfall and 24-hour rainfall unchanged. In the Howard County example, the smoothed values are 4.01 inches for the 100-year 2-hour, 4.69 inches for the 100-year 3-hour, and 5.83 inches for the 100-year 6-hour rainfall. This will produce intensities of 0.68 inches per hour between 2 and 3 hours and 0.38 inches per hour between 3 and 6 hours. The complete smoothing table for the 100-year data follows.

Table A7-1 NOAA Atlas 14 data and smoothed data for location in Howard County, MD

Duration	5-min	10-min	15-min	30-min	60-min	2-hr	3-hr	6-hr	12-hr	24-hr
Original rainfall Inches	0.72	1.14	1.44	2.21	3.04	3.86	4.20	5.39	7.00	8.47
Intensity In/hr	8.64	5.04	3.6	3.08	1.66	0.82	0.34	0.4	0.27	0.12
Smooth rainfall inches	0.69	1.14	1.48	2.16	3.04	4.01	4.69	5.83	7.09	8.47
Intensity In/hr	8.28	5.37	4.17	2.7	1.75	0.97	0.68	0.38	0.21	0.12
Rainfall Difference	-0.03	0.0	0.04	-0.05	0.0	0.15	0.49	0.44	0.09	0.0

The durations from 5-minutes to 60-minutes are relatively smooth (small difference between original and smoothed rainfall values). The 3-hour and 6-hour rainfall values are increased to provide a smooth relationship of intensity and duration (when plotted on a log-log scale).

This section of Appendix 7 discusses in detail how the WinTR-20 generates 24-hour storm distributions based on NOAA Atlas 14 data (5-minutes through 24-hour duration). A spread sheet was developed which automates the steps. This spread sheet will provide similar (though not exact) results when compared to the WinTR-20 program. The reason the results are not exact is that Fortran and Excel operate with different numbers of significant digits so rounding of numbers is a concern.

The procedure will be described using an example from a location in Howard County Maryland. The 100-year 24-hour storm distribution will be developed using the smoothed rainfall frequency data. The NOAA Atlas 14 data and the ratio of rainfall at each duration to the 24-hour rainfall are in the following table.

Table A7-2 NOAA 14 data and ratios for durations at a location in Howard County, MD

Duration	5-min	10-min	15-min	30-min	60-min	2-hr	3-hr	6-hr	12-hr	24-hr
Rainfall inches	0.69	1.14	1.48	2.16	3.04	4.01	4.69	5.83	7.09	8.47
Ratio to 24-hour	0.0815	0.1346	0.1747	0.255	0.3589	0.4734	0.5537	0.6883	0.8371	1.0

A symmetrical nested preliminary distribution is developed based on the ratios from 10-minutes to 24-hours. The mid-point of the preliminary distribution is 50% of the cumulative rainfall at 12.0 hours. It is symmetrical about 12 hours and places each duration 50% before 12 hours and 50% after 12 hours. For example, the 60-minute duration rainfall ratio is 0.3589. At 11.5 hours, one-half of 0.3589 is subtracted from 0.5 to calculate the cumulative ratio at 11.5 hours of 0.3205.

The preliminary distribution from 0.0 to 12.0 hours is shown in the following table.

Table A7-3 Preliminary rainfall distribution from 1 hour to 12 hours.

Time-hours	0.0	6	9	10.5	11	11.5	11.75	11.875	11.9167	12.0
Cum Ratio	0.0	0.08146	0.15584	0.22314	0.26328	0.32054	0.41623	0.4327	0.45927	0.5

Once this preliminary distribution is developed, the next step is to develop the distribution ratios at a time interval of 0.1 hour. The general concept is to interpolate the ratios between the points in the above table at an interval of 0.1 hour. The ratios at 6, 9, 10.5, 11.0 and 11.5 are preserved in the final distribution. Ratios for times of 0.1 to 11.7 hours are based on slightly curved line segments between the ratios at the points in the table above. The slight curvature insures a gradual increase of rainfall intensity from 0.0 to 11.7 hours. Values for 11.8 and 11.9 hours are linearly interpolated between ratios at 11.75, 11.875, and 11.9167 hours. After the distribution from 0.0 to 12.0 hours is developed the ratios from 12.1 to 24 are calculated by subtracting the ratio of the opposite value from 1.0. For example, the ratio at 12.1 equals 1.0 minus the ratio at 11.9 hours. The ratio at 12.2 hours is equal to 1.0 minus the ratio at 11.8. This continues all the way to the ends where at time 0.0 the ratio is 0.0 and at 24.0 hours the ratio is 1.0. The 5-minute rainfall ratio has not been considered yet. In order to include the 5-minute ratio, the ratio at 6-minutes (0.1 hour) is calculated as:

$$\text{6-minute ratio} = \text{5-minute ratio} + 0.2 * (\text{10-minute ratio} - \text{5-minute ratio})$$

To incorporate this value into the 24-hour distribution, the 6-minute ratio is subtracted from the ratio at 12.1 hours to determine the ratio at 12.0 hours. This causes the ratio at 12.0 hours to be slightly less than 0.5.

Table A7-4 Complete 24-hour distribution table in WinTR-20 (5-column) format at 0.1 hour time increment.

0.00000	0.00112	0.00225	0.00339	0.00454
0.00569	0.00685	0.00802	0.00920	0.01039
0.01158	0.01278	0.01400	0.01522	0.01644
0.01768	0.01892	0.02017	0.02143	0.02270
0.02398	0.02526	0.02655	0.02785	0.02916
0.03048	0.03181	0.03314	0.03448	0.03583
0.03719	0.03855	0.03991	0.04129	0.04267
0.04406	0.04546	0.04686	0.04828	0.04970
0.05113	0.05257	0.05402	0.05547	0.05694
0.05841	0.05989	0.06138	0.06287	0.06438
0.06589	0.06741	0.06894	0.07048	0.07202
0.07358	0.07514	0.07671	0.07828	0.07987
0.08146	0.08353	0.08562	0.08774	0.08989
0.09208	0.09429	0.09653	0.09880	0.10110
0.10343	0.10579	0.10818	0.11060	0.11305
0.11553	0.11801	0.12052	0.12306	0.12563
0.12822	0.13085	0.13351	0.13620	0.13892
0.14166	0.14444	0.14725	0.15008	0.15295
0.15584	0.15939	0.16307	0.16688	0.17083
0.17491	0.17913	0.18348	0.18797	0.19259
0.19734	0.20223	0.20726	0.21242	0.21771
0.22314	0.23037	0.23799	0.24602	0.25445
0.26328	0.27359	0.28447	0.29592	0.30795
0.32054	0.34028	0.36106	0.38855	0.42468
0.48323	0.57532	0.61145	0.63894	0.65972
0.67946	0.69205	0.70408	0.71553	0.72641
0.73672	0.74555	0.75398	0.76201	0.76963
0.77686	0.78229	0.78758	0.79274	0.79777
0.80266	0.80741	0.81203	0.81652	0.82087
0.82509	0.82917	0.83312	0.83693	0.84061
0.84416	0.84705	0.84992	0.85275	0.85556
0.85834	0.86108	0.86380	0.86649	0.86915
0.87178	0.87437	0.87694	0.87948	0.88199
0.88447	0.88695	0.88940	0.89182	0.89421
0.89657	0.89890	0.90120	0.90347	0.90571
0.90792	0.91011	0.91226	0.91438	0.91647
0.91854	0.92013	0.92172	0.92329	0.92486
0.92642	0.92798	0.92952	0.93106	0.93259
0.93411	0.93562	0.93713	0.93862	0.94011
0.94159	0.94306	0.94453	0.94598	0.94743
0.94887	0.95030	0.95172	0.95314	0.95454
0.95594	0.95733	0.95871	0.96009	0.96145
0.96281	0.96417	0.96552	0.96686	0.96819
0.96952	0.97084	0.97215	0.97345	0.97474
0.97602	0.97730	0.97857	0.97983	0.98108
0.98232	0.98356	0.98478	0.98600	0.98722
0.98842	0.98961	0.99080	0.99198	0.99315
0.99431	0.99546	0.99661	0.99775	0.99888
1.0				

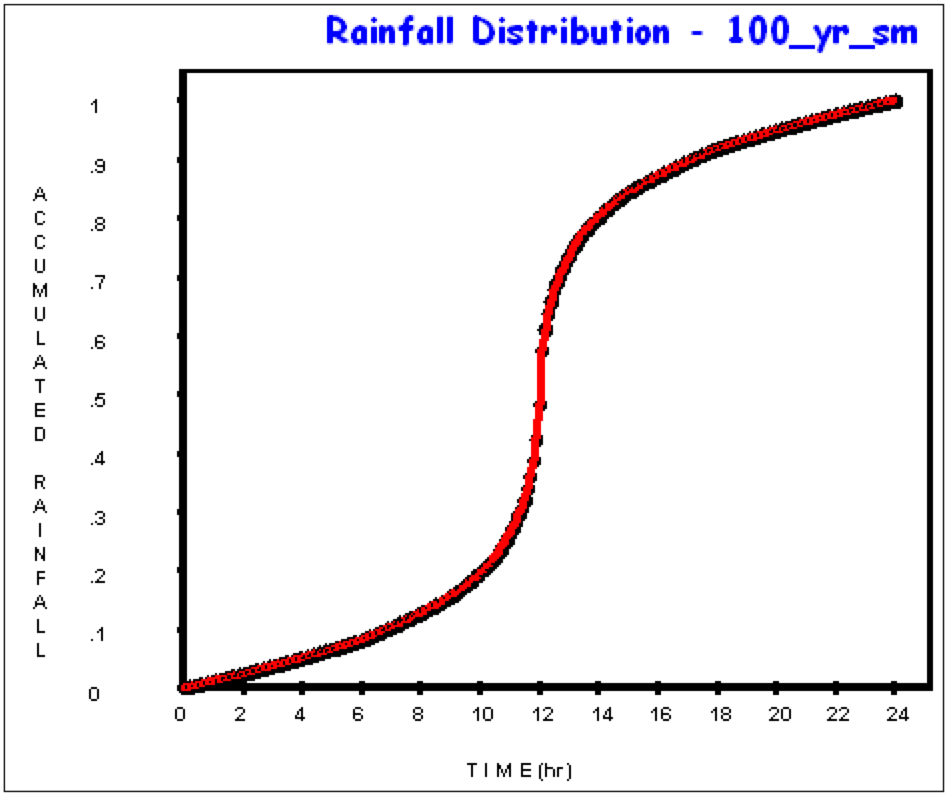


Figure A7-1 Plot of the final 100-year 24-hour storm distribution from WinTR-20.

This procedure is used to develop storm distributions for return periods from 1-year to 500-years. Each distribution may be different because the ratios of the original NOAA 14 data may vary between return periods.

Development of the 12-hour storm distribution from the 24-hour storm distribution

The 12-hour distribution is extracted from the 24-hour storm distribution developed in the previous section of Appendix 7. The 12-hour storm distribution represents the 12-hours in the 24-hour distribution from 6 hours to 18 hours.

In the example of the location in Howard County, Maryland described in the 24-hour storm section, the cumulative ratio at 6 hours is 0.08146. The cumulative rainfall ratio at 18 hours is 0.91854. The difference between these ratios is 0.83708. The 12-hour storm distribution cumulative rainfall must begin at 0.0 and end at 1.0, so to calculate the ratio at each time step of 0.1 hour, 0.08146 is subtracted from the cumulative rainfall ratio from the 24-hour storm and the result is divided by 0.83708 to obtain the cumulative ratio at that time step. Two time steps will be used in this example. The rest are computed in a similar way. At time 6.3 hours (0.3 hours in the 12-hour storm distribution), the 24-hour cumulative ratio is 0.08744. So,

Cumulative ratio at 0.3 hour = (0.08744 – 0.08146) / 0.83708 = 0.0075

Cumulative ratio at 3.0 hours = (0.15584 – 0.08146) / 0.83708 = 0.08886

The spread sheet developed to calculate the 12-hour storm distribution automates this process. The WinTR-20 does not have the 12-hour distribution calculation included, so if the 12-hour storm distribution is desired, it should be developed through the spread sheet and cut and pasted into the WinTR-20 input file using a text editor such as Notepad. A rainfall table header record with RAINFALL DISTRIBUTION: and a second record with an identifier (up to 10 characters) and a time interval in hours need to be placed before the table of numbers. At least one blank record needs to precede the RAINFALL DISTRIBUTION: record and follow the last line of table numbers.

Development of the 6-hour storm distribution from the 24-hour storm distribution

The 6-hour distribution is extracted from the 24-hour storm distribution developed in a previous section of Appendix 7. The 6-hour storm distribution represents the 6-hours in the 24-hour distribution from 9 hours to 15 hours.

In the example of the location in Howard County, Maryland described in the 24-hour storm section, the cumulative ratio at 9 hours is 0.15584. The cumulative rainfall ratio at 15 hours is 0.84416. The difference between these ratios is 0.68832. The 6-hour storm distribution cumulative rainfall must begin at 0.0 and end at 1.0, so to calculate the ratio at each time step of 0.1 hour, 0.15584 is subtracted from the cumulative rainfall ratio from the 24-hour storm and the result is divided by 0.68832 to obtain the cumulative ratio at that time step. Two time steps will be used in this example. The rest are computed in a similar way. At time 10.0 hours (1.0 hour in the 6-hour storm distribution), the 24-hour cumulative ratio is 0.19734. So,

Cumulative ratio at 1.0 hour = (0.19734 – 0.15584) / 0.68832 = 0.06029

Cumulative ratio at 3.0 hours = (0.48323 – 0.15584) / 0.68832 = 0.47564

The spread sheet developed to calculate the 6-hour storm distribution automates this process. The WinTR-20 does not have the 6-hour distribution calculation included, so if the 6-hour storm distribution is desired, it should be developed through the spread sheet and cut and pasted into the WinTR-20 input file using a text editor such as Notepad. A rainfall table header record with RAINFALL DISTRIBUTION: and a second record with an identifier (up to 10 characters) and a time interval in hours need to be placed before the table of numbers. At least one blank record needs to precede the RAINFALL DISTRIBUTION: record and follow the last line of table numbers.

APPENDIX 8
GISHYDRO2000:
DESCRIPTION AND FUNCTION

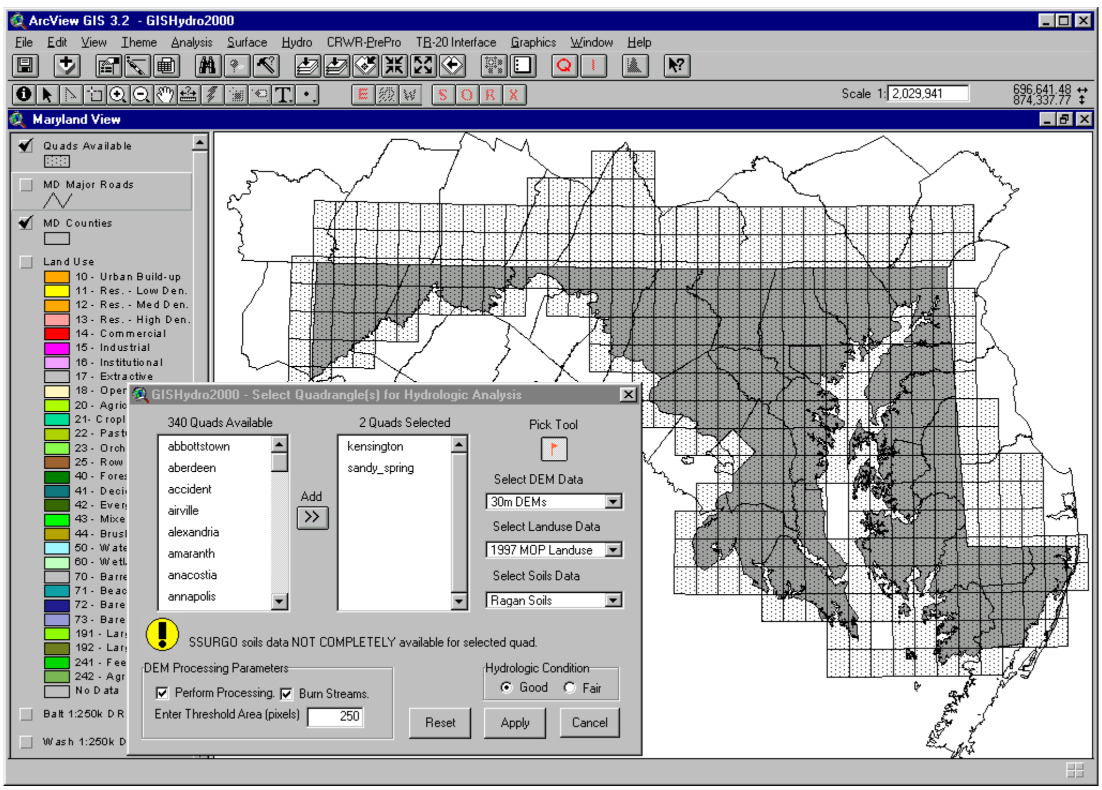
GISHydro2000: DESCRIPTION AND FUNCTION

This appendix provides an overview GISHydro2000 and some of its basic functionality. This information is given to provide background and to supplement suggested analysis procedures contained in the main body of this report. Specifically, this appendix provides a several page introduction to GISHydro2000 and brief tutorials on how to specify varying hydrologic conditions, how to override pre-defined land use categories in the GISHydro2000 database, and how to interact with this software to delineate sub-areas, specify time of concentration parameters, develop a reach routing table, and ultimately write a TR-20 input file and execute the TR-20 program.

A new version of GISHydro (called GISHydroNXT) is under development. This version is compatible with the ESRI ArcGIS software, currently in version 9.3.1 but will shortly be in version 10.0.

Overview

The program, GISHydro2000, developed at the University of Maryland, takes advantage of GIS technology to reduce the time required to perform hydrologic analyses while improving the integrity and reproducibility of these analyses. There are three steps in the analyses: data assembly, estimation of peak flows, and analysis/critique of modeled results.



- **Data Assembly**: Figure A8-1 shows the initial step of selecting information from a database that spans the entire state of Maryland as well as those areas of Pennsylvania, Delaware, and West Virginia draining into Maryland. The existence of redundant geographic information allows the user to examine the sensitivity of model output to changing interpretations of land use, topography, and soils. Included in the land use database is a coverage based on zoning maps that provides estimates of "Ultimate Development"**.**

- **Estimation of Peak Flows**: The engineer next indicates the location of key elements such as the overall watershed outlet (design point) and identifies the location of specific internal features (such as reservoirs or other existing infrastructure). At present two fundamentally different hydrologic analysis programs are supported: "TR-20," a rainfall-runoff model developed by the Natural Resources Conservation Service and required by the State of Maryland for all significant hydrologic analysis, and the U.S. Geological Survey peak flow regression equations.

- **Analysis / Critique of Modeled Results**: an important aspect of the software is that the time saved can be spent analyzing the model results. Multiple scenarios can be investigated in an effort to determine the most cost-effective or environmentally sound design. Also, multiple characterizations of the watershed in terms of differing land use, soils, and topographic data can be examined, indicating the sensitivity of modeled results to the input data.

Application

GISHydro2000 and earlier versions of this software have been used at MSHA since 1991. It is a standard component in the analysis of any watershed at MSHA and is recognized by the Maryland Department of the Environment as a valuable tool for these analyses. Other state, local, and private agencies use GISHydro2000 in their analyses as well.

The current version of GISHydro2000 works within the ArcView 3.2 (or higher) environment and also depends on the Spatial Analyst Extension (version 1.1 or higher). This software must be installed on the PC in order for GISHydro2000 to work. As of May 30, 2003, the list price for a single copy of ArcView 3.3 is $1,200. The cost of Spatial Analyst 2.0a is $2,500. The cost per license may be reduced if multiple licenses are purchased or if the purchase is made through special state contracts. The GISHydro2000 software is free and can be downloaded from the web at http://www.gishydro.umd.edu/.

Lookup Table: Maryland Department of Planning/Good Conditions

Lucode	Classifica	Hyd_a	Hyd_b	Hyd_c	Hyd_d	Imp	Lucat
10	Urban	61	75	83	87	0.38	u
11	Low Density Residential	54	70	80	85	0.25	u
12	Medium Density Residential	61	75	83	87	0.38	u
13	High Density Residential	77	85	90	92	0.65	u
14	Commercial	89	92	94	95	0.85	u
15	Industrial	81	88	91	93	0.72	u
16	Institutional	69	80	86	89	0.50	n
17	Extractive	77	86	91	94	0.11	n
18	Open Urban Land	39	61	74	80	0.11	n
20	Agriculture	67	78	85	89	0.00	n
21	Cropland	67	78	85	89	0.00	n
22	Pasture	39	61	74	80	0.00	n
23	Orchards	32	58	72	79	0.00	n
24	Feeding Operations	59	74	82	86	0.00	n
25	Row Crops	67	78	85	89	0.00	n
40	Forest	30	55	70	77	0.00	f
41	Deciduous Forest	30	55	70	77	0.00	f
42	Evergreen Forest	30	55	70	77	0.00	f
43	Mixed Forest	30	55	70	77	0.00	f
44	Brush	30	48	65	73	0.00	f
50	Water	100	100	100	100	0.00	s
60	Wetlands	100	100	100	100	0.00	s
70	Barren Land	77	86	91	94	0.50	n
71	Beaches	77	86	91	94	0.00	n
72	Bare Exposed Rock	77	86	91	94	1.00	n
73	Bare Ground	77	86	91	94	0.50	n
80	Transportation	83	89	92	94	0.75	n
191	Large Lot Agricultural	67	78	85	89	0.15	n
192	Large Lot Forest	30	55	70	77	0.15	f
241	Feeding Operations	59	74	82	86	0.10	n
242	Agricultural Buildings	59	74	82	86	0.10	n

Spatial Database

GISHydro2000 includes a large spatial database of land use, topography, and soils as well as other supporting data such as road networks, political boundaries, USGS gage locations, etc. All data are in the Maryland Stateplane Coordinate system, NAD 1983. The horizontal units of this database are in meters. The vertical units are in feet for all DEM data and in inches for precipitation data.

One of the most important calculations performed by this program is the assignment of curve numbers and the attribution of imperviousness given land use and hydrologic soil type information. This assignment is a table-lookup based procedure that depends on one of many possible tables as a function of the data source for the land use and hydrologic condition (i.e. good, fair, or poor). As an example, Table A8-1 corresponds to the Maryland Department of Planning generalized land use codes and to "good" hydrologic conditions.

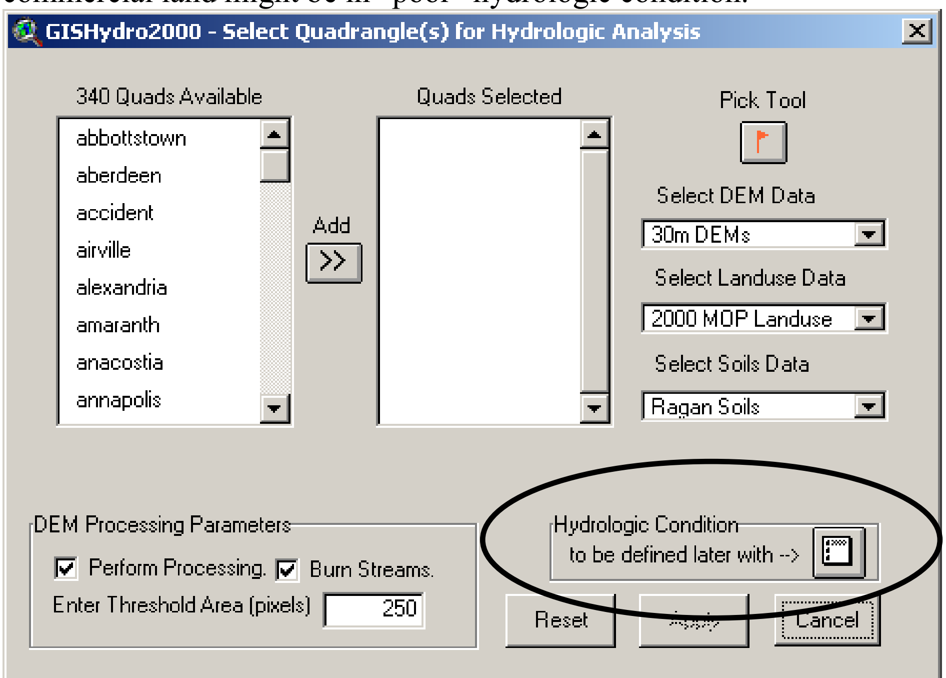
Present and Future: GISHydro2000 Website

The current version of this program, including documentation and a user's manual can be downloaded from the University of Maryland website:

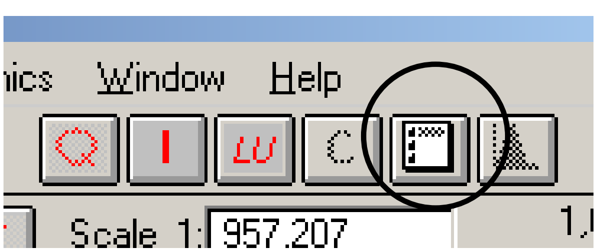
http://www.gishydro.umd.edu/

Modifying hydrologic condition within GISHydro2000

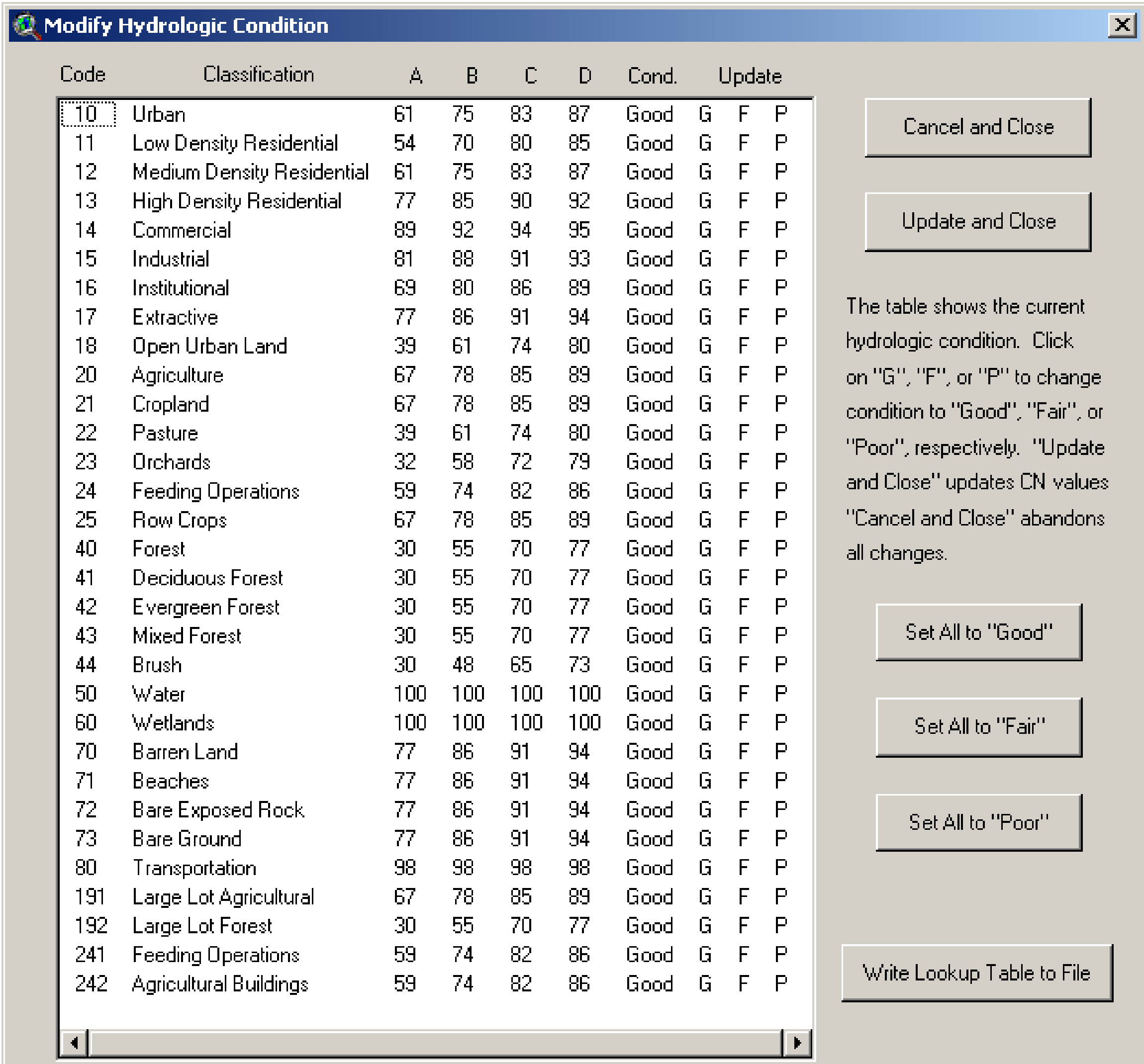
This section explains and illustrates a structural change to GISHydro2000 focused on the need to specify curve numbers within GISHydro2000 that vary according to land use category. A new "Modify Hydrologic Condition" dialog now allows the engineer to specify that, for instance, medium density residential land might be in "fair" hydrologic condition, while deciduous forest might be in "good" hydrologic condition, and commercial land might be in "poor" hydrologic condition.



The engineer proceeds as usual with the first indication of change shown below in the "Select Quadrangle(s) dialog box. The circled area shows a change where the user had previously checked either "Good" or "Fair" hydrologic condition to be applied uniformly across all land use categories. The user now makes no selection here, but postpones such decision(s) until slightly later in the analysis process. At this point, the engineer needs only to specify the other normal selections: quad(s), DEM, Land use, Soils, and parameters controlling DEM processing.



Once the engineer has selected the extent and types of data to be used, an "Area of Interest" view appears as previously. At this point the engineer should notice that the button circled in the image to the left becomes functional. Pressing this button initiates the “Modify Hydrologic Condition” dialog as shown below.



Code	Classification	A	B	C	D	Cond.	Update		
10	Urban	61	75	83	87	Good	G	F	P
11	Low Density Residential	54	70	80	85	Good	G	F	P
12	Medium Density Residential	61	75	83	87	Good	G	F	P
13	High Density Residential	77	85	90	92	Good	G	F	P
14	Commercial	89	92	94	95	Good	G	F	P
15	Industrial	81	88	91	93	Good	G	F	P
16	Institutional	69	80	86	89	Good	G	F	P
17	Extractive	77	86	91	94	Good	G	F	P
18	Open Urban Land	39	61	74	80	Good	G	F	P
20	Agriculture	67	78	85	89	Good	G	F	P
21	Cropland	67	78	85	89	Good	G	F	P
22	Pasture	39	61	74	80	Good	G	F	P
23	Orchards	32	58	72	79	Good	G	F	P
24	Feeding Operations	59	74	82	86	Good	G	F	P
25	Row Crops	67	78	85	89	Good	G	F	P
40	Forest	30	55	70	77	Good	G	F	P
41	Deciduous Forest	30	55	70	77	Good	G	F	P
42	Evergreen Forest	30	55	70	77	Good	G	F	P
43	Mixed Forest	30	55	70	77	Good	G	F	P
44	Brush	30	48	65	73	Good	G	F	P
50	Water	100	100	100	100	Good	G	F	P
60	Wetlands	100	100	100	100	Good	G	F	P
70	Barren Land	77	86	91	94	Good	G	F	P
71	Beaches	77	86	91	94	Good	G	F	P
72	Bare Exposed Rock	77	86	91	94	Good	G	F	P
73	Bare Ground	77	86	91	94	Good	G	F	P
80	Transportation	98	98	98	98	Good	G	F	P
191	Large Lot Agricultural	67	78	85	89	Good	G	F	P
192	Large Lot Forest	30	55	70	77	Good	G	F	P
241	Feeding Operations	59	74	82	86	Good	G	F	P
242	Agricultural Buildings	59	74	82	86	Good	G	F	P

From left to right across the table, this dialog shows the land use code, land use category, the A, B, C, and D curve numbers for each category, the current understood hydrologic condition, and then the letters “G”, “F”, and “P”. The engineer can update the hydrologic condition for any one category by pressing the appropriate letter “G” (Good), “F” (Fair), or “P” (Poor) as needed. If a wholesale change is desired, the buttons “Set All to ‘Good’”, “Set All to ‘Fair’”, and “Set All to ‘Poor’” change the hydrologic condition across all hydrologic conditions simultaneously.

Once all desired changes are made, the engineer should press, “Update and Close”, this will update all the indicated changes in the table and apply these changes to the “Curve Number” theme as it appears in the “Area of Interest” view. For reporting purposes, the “Write Lookup Table to File” behaves the same as the “Update and Close” button, but also provides a file browser dialog box for the engineer to direct an output text file for the updated lookup table. The “Cancel and Close” button exits the dialog with none of the changes that may have been entered taking effect.

A few cautionary words are necessary. If changes are made to the lookup table, then any previous calculations involving the curve number (e.g. selecting the “Basin Statistics” choice from the “Hydro” menu or the “Calculate Attributes” from the “CRWR-PrePro” menu must be repeated (after modifying the lookup table) so as to incorporate the revised curve number values. Also, if any custom land uses are added using the “Digitize Custom Land Use Polygon” (obtained by pressing the “*LU*”) button, the curve numbers associated with any added special land uses will appear in the “Modify Hydrologic Condition” dialog. However, the curve numbers associated with such specialized land use categories ***will not*** be editable because GISHydro2000 has no way of knoWing what the appropriate “Good”, “Fair”, and “Poor” hydrologic conditions for such polygons would be.

Modifying land use

The tool described in this section can be applied generally across all land use coverages contained within GISHydro2000.

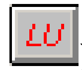
Reasons for Using Tool

There are several reasons why one might wish to use this tool:

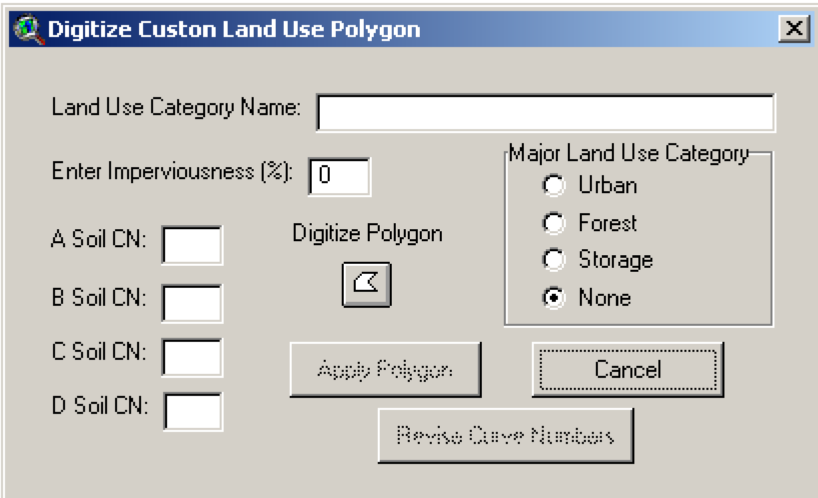
1. When working with ultimate zoning data, the base information contained within the GISHydro2000 database may not be current in the location of a particular watershed analysis. This tool can be used to update the base information to reflect recent zoning changes.
2. The most likely land use data to be used in GISHydro2000 to reflect “current” conditions are the data supplied by the Maryland Department of Planning (MDP). These data indicate generalize land cover across approximately 25 land cover categories. The hydrologic characteristics of some of these categories (e.g. “Institutional” are not particularly well-defined and may vary considerably from one location to another. This tool can be used to create a new land use category that reflects land cover/land use conditions that are well-understood by the engineer making the change through paper maps or field reconnaissance.
3. A second weakness of the MDP data is its broad “low density residential” land use category which includes housing densities from half-acre lots up to 2-acre lots. The imperviousness and/or curve numbers associated with this range of housing densities can vary considerably depending on whether the actual density is close to the upper or lower bound of this range. This tool can be used to create a new land use category that more precisely captures the actual housing density through the specification of curve numbers or degree of imperviousness specified directly by the engineer for this new land use category.

Using the Tool

Step 1 – Select the Quadrangles/Delineate the Study Watershed (as usual): The analysis performed by the engineer proceeds as before with the engineer using the "Q" button to define the quadrangles that are indicated for a particular analysis. GISHydro2000 will create the "Area of Interest" view with focused on the data for the selected quadrangles. The land use modification tool can now be used, although it is suggested that the user go one step further and also delineate the watershed before proceeding to use this tool since only the land use within the watershed need be updated.

Step 2 – Invoke the Land Use Modification Dialog: Press the "*LU*" (

) button, located to the right of the "Q" button used earlier to initiate the analysis. This will bring up the dialog box shown below:



* Note: Steps 3 through 6 below can be performed in any order provided the directions in these steps are followed appropriately.

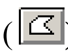
Step 3: Entering the Land Use Category Name: Enter in this box the text describing the land use category. You may want to include a special parenthetical comment indicating that this is a special, user defined category. For example, "Residential, 1-acre houses (user defined)." This field is for informational purposes only and is not a required input.

Step 4: Indicating the Major Land Use Category: There exist three special classes of land use that need to be indicated for correct calculation of the "Basin Statistics" and/or the regional regression equations. These categories are, "urban", "forest", and "storage". User simply needs to click on the category that applies to the new land use category being specified. If none of these categories apply, leave the selection set as the category, "none". Please note that the "forest" and "storage" categories assume and impose an imperviousness of 0%.

Step 5: Indicating the Curve Numbers and/or Imperviousness: The default imperviousness is 0% as the dialog box opens. There are no default curve number values. So long as the major land use category is "urban" or "none" the imperviousness box is editable. Any numerical entry in the imperviousness box will result in the calculation of the associated A, B, C, and D curve numbers according to the formulas:

$$x \cdot 98 + (1 - x) \cdot 39 = CN_A \qquad \text{(A Soil)}$$
$$x \cdot 98 + (1 - x) \cdot 61 = CN_B \qquad \text{(B Soil)}$$
$$x \cdot 98 + (1 - x) \cdot 75 = CN_c \qquad \text{(C Soil)}$$
$$x \cdot 98 + (1 - x) \cdot 80 = CN_D \qquad \text{(D Soil)}$$

where x is the imperviousness expressed as a fraction of 1. All curve numbers are rounded to the nearest integer value. Please note that any manual entry in the imperviousness box after the curve number boxes have been filled out will undo entries manually entered in the curve number boxes. If you wish to manually specify *both* curve numbers and imperviousness, you should first specify the imperviousness and then the curve numbers.

Step 6: Digitizing the Land Use Polygon: Press the "Digitize Polygon" button () and digitize on the computer screen the outline of the polygon of land use you are specifying. Two things to note: 1) To end the digitizing of the polygon, double-click rapidly at the last location of the polygon your are updating; 2) You cannot digitize multiple polygons for a given category simultaneously. If you have multiple polygons you wish to digitize that you wish to have the same land use, you must repeatedly perform identical data entry steps indicated here for each area as if each polygon were a different land use, but assigning the same land use category name, major land use, and curve numbers/imperviousness. If you digitize more than one polygon without hitting the "Apply Polygon" button in between, all polygons will be recorded into your updated land use/curve number coverages.

Step 7: Applying the Polygon: Only after both a polygon has been digitized and curve number/imperviousness information has been entered will the "Apply Polygon" button become active (black). At the time this button is pressed, the text information indicated in the dialog box along with the last digitized polygon (see Step 6 above) are written to disk. If the "Apply Polygon" button is not pressed and the dialog box is exited (through the use of the "Cancel" button or the "X" box at the upper-right corner of the dialog) then any information contained in the dialog box at the time of exiting is lost. The Land Use Modification Dialog may be opened once and multiple polygons of land use entered and applied, or the dialog may be opened multiple times each time specifying one or more polygons of land use.

Step 8: Revising the Curve Numbers: After one or more polygons of modified land use are entered and applied, the "Revise Curve Numbers" button becomes active "black". Until this button has been pressed, the land use and curve number themes have not been revised to reflect any of the changes entered in this dialog. This button needs to be pressed only once, at the conclusion of the entry of all modified land use polygons, but may actually be pressed anytime after the first land use change polygon has been completely entered. Note that once this button has been pressed, the legend colors for the display of the “Land Use” and “Curve Number” themes are changed. Since it is impossible to anticipate what kinds of land use will be entered by the engineer, no effort has been made to control the color legends for these themes. For the land use theme, the engineer must manually modify the legends for these themes with the appropriate colors associated with all previously existing and new categories of land use. This is chronologically the last button you will press when using this dialog. Once you are finished with this dialog you can proceed with your hydrologic analysis as done previously.

Step 9: Using the “Cancel” Button: Pressing this button (or the “X” button at the upper-right corner of the dialog) will cause the dialog box to close with any information contained in the dialog at the time of exiting to be permanently lost. For instance, you may wish to use this button if you are unhappy with the polygon you have digitized. You could then re-open the dialog box by pressing the “*LU*” with no memory of any information entered previously (the defined polygon or other text information) being retained since the last time the “Apply Polygon” button was pressed.

Documenting Modified Land Use: The “Digitize Custom Land Use Polygon” dialog stores information in two places during and after use of this dialog is completed. Non-GIS information is stored in the landuse lookup table. The digitized polygons are stored in a shapefile (3 physical files make up 1 shapefile). Both of these entities are written to the c:\temp directory.

Landuse Lookup Table

Lucode	Classifica	Hyd_a	Hyd_b	Hyd_c	Hyd_d	Imp	Lucat
10	Urban	89	92	94	95	0.30	u
11	Low Density Residential	54	70	80	85	0.25	u
12	Medium Density Residential	61	75	83	87	0.30	u
13	High Density Residential	77	85	90	92	0.65	u
14	Commercial	89	92	94	95	0.82	u
15	Industrial	81	88	91	93	0.70	u
16	Institutional	81	88	91	93	0.50	n
17	Extractive	77	86	91	94	0.11	n
18	Open Urban Land	39	61	74	80	0.11	n
20	Agriculture	67	78	85	89	0.00	n
21	Cropland	67	78	85	89	0.00	n
22	Pasture	39	61	74	80	0.00	n
23	Orchards	32	58	72	79	0.00	n
24	Feeding Operations	89	92	94	95	0.00	n
25	Row Crops	67	78	85	89	0.00	n
40	Forest	30	55	70	77	0.00	f
41	Deciduous Forest	30	55	70	77	0.00	f
42	Evergreen Forest	30	55	70	77	0.00	f
43	Mixed Forest	30	55	70	77	0.00	f
44	Brush	30	48	65	73	0.00	f
50	Water	100	100	100	100	0.00	s
60	Wetlands	100	100	100	100	0.00	s
70	Barren Land	77	86	91	94	0.50	n
71	Beaches	77	86	91	94	0.00	n
72	Bare Exposed Rock	77	86	91	94	1.00	n
73	Bare Ground	77	86	91	94	0.50	n
80	Transportation	100	100	100	100	1.00	n
191	Large Lot Agricultural	67	78	85	89	0.15	n
192	Large Lot Forest	30	55	70	77	0.15	f
241	Feeding Operations	67	78	85	89	0.10	n
242	Agricultural Buildings	67	78	85	89	0.10	n

The Landuse Lookup Table: This table is visible within the GIS as one of the tables called, “Landuse Lookup Table”. The file that contains the information displayed in this table is located on the machine’s hard-drive at, “c:\temp\templutab.dbf”. The default version of this table corresponding to the selection of Maryland Department of Planning land use data is shown below: The “Hyd_x” fields (columns) indicate the curve numbers that apply to this land use category for soil type “x”. The “Imp” field shows the default imperviousness associated with each land use category as a decimal fraction. The “Lucat” field indicates the major land use class (see Step 4) that applies to each land use category (“u”=urban, “f”=forest, “s”=storage, and “n”=none. The values and category descriptions appearing in the leftmost two fields will vary depending on the land use coverage selected by the engineer at the time the analysis is initiated. Additional records (rows) starting with values of Lucode = 501 will be added to this table if the land use modification dialog is used to indicate new land use polygons. This table should be included as a standard part of all hydrologic analysis reports.

The "lumod" shapefile: This file is not loaded into the GIS. It exists only on disk as "c:\temp\lumod.xxx" (where xxx are the 3 file extensions: "shp", "shx", and "dbf" that make up a shapefile.) If land use is changed as part of a given analysis, this shapefile should be included electronically as a standard part of the reporting of that analysis.

Some Comments on Representative Imperviousness Values

The NRCS has published some representative imperviousness values for several different categories of urban land. These are repeated below in Table 1.

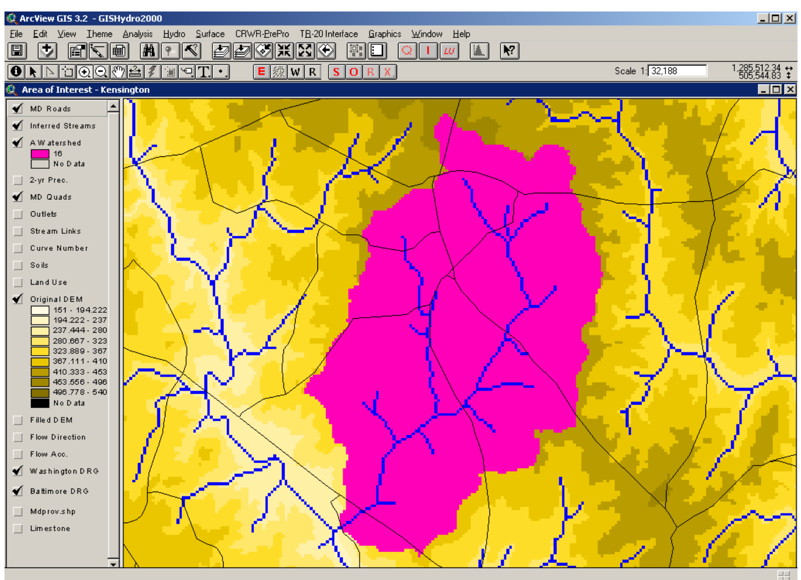
Table A8-1. Representative percent imperviousness values from NRCS.

Land Use Category	Imperviousness (%)
Commercial and business	85
Industrial	72
Residential (1/8 acre or less)	65
Residential (1/4 acre)	38
Residential (1/3 acre)	30
Residential (1/2 acre)	25
Residential (1 acre)	20
Residential (2 acres)	12

Imperviousness values used by default in GISHydro2000 are very consistent with Table 1 and may be viewed or changed by modifying the contents of the "Landuse Lookup Table" contained in GISHydro2000 and discussed above under "Documenting Modified Land Use".

Illustration

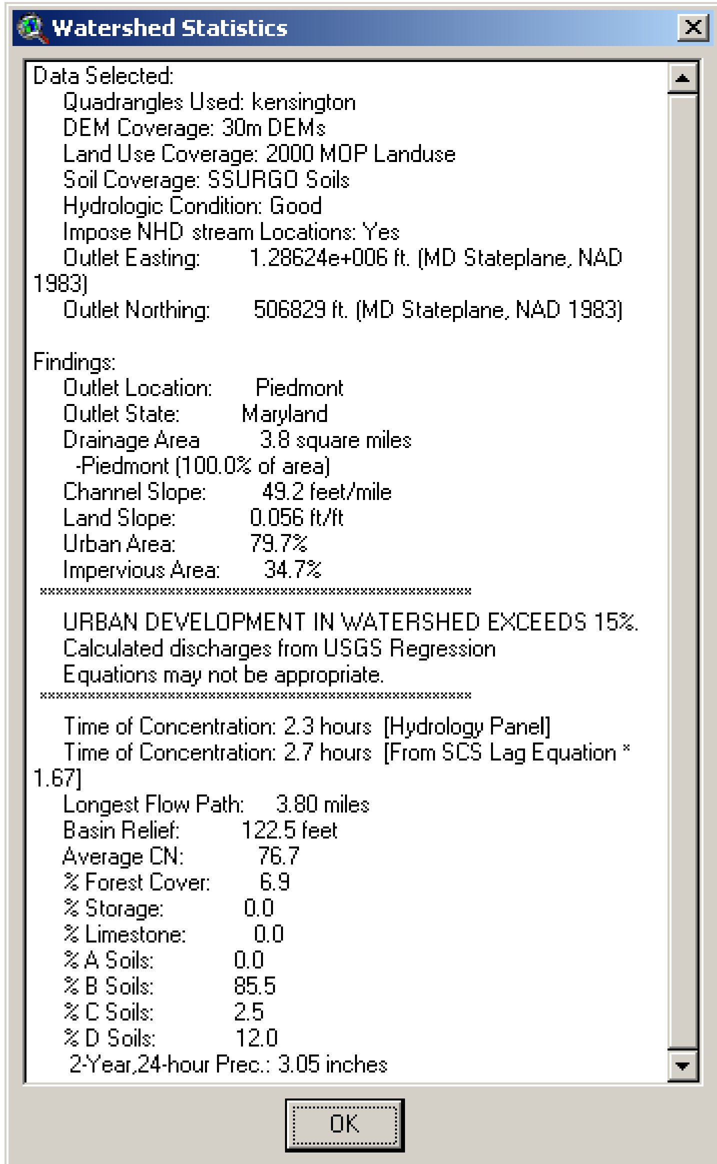
The screen capture to the right shows a small delineated watershed in the Kensington quadrangle. To illustrate the use of the land use modification tool, the default basin statistics are shown in the "Watershed Statistics" dialog box shown on the next page. (It is not necessary to

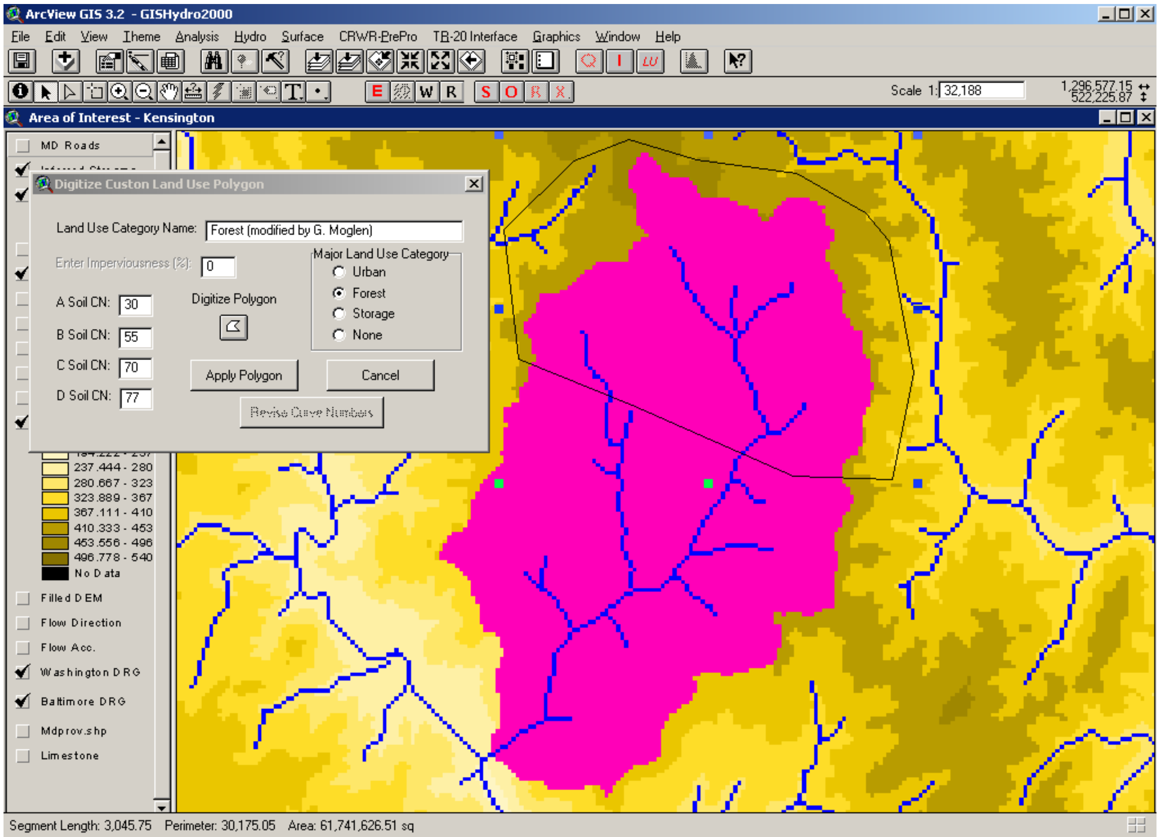


perform this step, but it is done here to illustrate the effects of the land use modification tool.

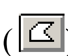
We now begin the process of updating the land use within the delineated watershed. For illustration purposes two new land use polygons will be indicated.

- **Polygon #1:** The first polygon will occupy the northern third of the watershed and will be of forested land use.
- **Polygon #2:** The second polygon will occupy the southern third of the watershed and will be of urban land use, with 10% imperviousness.

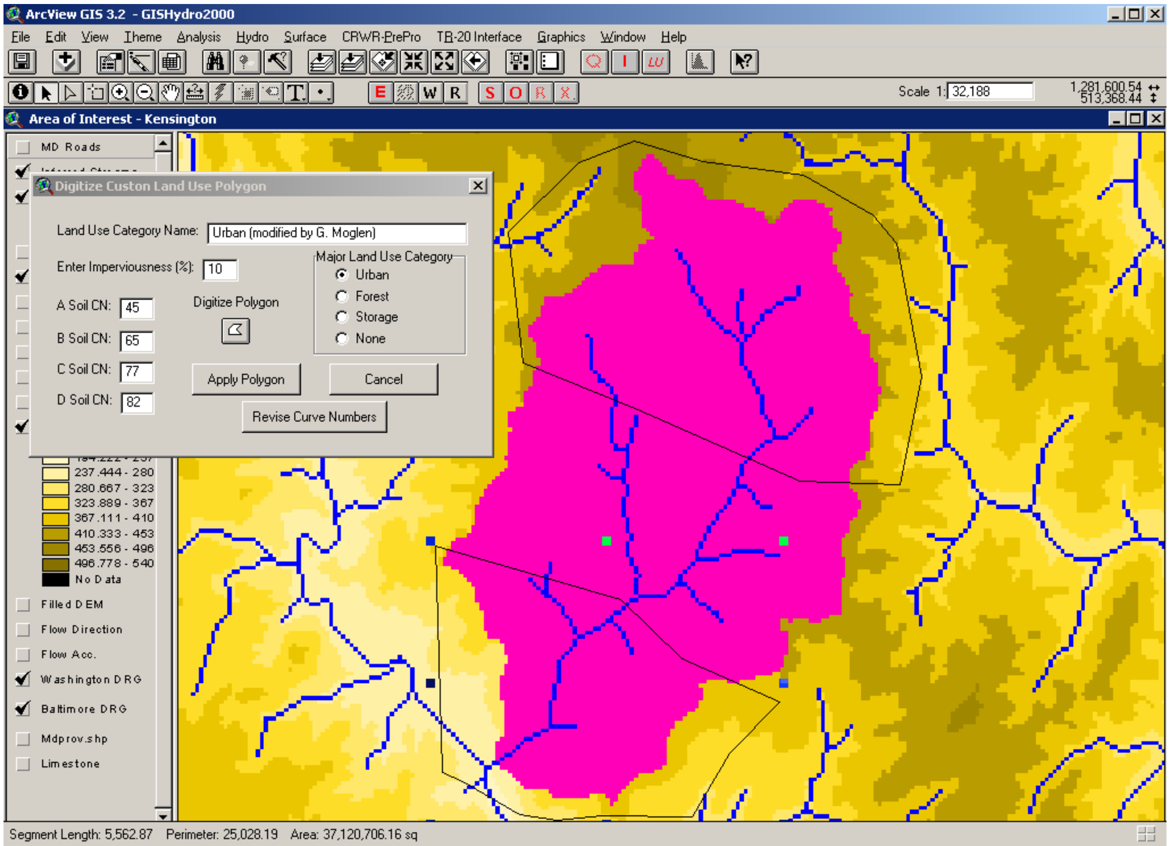




Polygon #1: Steps shown on this page:

1. Invoke the land use modification tool by pressing the "LU" button.
2. Indicate a name for the land use category. (Here we enter, "Forest (modified by G. Moglen)" to indicate both the land use type and the fact that this is a departure from the default 2000 land use defined by the MDP.)
3. Since this is a forested polygon, click on the "Forest" indicator under the "Major Land Use Category". Notice that this has the effect of "graying out" the imperviousness text box with the value fixed at 0%.
4. Set the curve numbers for the A-D soils by typing the values in the appropriate text box. The values shown are 30, 55, 70, and 77 for A, B, C, and D soils, respectively. These values need to be manually entered.
5. Press the "Digitize Polygon" button () and digitize on the computer screen the outline of the forested polygon. To end the digitizing process, double-click rapidly on the final point of the polygon. Notice that the digitizing process need only apply over the domain of the watershed. Land use modifications outside the boundaries of the watershed will have no effect on the basin statistics or subsequent calculations.

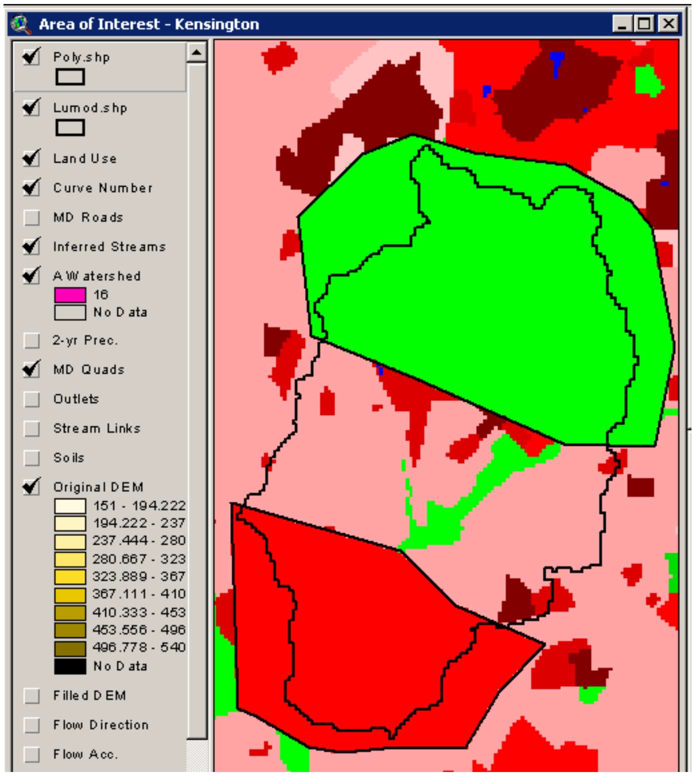
Press the "Apply Polygon" button to accept the text and polygon information shown above. Notice that the "Apply Polygon" button only becomes active after steps 2 through 5 have been completed. Also, steps 2 through 5 can be performed in any order.



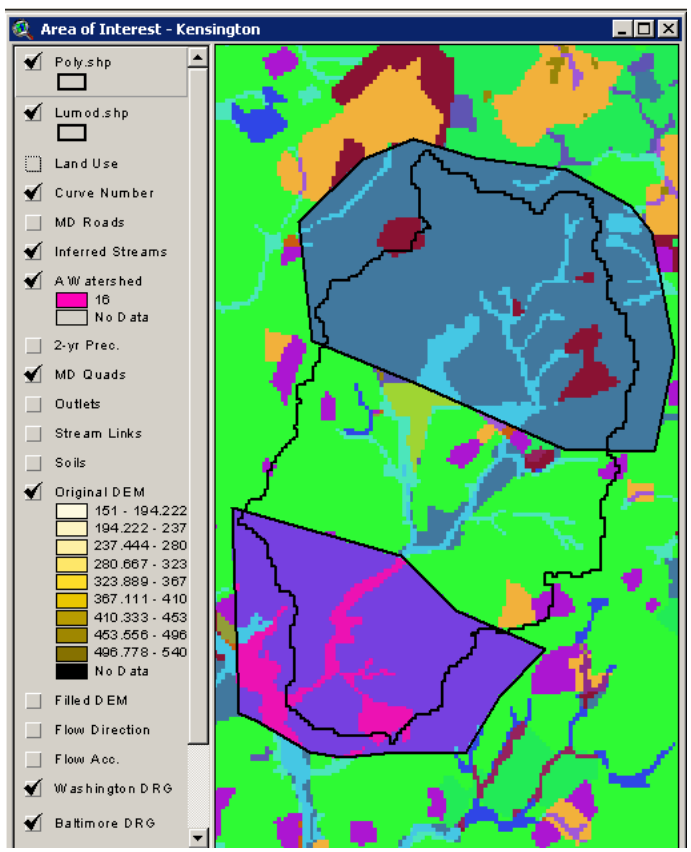
Polygon #2: Steps shown on this page:

1. Indicate a name for the land use category. Here we enter, "Urban (modified by G. Moglen)"
2. Since this is an urban polygon, click on the "Urban" indicator under the "Major Land Use Category".
3. In the "Enter Imperviousness" text box, type "10" to indicate 10% imperviousness. This will automatically populate the A-D curve number boxes followng the equations presented earlier on page 2. If different curve number values are desired they should be entered ***after*** the imperviousness is indicated.
4. Press the "Digitize Polygon" button () and digitize on the computer screen the outline of the forested polygon.
5. Press the "Apply Polygon" button to accept the text and polygon information shown above.

Having "applied" both polygons, we can now do the final step, which is to press the "Revise Curve Numbers" button. This has the effect of updating both the "Land Use" and "Curve Number" themes shown in the area of interest view per the modifications applied with the land use modification dialog. The resulting view is shown at the top of the next page:



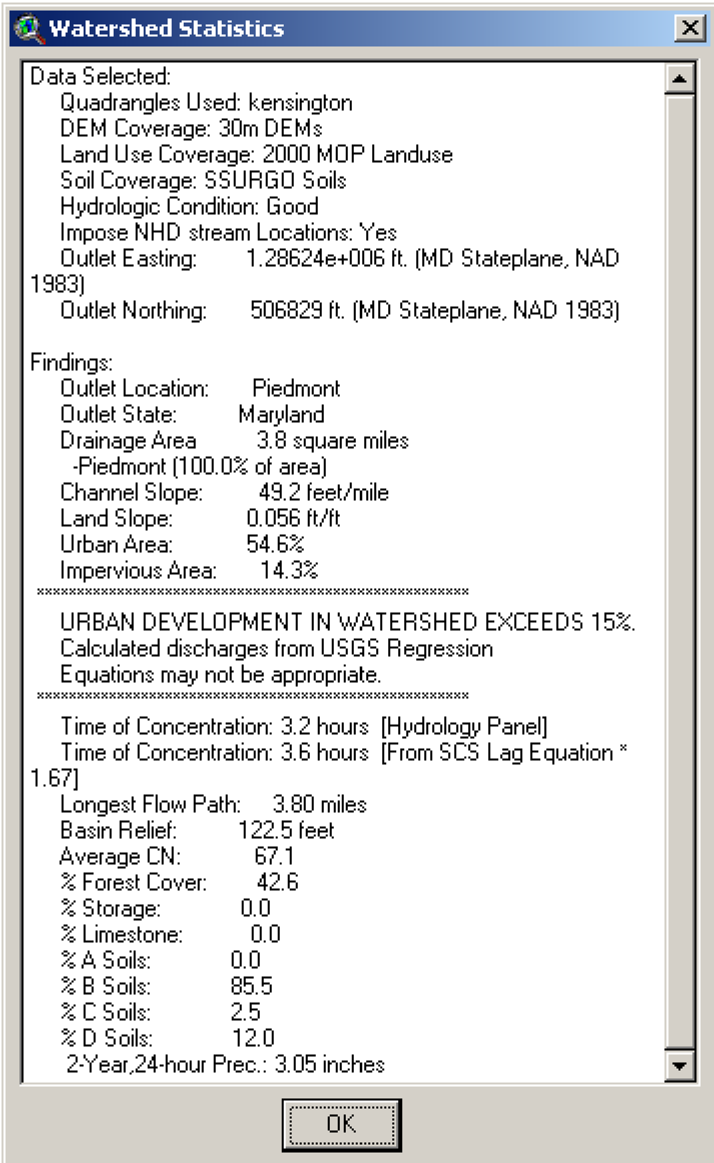
The view shows the land use as it now exists with the modifications described earlier. (It should be noted that this illustration at right has been enhanced a little bit to make the modifications to the land use theme more clear. The watershed outline is shown explicitly – this would not normally be the case, and the shapefile, "lumod.shp" has also been loaded into the view to make the land use changes clear. This is also not normally the case. Finally, the color scheme: green for the forested polygon and red for the urban polygon was chosen to make the land use changes more clear. The effect on the curve number theme is not as clear, but is shown in the illustration below to demonstrate that the modifications have propagated to the curve number themes as well. The areas within the two digitized polygons clearly exhibit different values than the neighboring areas outside these polygons. This is consistent with what one would expect for land use modifications such as the ones illustrated in this example.



The Landuse Lookup Table as it appears in the GISHydro2000 project is shown at right. Notice the two new records with Lucode equal to 501 and 502 at the bottom of this table. These are the two records that were added to this table through the use of the land use modification tool.

Landuse Lookup Table

Lucode	Classifica	Hyd_a	Hyd_b	Hyd_c	Hyd_d	Imp	Lucat
10	Urban	89	92	94	95	0.30	u
11	Low Density Residential	54	70	80	85	0.25	u
12	Medium Density Residential	61	75	83	87	0.30	u
13	High Density Residential	77	85	90	92	0.65	u
14	Commercial	89	92	94	95	0.82	u
15	Industrial	81	88	91	93	0.70	u
16	Institutional	81	88	91	93	0.50	n
17	Extractive	77	86	91	94	0.11	n
18	Open Urban Land	39	61	74	80	0.11	n
20	Agriculture	67	78	85	89	0.00	n
21	Cropland	67	78	85	89	0.00	n
22	Pasture	39	61	74	80	0.00	n
23	Orchards	32	58	72	79	0.00	n
24	Feeding Operations	89	92	94	95	0.00	n
25	Row Crops	67	78	85	89	0.00	n
40	Forest	30	55	70	77	0.00	f
41	Deciduous Forest	30	55	70	77	0.00	f
42	Evergreen Forest	30	55	70	77	0.00	f
43	Mixed Forest	30	55	70	77	0.00	f
44	Brush	30	48	65	73	0.00	f
50	Water	100	100	100	100	0.00	s
60	Wetlands	100	100	100	100	0.00	s
70	Barren Land	77	86	91	94	0.50	n
71	Beaches	77	86	91	94	0.00	n
72	Bare Exposed Rock	77	86	91	94	1.00	n
73	Bare Ground	77	86	91	94	0.50	n
80	Transportation	100	100	100	100	1.00	n
191	Large Lot Agricultural	67	78	85	89	0.15	n
192	Large Lot Forest	30	55	70	77	0.15	f
241	Feeding Operations	67	78	85	89	0.10	n
242	Agricultural Buildings	67	78	85	89	0.10	n
501	Forest (modified by G. Mog	30	55	70	77	0.00	f
502	Urban (modified by G. Mog)	45	65	77	82	0.10	u



Finally, the basin statistics can be recalculated for the example watershed that should now reflect the changes on the curve number. The resulting "Watershed Statistics" dialog is shown at left. Several values related to the land use and curve number modifications have clearly changed and are noted in Table 2 below.

Table 2. Comparison of Watershed Statistics for Original and Modified Land Use Data

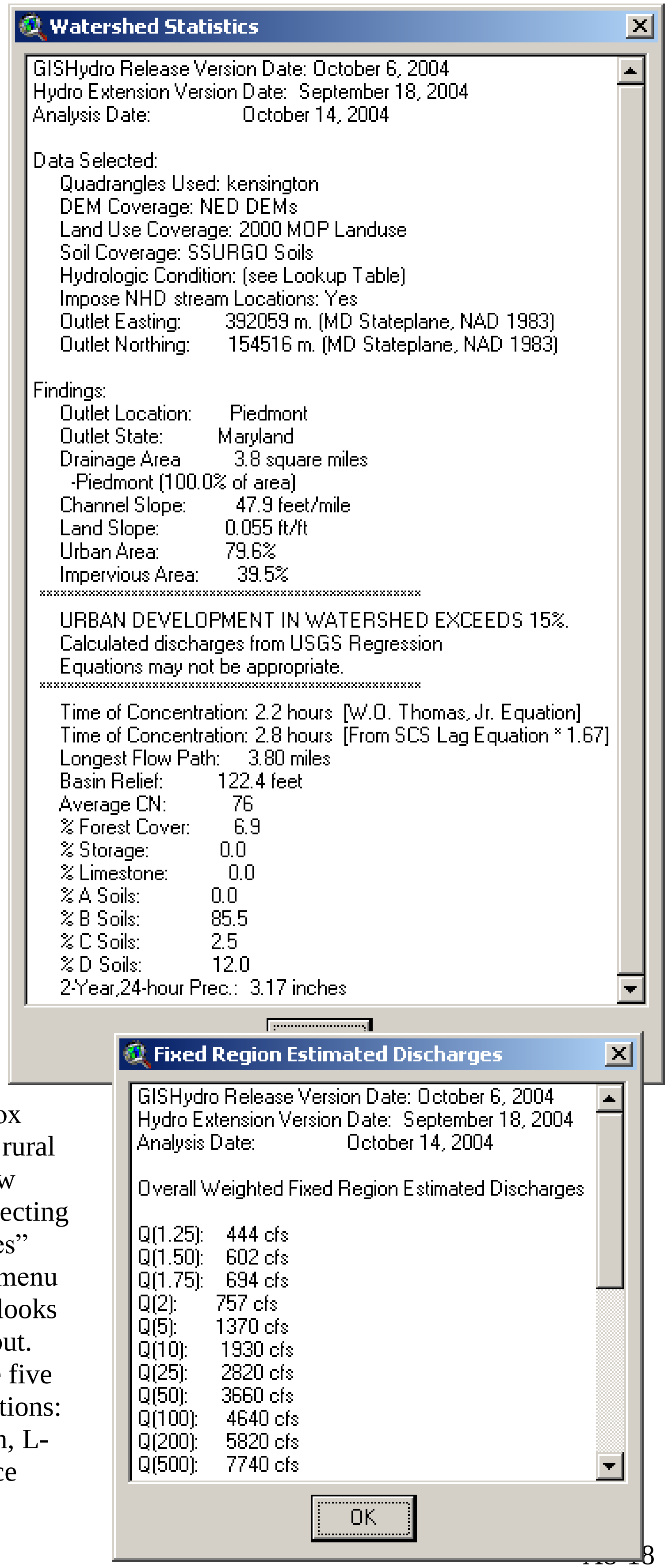
Parameter (units)	Original Land Use	Modified Land Use
Urban Area (%)	79.7	54.6
Impervious Area (%)	34.7	14.3
T_c – Hyd. Panel (hours)	2.3	3.2
T_c – SCS Lag (hours)	2.7	3.6
Average Curve Number	76.7	67.1
Forest Cover (%)	6.9	42.6

An TR-20 Example Analysis Using GISHydro2000

Hydro Menu Analysis:

We will present here a brief sample analysis using GISHydro2000 on the same watershed studied earlier in this appendix. This watershed is located within the Kensington, MD quadrangle and has its outlet at (x=392,059 m, y=154,516 m) in the Maryland Stateplane coordinate system. Pressing the “Basin Statistics” menu choice from the “Hydro” menu produces the Watershed Statistics box shown at right. This box details the data and parameters selected for the analysis as well as the findings for the particular watershed shown.

Pressing the “Calculate Thomas Discharges” menu choice from the “Hydro” menu further calculates the estimates from the Fixed Region regression equations presented in Appendix 3. The calculated discharges are shown in the “Fixed Region Estimated Discharges” dialog box shown at right. Next the USGS rural regression equations from Dillow (1996) can be determined by selecting the “Calculate Dillow Discharges” menu choice from the “Hydro” menu (output dialog is not shown but looks similar to the Fixed Region output. Finally, a comparison across the five potential sets of regression equations: Carpenter, Dillow, Fixed Region, L-moment, and Region of Influence



(ROI) can be requested by selecting the "Compare Discharges" menu choice from the "Hydro" menu. The resulting table for this example watershed is shown below:

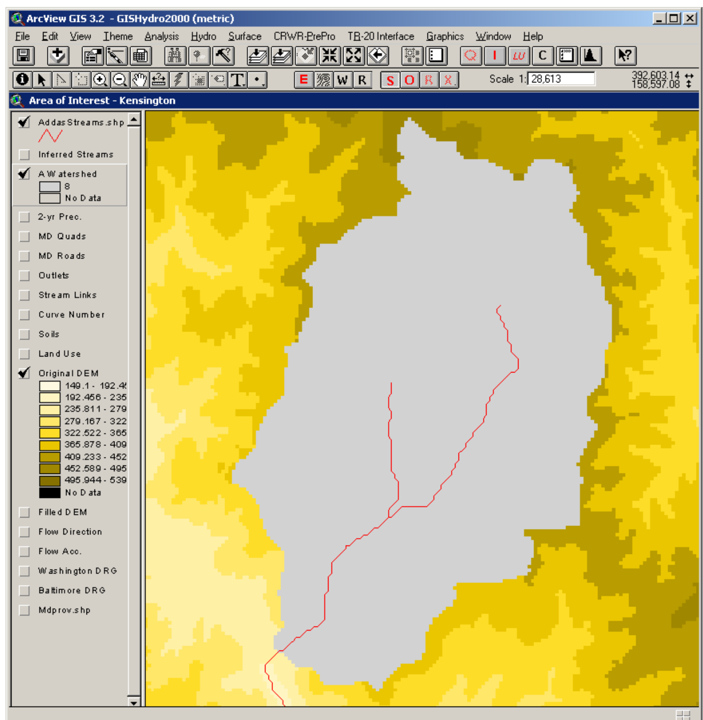
OVERALL Calculated Discharges

Return_Period	Carpenter	Carpenter+1SE	Dillow	Dillow+1SE	Thomas	Thomas+1SE	L-Moment	L-Moment+1SE	ROI	ROI+1SE
1.25 Year	-999.0	-999.0	-999.0	-999.0	444.0	630.0	-999.0	-999.0	-999.0	-999.0
1.50 Year	-999.0	-999.0	-999.0	-999.0	602.0	824.0	-999.0	-999.0	-999.0	-999.0
1.75 Year	-999.0	-999.0	-999.0	-999.0	694.0	941.0	-999.0	-999.0	-999.0	-999.0
2 Year	382.0	557.0	495.0	680.0	757.0	1020.0	411.0	581.0	772.0	1140.0
5 Year	698.0	1020.0	934.0	1260.0	1370.0	1770.0	798.0	1100.0	1380.0	2050.0
10 Year	998.0	1500.0	1340.0	1830.0	1930.0	2440.0	1170.0	1610.0	1900.0	2880.0
25 Year	1520.0	2380.0	1990.0	2810.0	2820.0	3550.0	1800.0	2550.0	2710.0	4270.0
50 Year	2040.0	3310.0	2570.0	3780.0	3660.0	4670.0	2450.0	3550.0	3330.0	5420.0
100 Year	2690.0	4550.0	3260.0	5030.0	4640.0	6070.0	3290.0	4900.0	4280.0	7200.0
200 Year	-999.0	-999.0	-999.0	-999.0	5820.0	7850.0	-999.0	-999.0	5260.0	9190.0
500 Year	-999.0	-999.0	5350.0	9330.0	7740.0	10900.0	6310.0	10200.0	6840.0	12600.0

This table allows for the rapid comparison of peak discharges across all regression equation methods and return periods. Additionally, it provides the +1SE confidence window for guidance in the TR-20 calibration step. In this example, we will aim to calibrate the 100-yr event for which the Fixed Region (Thomas) method window is 4,640 ft^3/s to 6,070 ft^3/s.

CRWR-PrePro Analysis:

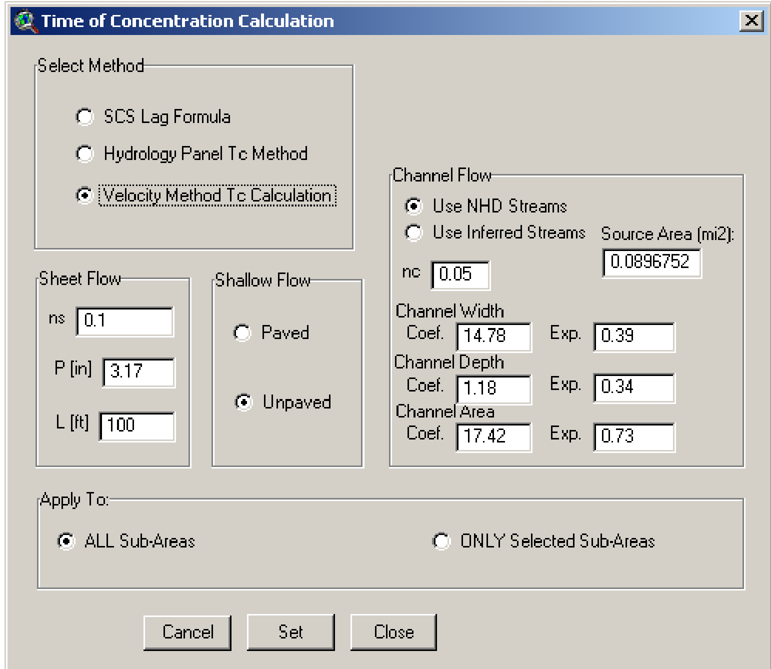
We are now ready to begin setting up the example watershed for analysis by the TR-20 program. The first step is to specify streams to guide the watershed subdivision process. Using the "S" tool, two stream heads are selected as shown in the figure at right. From the "CRWR-PrePro" menu we select the "Add Streams" menu choice and then respond "No" (default) to use only the two added streams to guide the watershed delineation process. GISHydro2000 will create sub-watersheds (or sub-areas) at the outlet of all stream confluences so these two streams should result in two sub-watersheds upstream of the confluence and one sub-area downstream of the confluence. Next the "Delineate Subwatersheds" menu choice is chosen from the "CRWR-PrePro" menu which creates the actual subdivided version of the study watershed.



Time of Concentration with the velocity method in GISHydro2000

We now illustrate the calculation of the time of concentration using the "Time of Concentration Calculation" dialog which results from the selection of the "Set Tc

Parameters" menu choice from the "CRWR-PrePro" menu choice. This dialog is shown at right. The velocity method divides the total travel time into increments of overland (sheet) flow, shallow concentrated flow, and channel flow.

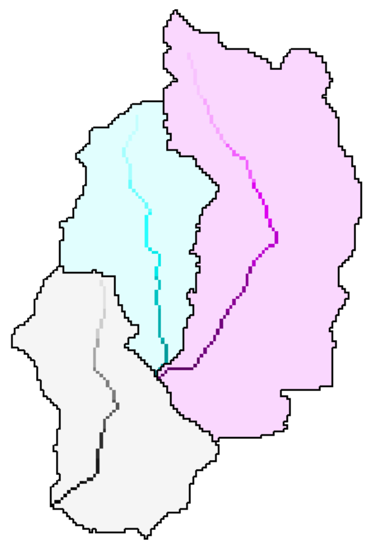


- Overland flow is typically assumed to take place for a comparatively short distance at the upstream extreme of the flow path. From conversations with Don Woodward (NRCS-retired) and Bill Merkel (NRCS) the appropriate upper-bound for this length is generally accepted to be 100 feet (this is the GISHydro2000 default value). A sheet flow Manning's roughness and the 2-yr, 24-hour rainfall depth are the other remaining parameters. The default value for the Manning's roughness is 0.1 while the default 2-yr, 24-hour rainfall depth is determined internally from the embedded NOAA Atlas 14 datasets. Notice that the 3.17 inch precipitation depth appeared in the "Watershed Statistics" dialog shown earlier.
- Channel flow occurs over those distances where a well-defined channel exists. In lieu of a heavy digitizing task, GISHydro2000 provides two alternatives for defining channels.
    - The first alternative defines channels to be those areas strictly digitized as blue lines in the 1:100,000 National Hydrography Dataset (NHD) developed by the USGS. 1:24,000 scale mapping would be more appropriate, but is not universally available over the spatial extent covered in the GISHydro2000 database.
    - The second alternative allows the user to specify a minimum "source area" which is interpreted as the minimum area required to form a channel. The smaller the value indicated, the greater the drainage density and vice-versa. A default value of 0.0896 mi^2 is suggested based on the author's anecdotal experience that this value seems to approximately correspond to the upstream extent of digitized 1:100,000 scale blue lines in Maryland. Since GISHydro2000 keeps track of drainage area for every pixel in the Area of Interest view, it is a simple matter to determine which pixels exceed this source area and are, thus, considered channels.

  Channel velocities are determined by a user specified Manning's n and channel geometry equations from the FWS (McCandless and Everett, 2002; McCandless, 2003a, McCandless, 2003b). Default values are suggested for channel geometry based on the physiographic location of the watershed.

- Swale flow occurs as the residual of that which is neither overland nor channel flow. There is only one choice of parameters for swale flow. A roughness parameter corresponding to either “paved” or “unpaved” conditions must be selected. “Unpaved” is the default setting.

Once the user has specified the method and parameter settings, the “Set” and “Close” buttons are used. When the “CRWR-PrePro: Calculate Attributes” menu choice is selected, the time of concentration is determined as one of several watershed parameters that are calculated and written to various internal tables in preparation for writing the ultimate TR-20 input file. Upon completion of the attribute calculation the engineer will notice a series of new grids in the “Area of Interest” view with the names “Longest Path Sub x” where x is a number from 0, 1, …n -1 for n sub-areas.



Shown on the right, the “Longest Path” grids isolate the unique flow path in each sub-area that corresponds to the maximum travel time for that sub-area. The value of this set of grids is not so much the visual representation of the longest flow path, but the associated table for this grid. A portion of such a table is shown on this and the next page. This table gives a pixel-by-pixel accounting of the time of concentration calculation from the upstream extent of the longest flow path (pixel value 1) to the downstream outlet of the sub-area (pixel value 82, in this case – shown on the next page). From left to right the table entries are: ***Value*** (an identification number increasing from 1), ***Count*** (always 1), ***Type*** (overland, swale, or channel), ***Mixed*** (“No” if flow is entirely overland, swale, or channel, “Yes” if flow is partially overland and swale), ***Da*** (the drainage area in number of 30m pixels), ***Slope*** (the local slope for that pixel, dimensionless), ***Width*** (bankfull width in feet, -1 if not a channel), ***Depth*** (bankfull depth in feet, -1 if not a channel), ***Xarea*** (bankfull cross-sectional area in ft^2, -1 if not a

Attributes Of Longest Path Sub 2

Value	Count	Type	Mixed	Da	Slope	Width	Depth	Xarea	L_length	Tot_length	Vel	L_time	Tot_time
0	2801												
1	1	overland	No	1	0.0072	-1.00	-1.00	-1.00	98.4	98	0.15	0.176	0.176
2	1	overland	Yes	2	0.0152	-1.00	-1.00	-1.00	139.2	238	1.60	0.024	0.201
3	1	swale	No	5	0.0518	-1.00	-1.00	-1.00	98.4	336	3.64	0.008	0.208
4	1	swale	No	7	0.0610	-1.00	-1.00	-1.00	98.4	434	3.95	0.007	0.215
5	1	swale	No	9	0.0518	-1.00	-1.00	-1.00	98.4	533	3.64	0.008	0.222
6	1	swale	No	10	0.0610	-1.00	-1.00	-1.00	98.4	631	3.95	0.007	0.229
7	1	swale	No	11	0.0610	-1.00	-1.00	-1.00	98.4	730	3.95	0.007	0.236
8	1	swale	No	12	0.0610	-1.00	-1.00	-1.00	98.4	828	3.95	0.007	0.243
9	1	swale	No	13	0.0427	-1.00	-1.00	-1.00	139.2	967	3.31	0.012	0.255
10	1	swale	No	14	0.0305	-1.00	-1.00	-1.00	98.4	1066	2.79	0.010	0.265
11	1	swale	No	16	0.0274	-1.00	-1.00	-1.00	139.2	1205	2.65	0.015	0.279
12	1	swale	No	28	0.0305	-1.00	-1.00	-1.00	98.4	1303	2.79	0.010	0.289
13	1	swale	No	40	0.0396	-1.00	-1.00	-1.00	98.4	1402	3.18	0.009	0.298
14	1	swale	No	61	0.0396	-1.00	-1.00	-1.00	98.4	1500	3.18	0.009	0.306
15	1	swale	No	68	0.0305	-1.00	-1.00	-1.00	98.4	1599	2.79	0.010	0.316
16	1	swale	No	75	0.0305	-1.00	-1.00	-1.00	98.4	1697	2.79	0.010	0.326
17	1	swale	No	84	0.0213	-1.00	-1.00	-1.00	98.4	1796	2.34	0.012	0.338
18	1	swale	No	86	0.0396	-1.00	-1.00	-1.00	98.4	1894	3.18	0.009	0.346

channel), ***I_length*** (single pixel {incremental} flow length in feet), ***Tot_length*** (total length from upstream end of flow path in feet), ***Vel.*** (velocity in ft/s), ***I_time*** (single pixel {incremental} travel time in hours), ***Tot_time*** (total travel time from upstream end of flow path in hours).

Attributes Of Longest Path Sub 2

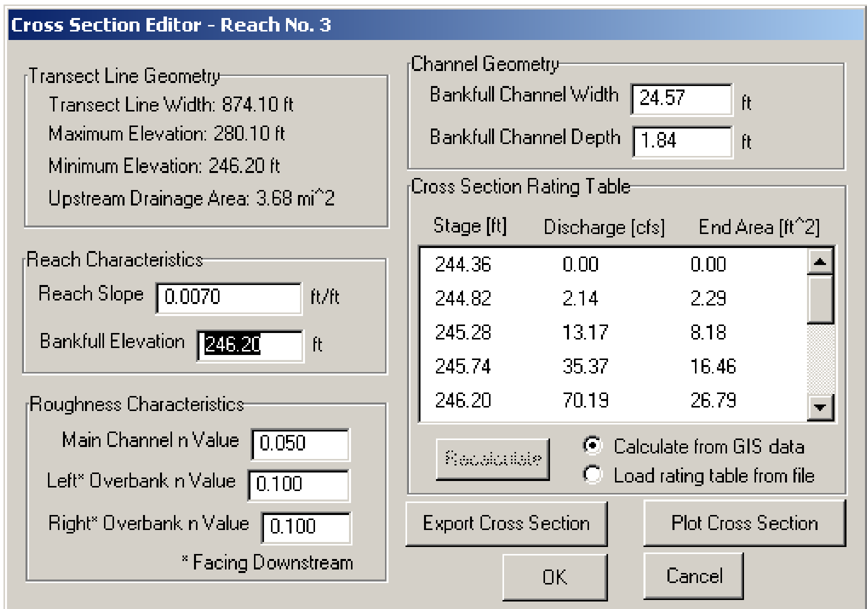
Value	Count	Type	Mixed	Da	Slope	Width	Depth	Xarea	I_length	Tot_length	Vel	I_time	Tot_tim
64	1	channel	No	10002	0.0072	24.03	1.80	43.25	98.4	7074	3.41	0.008	0.917
65	1	channel	No	10010	0.0072	24.03	1.80	43.28	98.4	7172	3.41	0.008	0.925
66	1	channel	No	10048	0.0072	24.07	1.81	43.40	98.4	7271	3.41	0.008	0.933
67	1	channel	No	10053	0.0072	24.07	1.81	43.41	98.4	7369	3.41	0.008	0.941
68	1	channel	No	10056	0.0305	24.08	1.81	43.42	98.4	7468	7.02	0.004	0.945
69	1	channel	No	10059	0.0579	24.08	1.81	43.43	139.2	7607	9.68	0.004	0.949
70	1	channel	No	10597	0.0072	24.57	1.84	45.11	139.2	7746	3.45	0.011	0.960
71	1	channel	No	10606	0.0072	24.58	1.84	45.14	98.4	7844	3.45	0.008	0.968
72	1	channel	No	10611	0.0072	24.59	1.84	45.16	139.2	7984	3.45	0.011	0.979
73	1	channel	No	10626	0.0072	24.60	1.84	45.21	98.4	8082	3.45	0.008	0.987
74	1	channel	No	10642	0.0072	24.61	1.84	45.25	139.2	8221	3.45	0.011	0.998
75	1	channel	No	10658	0.0274	24.63	1.84	45.30	139.2	8360	6.75	0.006	1.004
76	1	channel	No	10761	0.0305	24.72	1.85	45.62	98.4	8459	7.13	0.004	1.008
77	1	channel	No	10768	0.0213	24.73	1.85	45.65	139.2	8598	5.97	0.006	1.014
78	1	channel	No	10786	0.0072	24.74	1.85	45.70	139.2	8737	3.47	0.011	1.025
79	1	channel	No	10797	0.0061	24.75	1.85	45.73	139.2	8876	3.19	0.012	1.037
80	1	channel	No	10807	0.0072	24.76	1.85	45.77	139.2	9016	3.47	0.011	1.049
81	1	channel	No	10841	0.0091	24.79	1.85	45.87	98.4	9114	3.91	0.007	1.056
82	1	channel	No	10847	0.0072	24.80	1.85	45.89	139.2	9253	3.47	0.011	1.067

Based on the results obtained and documented in these "Longest Path" grids and tables, the user may choose to iterate somewhat by varying the method of indicating where channel flow begins, the source area to form a channel, whether the swale flow is paved or unpaved, etc, although it should be noted that if the user selects different parameters for the time of concentration calculation, the longest flow path may "jump" to a different location in the watershed, so it is important that the user always examine the longest flow path theme and confirm that they are consistent with his/her understanding of the upstream extent of the channel and channel roughness characteristics. Once this consistency has been verified, the user can use the GIS interface to export these longest flow path tables to individual text (or other format) files for reporting purposes.

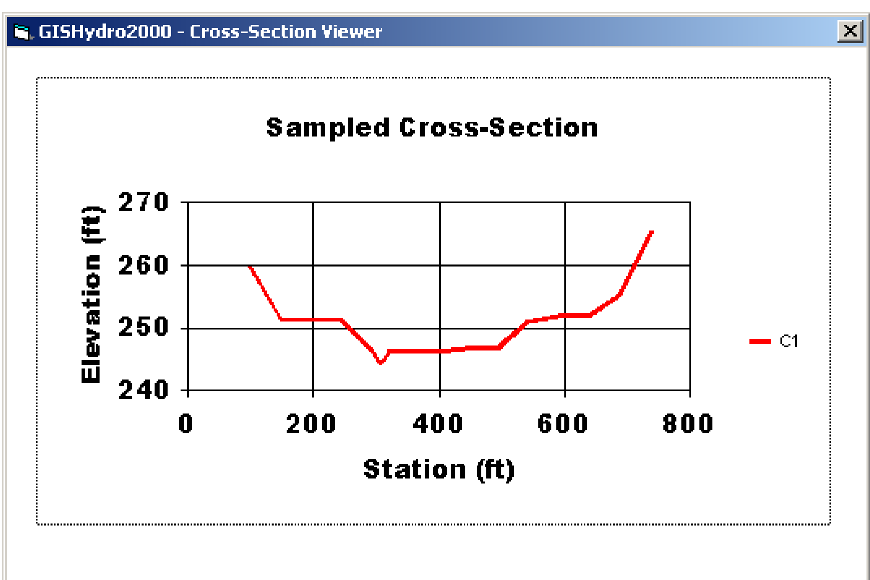
Once the sub-area attributes have been calculated it is necessary to develop the schematic representation of the watershed. This is simply the "stick diagram" representation that allows GISHydro2000 to understand the topological connectivity of the various sub-areas to one another. The schematic is generated by selecting the "Generate Schematic" menu choice from the "CRWR PrePro" menu.

The Cross Section Editor in GISHydro2000

A key part of the TR-20 input file is the rating table associated with all routing reaches within the watershed being studied. This rating table reports the elevation, discharge and cross-sectional area at 20 different stages within the cross-section. This rating table is generated through the use of the Cross Section Editor dialog box. In turn, this dialog box is invoked by using the add transect, , tool. This tool becomes active once the entire CRWR-PrePro menu has been used to define sub-areas, define time of concentration methods, sub-area attributes have been calculated, and sub-area connectivity has been determined. Routing reaches are identified by a green vector line color in the "Hydrolxx.shp" file created by the "Generate Schematic" menu choice. The engineer selects the add transect tool and drags a line across the location of the cross-section that is desired for determining the routing characteristics for that reach. The resulting Cross Section Editor dialog box is shown on the previous page. The upper-left corner of this box simply reports the GIS findings for the transect line drawn. These properties are not editable. All remaining quantities represent editable values that the engineer can modify as deemed appropriate. Shown in the table are the default Manning's n values and the determined reach slope, bankfull elevation, and channel geometry given the drainage area at the cross-section location.



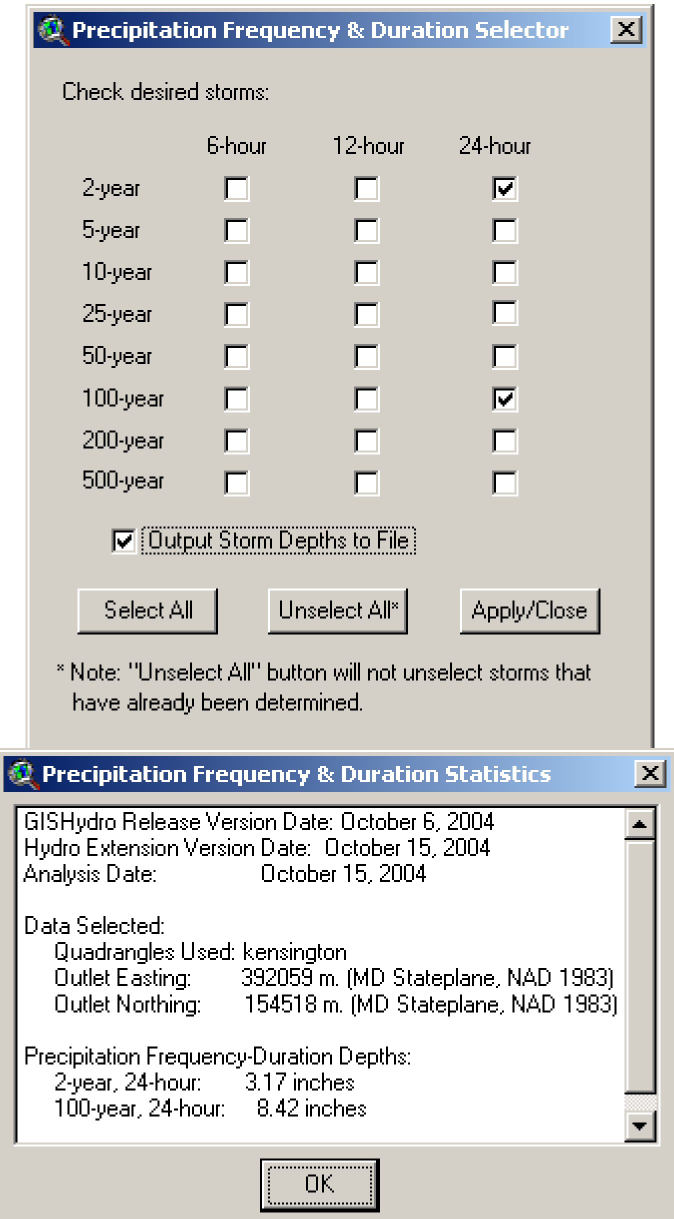
The cross-section properties and resulting rating table are determined using a combination of the FWS equations (McCandless and Everett, 2002; McCandless, 2003a, McCandless, 2003b) for the in-channel portion of the rating table and the actual sampled topography from the DEM for the out-of-channel portion of the rating table. The first 5 of the 20 points in the rating table are dedicated to the in-channel portion of the rating table. By default, when a cross-section is drawn by the engineer, the FWS equations for the appropriate hydrologic region area applied based on the detected drainage area. These values can be edited by the engineer if desired. Out-of-bank geometry is determined in equal elevation intervals from the bankfull elevation to the lower of the two floodplain elevations intersected by the drawn transect. The resulting default rating table is shown in the middle of the right-hand side of the dialog. If any values such as the Manning's coefficients, reach slope, or channel geometry are edited, the "Recalculate" button becomes active and the engineer must press this button to trigger the recalculation of the



rating table given the modified values. The engineer may press the “Plot Cross Section” button to view the actual cross-section geometry as shown in the figure below. The coordinates of this transect may be exported for other uses using the “Export Cross Section” button. Further, if a different rating table is desired rather than the one generated by GISHydro2000, this may be imported using the “load rating table from file” button just below the rating table Window. Once all values have been inspected and approved by the engineer, the “OK” button is pressed and the rating table for that reach has been established. This process must be repeated for each routing reach in the watershed.

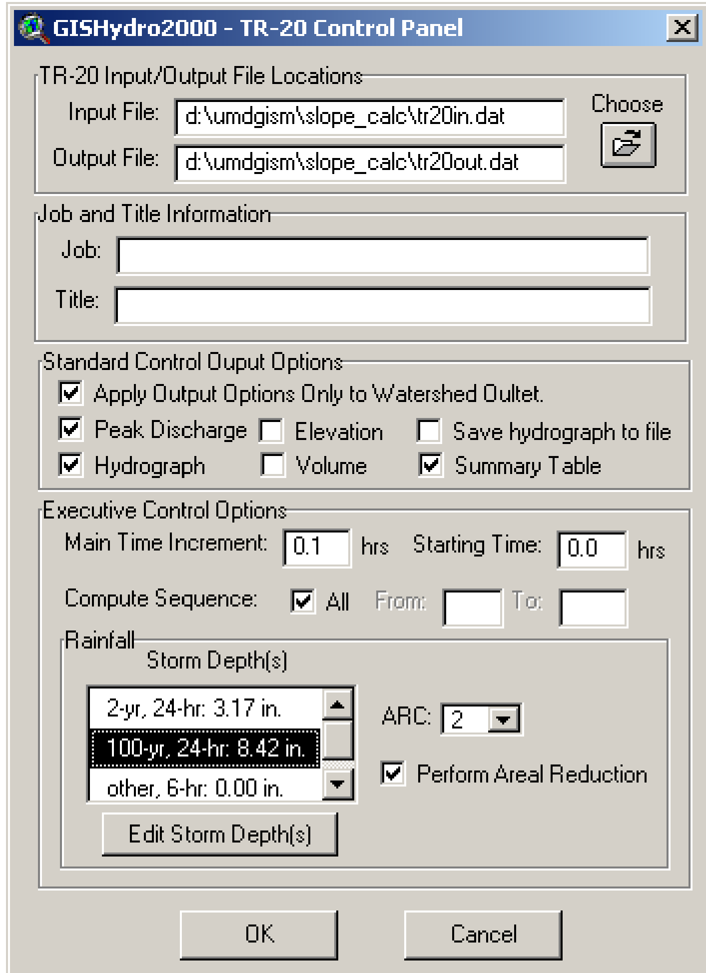
Precipitation Depths

The precipitation frequency data from the recently produced NOAA Atlas 14 are embedded in GISHydro2000. By default, the 2-yr, 24-hour precipitation is loaded into the “Area of Interest” view at the outset of the analysis. Once a watershed is delineated, the user may select the “Precipitation Depths” menu choice from the “TR-20 Interface” menu. Storm frequencies from the 2- through 500- year events are available at 6-, 12-, and 24-hour durations. The user must select all desired storm depths that he/she plans to model. At right the dialog with the 2 and 100 year, 24 hour storms are selected. Choosing the “Apply/Close” button produces the dialog shown at right which indicates the area-averaged storm depths for these frequencies/durations. The user is able to cycle back to this choice to select additional storms as desired.



The TR-20 Control Panel

The final step to complete the generation of the TR-20 input file, is to choose the “Control Panel” menu choice from the “TR-20 Interface” menu. The resulting dialog box shown on the next page will appear. This dialog allows the engineer to specify all the values that are necessary for TR-20 to run, but are not capable of being



determined directly by the GIS. The engineer must specify names for the input and output files, and can optionally indicate job and title information. Check boxes can be toggled on and off for the engineer to indicate the level of desired output.

The bottom of the panel concerns storm parameters. The user must select at least one storm magnitude (note that the "Edit Storm Depth(s)" button may be used to modify storm depths as necessary). Also note that only those storms selected using the "Precipitation Depths" menu choice appear as available for selection here. If needed, the user is able to specify an "other" storm depth for 6, 12, or 24 hours using the "Edit Storm Depth(s)" button. The selected storm(s) are indicated by a reverse text color pattern (white text, black background). The areal reduction factors described at the end of Chapter 3 and in Appendix 7 of this report are applied by default (if the check box is left on) based on the overall area of the entire watershed. A Type II design storm with ARC=2 soil conditions are all control panel defaults.

Once all necessary information has been specified, the "OK" button is pressed triggering the writing of the TR-20 input file to disk. The final menu choice, "Execute TR-20", will automatically run the input file specified in the control panel and open a text editor Window with the resulting TR-20 output file pre-loaded for inspection of the model results.

A Brief Note on Calibration

Using only default values, the initial TR-20 modeled hydrograph peak in this example was 4,447 ft^3/s which does not fall into the Fixed Region (Thomas) equations Window of 4,640 ft^3/s to 6,070 ft^3/s. Thus, the need for some calibration is indicated. As discussed in earlier examples, this calibration can take many forms. For illustration here, we judge that the Tc calculations were perhaps too long leading to a lower estimate of the peak discharge. Using GISHydro2000 we cycle back to the "Set Tc Parameters" menu choice and make two changes: 1) use the inferred streams option rather than using the default NHD digitized streams to define the stream heads, and; 2) change the channel roughness from 0.05 to 0.04. This moves the calculated Tc for sub-areas {0, 1, and 2} from {1.622, 1.603, and 1.067} to {1.068, 1.259, and 0.901}, respectively. Although the Tc is reduced in all sub-areas, the greatest reduction is in the Tc for sub-area 0 where previously there was no channel flow portion to the overall Tc value because there is not any digitized NHD stream within this sub-area. This is a common problem that the user should look out for when estimating Tc values based on the NHD stream network. The smaller estimates of the Tc values result in an increased estimate of the modeled 100-yr peak discharge of 5,245 ft^3/s, which falls acceptably within the calibration Window.

APPENDIX 9
LINKS TO WEBSITES WITH HYDROLOGIC RESOURCES AND PROGRAMS

Site Name	Website Link	Information
University of Maryland GISHydro	www.gishydro.umd.edu	Download software and references for GISHydroNXT and GISHydro2000
NRCS Water Quality and Quantity Technology Development Team	www.wsi.nrcs.usda.gov/products/W2Q/H&H/H&H_home.html	Download NRCS software and technical references: TR-55, TR-20
US Army Corps of Engineers – Hydrologic Engineering Center	www.hec.usace.army.mil	Download software and references: HEC-RAS, HEC-HMS
USGS Water Resources – Surface Water Data	waterdata.usgs.gov/nwis/sw	Stream gage data and statistics
USGS Water Resources – MD, DE, DC	md.water.usgs.gov/ water.usgs.gov/md/nwis/sw	Stream gage data and statistics for MD, DE, and DC.
USGS Water Resources – WATSTORE - GIS Surface Water Data	water.usgs.gov/GIS/metadata/usgswrd/sfbc.html	Stream gage data and watershed characteristics, GIS format
FHWA Hydraulics Engineering	www.fhwa.dot.gov/engineering/hydraulics/	Hydraulic Engineering Circulars and other references
Maryland State Data Center	planning.maryland.gov/msdc/home.shtml	Comprehensive plan references and maps
Maryland Department of the Environment – Research Center	www.mde.state.md.us/ResearchCenter/index.asp	References for Stormwater Management, Flood Hazard Mitigation, Water Quality
Maryland Department of Natural Resources – Guide to Finding DNR Publications	www.dnr.state.md.us/irc/publications.html	References and publications
U.S. Fish and Wildlife Service, Chesapeake Bay Office – Stream Survey Publications	www.fws.gov/chesapeakebay/streampub.html	Maryland stream hydraulic geometry
NRCS Geospatial Data Gateway	http://datagateway.nrcs.usda.gov/	GIS data products including DEMs, land use, stream line work, HUC boundaries, and soil types.
Maryland State Highway Administration	http://www.sha.state.md.us/	MSHA references and downloads