An Evaluation of the Use of Runoff Models
To Predict Average Annual Runoff
From Urban Areas

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Executive Summary

The Toxics Subcommittee gave the Interstate Commission on the Potomac River Basin (ICPRB) the task of updating the estimates of chemical contaminant loads in urban runoff in the Chesapeake Bay Basin for the revision of the Chesapeake Bay Toxics Loading and Release Inventory. This report describes the results of a preliminary phase of that project. Several runoff models were evaluated to determine which model is most suitable to use in estimating average annual chemical contaminant loads from urban areas. The following models were examined:

- The Simple Method
- The Chesapeake Bay Program Watershed Model
- The Curve Number Method, as implemented in *The National Engineering Handbook, Section Four, Hydrology* (1985).
- The Curve Number Method, as implemented in *Urban Hydrology for Small Watersheds* (1986).

Runoff is calculated in the Simple Method by using an regression equation which relates average annual runoff to annual precipitation, watershed area, and the fraction of the watershed which is impervious. The Watershed Model uses the Hydrologic Simulation Program--Fortran (HSPF) to calculate runoff from pervious and impervious surfaces in urban areas. There are two different ways of implementing the Curve Number Procedure. The *Nation Engineering Handbook* recommends estimating runoff from pervious and impervious areas separately. In this report, this is referred to as the "distributive method." The Curve Number Procedure was explicitly extended to urban areas in *Urban Hydrology for Small Watersheds*, where curve numbers for specific types of urban land uses--industrial, commercial, and residential--were developed, as weighted averages of the curve numbers for impervious surfaces and grassed areas. In this case, the curve numbers for urban areas are "lumped." Both versions of the Curve Number Procedure were used to predict runoff in two daily water quality simulation models, the Generalized Watershed Loading Functions (GWLF) and the Environmental Policy Integrated Climate (EPIC).

Ideally, the best way to evaluate runoff models is to compare their predictions against empirical data. In the original conception of this project, the runoff models were to be evaluated by comparing the annual runoff predicted by the models for a gaged, urbanized watershed with the annual runoff calculated from the gage record by baseflow separation. It proved impossible to make such a simple comparison, because there existed no gaged watershed in the Chesapeake Bay Basin which was completely urbanized and had available all of the land use and soil data necessary to run the models.

Data was available for three gaged watersheds in which urban land uses were dominant: Rock Creek in Maryland and the District of Columbia, Beaverdam Run in Maryland, and Difficult Run in Virginia. Forests or agricultural land occupy a significant portion of these watersheds, so the

Simple Method, which is applicable only to urban land, could not be used to calculate runoff from them. Nevertheless, using the land use, soil, and streamflow data available for these three watersheds, the runoff models were compared, in the following manner:

- A computer program was developed to estimate average annual runoff from stream gage records using standard baseflow separation techniques.

- The predicted runoff from the gaged watersheds were calculated using the EPIC and GWLF models with both distributed and lumped urban curve numbers, and the predictions were compared to the runoff estimates from baseflow separation.

- The Simple Method, the Watershed Model, and the curve number models were used to calculate average annual runoff from the strictly urban areas of the three watersheds.

For the most part, the models were run using county-level land use and soil data. The effect of using the available basin-wide land use and soils data was also examined. The performances of the models were then evaluated according to three criteria: (1) an indirect comparison with runoff estimate derived from baseflow separation, (2) theoretical soundness of the modeling approach, and (3) availability of input data and ease of implementation. The following conclusions were reached:

- The results of comparing curve number model predictions of average annual runoff with baseflow estimates were inconclusive without interpretation. A qualitative analysis of the expected biases in model prediction, however, led to the conclusion that the lumped curve number models underpredicted runoff. When all models were used to calculate average annual runoff from urban areas alone, it was found that all of the models which calculated runoff from pervious and impervious areas separately--the distributed curve number models, the Simple Method, and the HSPF Watershed Model--had similar predictions, in contrast to the lumped curve number models. The estimate of runoff from the baseflow separation could not be used to discriminate between the distributed curve number models, the Simple Method, and Watershed Model.

- There is no theoretical justification for calculating the curve numbers for urban land uses as the weighted average of curve numbers for impervious surfaces and curve numbers for grassed areas. The use of curve numbers for impervious surfaces is itself open to question, since conceptually, a curve number is a measure of the infiltration capacity of the soil. Therefore, there is little theoretical justification for using the Curve Number Procedure on urban land. On the other hand, the HSPF Watershed Model uses a more standard conceptual model of runoff from impervious surfaces, and the runoff calculation in the Simple Method is based on a regression equation for urban watersheds.

- The HSPF Watershed Model already calculates annual runoff from urban pervious and impervious land, and it is therefore a straightforward task to use this information to calculate the average annual runoff from urban land. Average annual runoff can also be easily calculated from Watershed Model output using the Simple Method. The curve number models, on the other hand, require more detailed soil and land use information. Soil information is available for the entire basin only at a coarse resolution. Recent urban land use data necessary for lumped curve number models is not available basin-wide.

Using the Curve Number Procedure to calculate average annual urban runoff therefore requires more effort but has little empirical or theoretical justification. Either the Simple Method or the HSPF Watershed Model could be used to calculate average annual runoff from urban areas. The HSPF Watershed Model is the means by which the Chesapeake Bay Program calculates nutrient loads from land uses in the Chesapeake Bay Basin. It would be a natural extension of the use of this model, in the context of the Chesapeake Bay Program, to use the model output to calculate chemical contaminant loads in runoff from urban areas. In fact, it would appear that some explanation would be necessary if the model was not used to calculate average annual runoff for the estimation of chemical contaminant loads. To this end, the following recommendations were made:

- Use HSPF Watershed Model estimates of annual runoff for urban pervious and impervious areas to calculate the estimates of average annual runoff from urban areas necessary for estimating chemical contaminant loads in urban runoff.

- Improve the representation of urban land uses and impervious areas in the GIS land use layers supporting the Watershed Model.

- Use the runoff estimates from the Simple Method to help guide any recalibration of the runoff from urban areas in the Watershed Model.

Table of Contents

List of Figures

List of Tables

Introduction

There are many sources of chemical contaminants which have the potential of impairing Chesapeake Bay ecosystems. Both industrial and municipal point discharges can emit metals and synthetic organic compounds. Pesticides can be found in runoff and groundwater discharging from agricultural lands. Sediments contaminated in the past can continue to have adverse impacts even after the activities which contaminated them have ceased. Stormwater from urban areas can be a source of metals and organic compounds which are washed off streets, parking lots, sidewalks, and lawns.

To evaluate the potential impact of chemical contaminants on the ecology of Chesapeake Bay, planning level estimates of the average annual chemical contaminant loads from these sources are necessary. Olsenholler (1991) estimated average annual chemical contaminant loads in urban runoff in the Chesapeake Bay Basin. She used a loading function approach, in which the chemical contaminant load was calculated as the product of the average annual runoff volume and an event mean concentration (EMC) for each chemical contaminant. The EMCs were derived from data collected for the National Urban Runoff Program, 1978-1982. Average annual runoff was estimated using the Simple Method, developed by Shueler (1987).

The Toxics Subcommittee gave the Interstate Commission on the Potomac River Basin (ICPRB) the task of updating the estimates of chemical contaminant loads in urban runoff in the Chesapeake Bay Basin for the revision of the Chesapeake Bay Toxics Loading and Release Inventory. This report describes the results of a preliminary phase of that project. Several runoff models were evaluated to determine which runoff model is most suitable to use in estimating average annual chemical contaminant loads from urban areas. In particular, this project compares the performance of the Simple Method with the Hydrologic Simulation Program--Fortran (HSPF) and several varieties of the Curve Number Procedure. HSPF is the model used in the Chesapeake Bay Watershed Model. Estimates of urban runoff can be obtained from the Watershed Model's output. The Curve Number Procedure, developed by the Natural Resource Conservation Service (NRCS, formerly the Soil Conservation Service, SCS), is perhaps the most widely used method to predict runoff for hydraulic design. The method was explicitly extended to urban areas in the NRCS publication *Urban Hydrology for Small Watersheds* (1986). The Curve Number Procedure is used to predict runoff in several daily water quality simulation models, including Generalized Watershed Loading Functions (GWLF) and the Agricultural Research Service's models such as Simulator for Water Resources in Rural Basins (SWRRB) and Environmental Policy Integrated Climate (EPIC).

Ideally, the best way to evaluate runoff models is to compare their predictions against empirical data. In the original conception of this project, the runoff models were to be evaluated by comparing the annual runoff predicted by the models for a gaged, urbanized watershed with the annual runoff calculated from the gage record by baseflow separation. This simple comparison proved impossible for several reasons.

First, there were no fully urbanized watersheds in the Chesapeake Bay Basin for which all of the information necessary for the models was readily available. The Curve Number Procedure needs land use and soils data delimited by watershed, but even where land use and soils data were available, they were not delimited by watershed.

Land use and soils data were available for three gaged watersheds where urban land was the predominant land use: Rock Creek in Maryland and the District of Columbia, Beaverdam Run in Maryland, and Difficult Run in Virginia. Significant portions of these watersheds are not urban, however. (About one-third of the Rock Creek is not urban and about one-half of Beaverdam Run and Difficult Run is not urban.) Since the Simple Method was conceived to be used on urban land uses only, it would not be appropriate to compare its predictions of runoff from the entire gaged watershed with the predictions of the other models, which are capable of estimating runoff from non-urban land uses, like forest and cropland. And although the output from the Watershed Model could be used to calculate runoff from the entire gaged watershed, including the agricultural and forested areas, the effort spent making the calculation could not be justified, since it might not be clear whether differences in predicted runoff between HSPF and the curve number models should be accounted for by differences in their predictions for urban or non-urban areas. In addition, the output from the model represents average conditions for model segments, which are many times larger than the watersheds examined in this study.

Second, even if it were possible to compare the models' predictions of average annual runoff with an estimate of average annual runoff calculated by base flow separation, it must be kept in mind that base flow separation techniques do not provide a simple record of observed runoff. All base flow separation techniques are to some extent arbitrary. The use of base flow separation techniques is even more problematic in urbanized watersheds, where detention ponds and other flood-control structures retard runoff from reaching the stream.

Nevertheless, the existence of a stream gage record for these watersheds does provide a way to directly compare the runoff predictions from different methods of implementing the Curve Number Procedure on urban watersheds, and to indirectly compare the predictions of the Curve Number Procedure with the Simple Method and the HSPF Watershed Model.

Using GWLF and EPIC, different methods of implementing the Curve Number Procedure were used to calculate the average annual runoff from the three urbanized watersheds. In each case, average annual runoff was calculated for the entire watershed above the United States Geological Survey (USGS) gaging station, including the forested and agricultural areas. The results from these simulations were compared to estimates of the average annual runoff derived from baseflow separation performed on the daily discharge records from the three watersheds.

The portion of average annual runoff from urban land alone was calculated for the different methods of implementing the Curve Number Procedure. In other words, average annual runoff was recalculated without the contribution from agricultural and forested areas. The average annual runoff predicted by these models from urban land uses was then compared to the estimates from the Simple Method and the Watershed Model. The performances of the models were evaluated according to three criteria: (1) theoretical soundness of the approach, (2) an indirect comparison with runoff estimate derived from baseflow separation, and (3) availability of input data and ease of implementation.

The Curve Number Procedure

The National Resource Conservation Service has developed a method for estimating runoff from rainfall on the basis of watershed characteristics such as land use and soil type. Land uses are assigned curve numbers based on soil type, and the condition of the soil and the vegetation covering it. These curve numbers can then be used to predict the amount of runoff generated by a given volume of precipitation. The most complete specification of the Curve Number Procedure is found in the *National Engineering Handbook, Section Four, Hydrology* (hereafter abbreviated as *NEH-4*). *NEH-4* has undergone several revisions since it was originally published in 1956. The 1986 edition, which is the last complete revision, will be referenced in this report. Rallison (1980) and Rallison and Miller (1982) give overviews of the development of the Curve Number Procedure.

Basics of the Curve Number Procedure

The basis of the Curve Number Procedure is a hypothesized relation between runoff and infiltration

$$\frac{F}{S} = \frac{Q}{P - I_a} \tag{1}$$

where F is the actual retention of precipitation during a storm, S is the maximum potential retention, Q is runoff, P is precipitation, and I_a is the initial rainfall abstraction, which represents the precipitation intercepted by vegetation or other surfaces, and depression storage. This proportion is not a physically-based relation; it is best justified on pragmatic grounds.

An additional assumption is made that the initial abstraction is proportional to the maximum potential retention

$$I_a = 0.2S \tag{2}$$

Substituting this equation into (1) and solving for Q

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{3}$$

The maximum potential retention, when given in centimeters, is related to a curve number CN by the equation

$$S = \frac{2540}{CN} - 25.4 \tag{4}$$

Rallison and Miller (1982) describe how curve numbers were estimated for different land uses and soil types. A gaged watershed with homogeneous land use cover and soil type was selected. Runoff was plotted against rainfall for the annual floods (i.e. the largest flows). A grid of curve numbers was laid over the plotted annual floods, and the median curve number was selected to represent the curve number for this land use and soil type. When data was available from more than one watershed for a given land use and soil type, the curve number was represented by the average of the median values.

Antecedent Moisture Conditions

In fact, three different curve numbers were estimated by this method for each land use and soil type. The median value is designated CN_{II}. CN_{III} is the curve number which envelops the data from above, while CN_I is the curve number which envelops the data from below.

The three curve numbers were associated with antecedent moisture conditions. All other things equal, more runoff is produced when the soil is wetter, because as the soil becomes wetter, less of the soil's retention capacity is available to store additional precipitation. The *NEH-4* therefore recommended taking into account the antecedent moisture conditions of the soil when using the Curve Number Procedure. Until recently, the following procedure was recommended. Three antecedent moisture conditions are defined according to the total rainfall for the five previous days. Table 1 gives the definition of the three conditions in terms of antecedent rainfall. CN_I is used under dry conditions, AMC I, CN_{II} is used under average conditions, AMC II, and CN_{III} is used under wet conditions, AMC III. As will be discussed below, this method is no longer recommended by the NRCS.

Distributed and Lumped Urban Land Uses

The Curve Number Procedure was originally developed for agricultural or rural land uses. Land uses were classified according to cover crop and conservation practices. Soils were classified into four hydrologic groups, A, B, C, and D, according to the infiltration rate of the soil. Soils in Hydrologic Group A have the highest rates of infiltration, while soils in Group D have the lowest. NRCS has classified most of the soils in the United States by hydrologic group. Such classifications can be found in *the NEH-4* or *Urban Hydrology for Small Watersheds* (Technical Release 55, hereafter referred to as *TR-55*). In addition to land use and hydrologic group, the hydrological condition of the soil cover can be taken into account. Soil covers are in good, fair, or poor hydrologic condition, depending on the extent of ground cover.

As described in the previous sections, curve numbers were estimated from data obtained on homogeneous watersheds. When watersheds contain more than one land use or soil type, the *NEH-4* recommended two different methods. The amount of runoff for a given storm could be calculated for each homogeneous complex in the watershed. The total runoff in the watershed then could be calculated as the average of the runoff of the individual complexes, weighted by their area. In the terminology of watershed modeling, the curve number is treated as a ***distributed*** parameter. Alternatively, a curve number for the entire watershed could be calculated as the weighted average, by area, of the curve numbers of distinct areas. In this case, the curve number is treated as a *lumped* parameter of the watershed, and runoff is calculated for the entire watershed using the lumped curve number. Since the runoff equation is non-linear in the curve number, the use of distributed curve numbers is more theoretically sound. The *NEH-4* suggests using lumped curve numbers when there are no areas that differ greatly in their curve numbers. Lumped curve numbers are easier to use, especially with multiple storms, and will give accurate results as long as the curve numbers in distinct areas of the watershed do not differ greatly among themselves.

The *NEH-4* recommends using distributed curve numbers for urban watersheds. No curve numbers are recommended for urban land uses as such. The *NEH-4* notes, however, that land uses in urban areas may not contribute runoff in proportion their area in the watershed. It cites a study of an urban drainage area near Royal Oak, MI. The watershed was 25% impervious, and one might expect that runoff would be at a minimum of 25% of the rainfall, assuming that all the precipitation on impervious surfaces contributed to runoff. Observed runoff was frequently less than half 25% of precipitation.

The NRCS publication *Urban Hydrology for Small Watersheds* (*TR-55*) specifically addresses the use of curve numbers in urban watersheds. Unlike the *NEH-4*, *TR-55* recommends specific curve numbers for urban land uses. These curve numbers are not derived using the methods described in the previous sections. That is, they do not represent empirically-derived median curve numbers from homogeneous urban watersheds. Rather, urban curve numbers are averages of the curve numbers for pasture and impervious surfaces, weighted according to the percent of impervious surface in that land use category. For example, *TR-55* assumes that high density residential areas are 65% impervious. On a B soil, the curve number for pasture is 61 and the curve number for impervious surfaces is 98. The curve number for high density residential areas on a B soil is thus .65*98+.35*61= 85. Thus *TR-55* lumps curve numbers for urban land uses.

Continuous Curve Number Models

Curve numbers, when originally developed, were used to calculate runoff for events with a particular return period, a two-year storm or a ten-year storm, for example. With the advent of computers and the growing interest in watershed simulation models of water quality, curve numbers were adapted to continuous simulations. A computer model, using daily precipitation as an input, could calculate runoff on a daily basis. The simulation model could also adjust the curve number on a daily basis to take into account antecedent moisture conditions, and the curve number could be allow to vary continuously with soil moisture.

In the northern parts of the country, large runoff events are often associated with snowmelt. Models have been developed to keep track of the size of the snowpack and estimate runoff from snowmelt as a function of temperature. The Curve Number Procedure can be used with the snowmelt volume to predict the amount of runoff from snowmelt.

Continuous curve number models therefore must perform three additional tasks:

1-Calculate antecedent moisture conditions on a daily basis.
2-Calculate a curve number on the basis of antecedent moisture conditions.
3-Model snowpack and snowmelt volumes.

Two continuous curve number models were examined, Generalized Watershed Loading Functions (GWLF) and Environmental Policy Integrated Climate (EPIC-- formerly the Erosion Productivity Impact Calculator). Both of these models simulate water quality in both runoff and subsurface flow. Only the aspects of the models representing runoff will be discussed below.

GWLF. GWLF uses the method of the *NEH-4* to calculate antecedent moisture conditions. CN_{II} is used as an input to the model. CN_{I} and CN_{III} are calculated from CN_{II} by the following equations:

$$CN_I = \frac{CN_{II}}{2.334 - 0.01334\, CN_{II}} \tag{5}$$

$$CN_{III} = \frac{CN_{II}}{0.4036 + 0.0059\, CN_{II}} \tag{6}$$

These equations reproduce the relation between curve numbers found in the *NEH-4*.

The curve number on a given day is calculated as a function of the antecedent moisture conditions. If the total five-day antecedent rainfall plus snowmelt is less than the upper limit of AMC I, the daily curve number is linearly interpolated between CN_I and CN_{II}. If the antecedent moisture lies between the upper and lower limits of AMC II, the curve number is linearly interpolated between CN_{II} and CN_{III}. If the antecedent moisture is larger than the upper limit of AMC II, the curve number is equal to CN_{III}.

Precipitation is added to the snowpack if the average daily temperature is less than freezing. Snowmelt is calculated using a degree-day equation

$$M = 0.45\, T \tag{7}$$

where M is the daily snowmelt (cm) and T is the average daily temperature (°C). Further details on GWLF can be found in the *User's Manual* (Haith et al., 1992).

EPIC. EPIC is a field-scale model developed by the Agricultural Research Service of the United States Department of Agriculture. Unlike GWLF, EPIC can represent a multi-layer soil profile. A water balance is performed on each layer in the soil profile on a daily time step. A saturated conductivity SC (mm/h) is associated with each soil layer on the basis of soil texture and other soil properties. The travel time TT (h) is calculated for each layer according to the equation

$$TT = \frac{PO - FC}{SC} \qquad \textbf{(8)}$$

where PO is the porosity (mm) and FC is the field capacity (mm) of the soil layer. Daily percolation P (mm) from a layer is calculated from the following equation:

$$P = (SW - FC)\,[1 - \exp(t/TT)] \qquad \textbf{(9)}$$

where SW is the soil water content of the layer (mm) and t is the time step (h).

EPIC also models the growth of crops . Evapotranspiration from each soil layer is calculated according the demand of the crop for water at that stage of growth. For details see the EPIC *User's-Guide* (Mitchell et al., 1996).

Daily curve numbers are calculated on the basis of the soil water content of the root zone. Actually, EPIC calculates the maximum soil retention potential S on a daily basis

$$S = S_I\left(1 - \frac{FCC}{FCC + \exp(W_I - W_{II}(\,FCC))}\right) \qquad \textbf{(10)}$$

S_I is the soil retention associated with CN_I. FCC is calculated by

$$FCC = \frac{SW - WP}{FC - WP} \qquad \textbf{(11)}$$

where WP is the wilting point (mm) of the root zone. W_I and W_{II} are chosen so that S is the retention associated with CN_I when FCC = 0.6 and S is the retention associated with CN_{III} when

$$\frac{SW - FC}{PO - FC} = 0.5 \tag{12}$$

where PO is the porosity of the root zone (mm). Like GWLF, EPIC uses formulas to calculate CN_I and CN_{III} from CN_{II}

$$CN_I = CN_{II} - \frac{20(100 - CN_{II})}{100 - CN_{II} + \exp[2.533 - 0.0636(100 - CN_{II})]} \tag{13}$$

$$CN_{III} = CN_{II} \exp[0.00673\,(100 - CN_{II})] \tag{14}$$

EPIC also models snowmelt,

$$M = T(1.52 + 0.54PT) \tag{15}$$

where M is snowmelt (mm), T is mean daily temperature (°C), and PT is snowpack temperature (°C), which is the minimum of the temperature of the soil in the second layer and the temperature at the soil's surface, adjusted for snow cover. Further details on EPIC can be found in Mitchell et al. (1996).

Comparison of GWLF and EPIC Models. GWLF is a much simpler model that EPIC. The runoff portion of GWLF operates independently of the other processes represented in the model. In addition to the areas in the watershed associated with each curve number value, GWLF needs only daily precipitation and daily mean temperature to calculate runoff. Daily mean temperature is needed only to represent the snowpack and snowmelt. The runoff component in EPIC, on the other hand, is fully integrated with the other components of the model. The curve number is a function of the soil water content of the root zone, which is determined, not only by percolation, but by crop transpiration. Since crop growth is determined in part by the availability of nutrients, it is possible that even nutrient losses could effect the quantity of runoff. EPIC needs a detailed characterization of the soil profile, though this data is easily available from the NRCS's SOILS 5 database. EPIC also needs model parameters for each crop modeled. Parameters for most crops and grasses are available, but, as will be discussed below, parameters are not available for deciduous trees.

It should be noted that, unlike GWLF and the original recommendations of the *NEH-4*, curve numbers in EPIC are not bounded by CN_{III}. In fact, it is possible for the calculated curve number to be a good deal larger than CN_{III} under saturated or near saturated conditions. As a result, EPIC tends to predict higher values runoff than GWLF. The theoretical justification for using curve numbers larger than CN_{III} is unclear, since CN_{II} is supposed to be the upper bound on curve numbers for annual floods.

It should also be noted that the NRCS favors the ARS' approach to continuous curve numbers. This approach is embodied not only in EPIC, but in a whole family of water quality models ARS is developing. In fact, the most recent revisions of the *NEH-4* has dropped any mention of the method of calculating antecedent moisture conditions on the basis of total five-day antecedent rainfall. Thus, although GWLF more closely follows the original recommendations for calculating curve numbers, the methods it uses are no longer the official methods of the NRCS, and the methods used in EPIC are likely to be closer to the NRCS's recommendations in the future (personal communication, Donald E. Woodward, National Hydrologist, NRCS).

Limitations of the Curve Number Procedure

The Curve Number Procedure is one of the most widely used methods for calculating runoff. It is applied in many circumstances beyond those which its developers intended. Continuous curve numbers are an example of this. The Curve Number Procedure was originally developed to study the effect of land use changes on small watersheds. It was used to calculate design flows for culverts and other hydraulic structures. Since curve numbers are now used in other circumstances, it is important to be aware of the limitations of the method. Its limitations have been recognized by both its developers and outside investigators. Some of the limitations pertinent to this project are discussed below.

Initial Abstraction. The plot of the data used to formulate the relation between the initial abstraction, I_a and maximum potential retention, S, in *NEH-4* shows a good deal of scatter. *NEH-4* discusses the fact that estimates of I_a are subject error, due to difficulties in determining when rainfall began, difficulties in determining the time at which runoff began, and the impossibility of determining how much of the initial interception later became runoff. Hjelmfelt (1991) mentions several authors who questioned the validity of the relationship, $I_a = 0.2\ S$, but he doubts whether better simple relationship can be discovered.

TR-55 cautions that the assumed relationship between maximum retention and initial abstraction is based on data from agricultural watersheds and may not be valid in urban areas. Less detention storage may take place on some impervious surfaces; other may have surface depressions that store more runoff.

Curve Number of Impervious Surfaces. *NEH-4* recommended the use of a constant curve number of 100 for impervious surfaces. The theoretical motivation for this recommendation is apparent. A curve number of 100 implies that there is no infiltration into the soil surface. However, because of the relation between initial abstraction and maximum potential storage, it also implies that there is no interception or depression storage. All rainfall will become runoff. *TR-55* recommends a curve number of 98 for impervious surfaces. The theoretical justification for this is less clear, but at least there is some allowance made for interception and depression storage. A curve number of 98 will be used for impervious surfaces in this study. In any case, the curve number for impervious surfaces was not determined in the same manner as the curve numbers for other land covers, that is, it was not determined by the measurement of runoff from homogeneous watersheds.

Curve Numbers Under Dry Conditions and Other Factors. According to Hjelmfelt (1991), several investigators have found that while high antecedent precipitation is associated with smaller values of the maximum potential retention and thus larger curve numbers, a wider range of values for the maximum potential retention are found under drier conditions. He suggests that other factors such as rainfall intensity or temperature, in addition to antecedent precipitation, may effect retention under drier conditions.

It is often noted that the Curve Number Procedure does not take into account rainfall intensity and other factors, but, as Hjelmfelt points out, if it did, it would become a physically-based infiltration model. The Curve Number Procedure is not, however, an infiltration model. It can be thought of, in Hjelmfelt's words, as a "frequency transformer," which takes a rainfall frequency distribution and transforms it into a runoff frequency distribution. To put it more simply, the Curve Number Procedure is an empirically-based method for predicting the volume of runoff from precipitation, based on soil type, land use, and some consideration of antecedent moisture conditions.

Hydrologic Simulation Program--Fortran (HSPF)

The Hydrologic Simulation Program--Fortran (HSPF) is used in the Chesapeake Bay Program Watershed Model. HSPF is a continuous simulation model that operates on a user-defined time step. In the Watershed Model, the time step is two hours. HSPF can represent hydrologic and water quality processes in runoff, subsurface flow, and in stream reaches. Although many model parameters can be set from literature values, HSPF usually needs to be calibrated against observed data.

Runoff from pervious and impervious land is simulated separately in HSPF. In this respect HSPF is a distributed parameter model, although the pervious and impervious land segments in HSPF may function as lumped parameter models for the pervious and impervious areas of the watershed. This is the case in the Watershed Model. The Watershed Model distinguishes impervious land, forest land, urban pervious land, pasture and cropland. Within these categories model parameters are lumped, so that, for example, no one soil is represented in urban pervious land, and a "composite crop", rather corn, wheat, or soybeans, is grown on the cropland.

On impervious land, all precipitation is converted to runoff except for precipitation which is stored in retention capacity and detention storage. Retention capacity represents the storage in roof-top catchments, asphalt wetting, and urban vegetation. Detention storage represents what is sometimes called depression storage: storage on impervious surfaces caused by depressions or the unevenness in pavement. Both detention storage and retention capacity are user-specified inputs to the model.

In pervious urban segments, runoff occurs after precipitation has satisfied the interception capacity, detention storage and its infiltration capacity of the segment. Interception capacity refers to capacity of vegetation to intercept precipitation before it reaches the ground. Detention storage again refers to the capacity of the surface to store water in puddles and depressions. Infiltration is modeled as a series of flow and storages governed by model parameters. More details on HSPF can be found in the *User's Manual* (Johnson et al., 1984).

The Simple Method

The Simple Method was developed by Shueler (1987) for the Metropolitan Washington Council of Governments. It is a loading function approach to calculating the pollutant load in urban runoff. The load in a volume of runoff is calculated as the product of an mean concentration and a volume of runoff. The Simple Method calculates runoff volumes by the following equation:

$$R = P P_j R_v A / 100 \tag{16}$$

where R is the annual runoff volume (m^3), P is annual precipitation (cm), P_j is the fraction of rainfall events that produce runoff, R_v is the mean runoff coefficient, and A is area of the watershed (ha). The mean runoff coefficient is the proportion of rainfall converted to direct runoff. A statistical analysis of runoff coefficients from 50 sites in the National Urban Runoff Program (NURP) showed that R_v could be represented as a function of the percent imperviousness I of the watershed

$$R_v = 0.05 + .009 I \tag{17}$$

The adjusted R^2 for the regression estimate of this equation was 0.71. Schueler reports that R_v was found to be "only weakly correlated with storm-related variables such as precipitation volume, intensity, and duration." (p. A.8)

Schueler suggested a value of 0.9 for P_j, based on a comparison the rainfall reported at National Airport and the reported runoff at NURP sites in metropolitan Washington. A double mass curve analysis showed that 10% of the annual precipitation volume produced no runoff. Shueler noted that 50% of the storm events had less than 0.5 cm of precipitation. Precipitation from these storms may not satisfy interception, depression storage, and infiltration, and therefore may produce no runoff.

Comparison of Continuous Curve Number Models With The Estimate of Average Annual Runoff Derived From Gage Records By Baseflow Separation

The continuous curve number models, GWLF and EPIC, were tested on three urbanized watersheds: Rock Creek, in Montgomery County, MD, and the District of Columbia; Difficult Run, in Fairfax County, VA; and Beaverdam Run, in Baltimore County, MD. County-level land use and soil data in GIS format were available for all three watersheds with one exception: there was no county land use data for Difficult Run. The GIRAS (Geographic Information Retrieval and Analysis System) digital land use layer, available at the Chesapeake Bay Program Office, was used to determine land use in the Difficult Run Watershed.

All three watersheds have USGS gaging stations with daily flow records. Table 2 gives the gaging stations for each watershed. The purpose in using these watersheds was to compare the average annual runoff predicted by the models with the estimate of average annual runoff obtained from gage records by separating the baseflow from streamflow. It must be noted, however, that the runoff estimate derived from baseflow separation is, in its own way, a model of runoff, and therefore the temptation to interpret this exercise as a comparison of the models' predictions with observation should be used with caution.

The Runoff Estimate From Baseflow Separation
During and after storms, streamflow increases due to stormwater runoff entering the stream. In periods of dry weather, streamflow is sustained by baseflow. The source of baseflow is the discharge of groundwater to the stream. Baseflow is often represented as a discharge from a linear reservoir. That is, groundwater discharges to streamflow in proportion to the volume of water stored in groundwater. Thus streamflow will fall as periods of dry weather continue until groundwater is recharged by precipitation.

Storms, of course, increase streamflow more directly by generating runoff. Runoff sharply raises streamflow which then tapers off into dry-weather baseflow. Sometimes, a third component of streamflow is recognized, interflow, which represents shallow subsurface flow through upper soil layers. Some researchers believe that interflow is the primary process by which precipitation is transported to streams in forests. It is often omitted from the analysis of streamflow, and will be omitted in this analysis, since urban land is the dominant land use.

Several techniques exist to separate the baseflow component of streamflow from runoff for design storms. Linsley et al. (1958) is an often-cited reference for these techniques. The different techniques are variations on a set of themes. They start with a streamflow hydrograph, a graph of streamflow versus time. Figure 1 shows a typical hydrograph. The hydrograph rises sharply shortly after the storm begins, as runoff contributes to streamflow. Streamflow will peak and then fall. At some point in the "receding limb" of the hydrograph, the contribution of runoff will stop, and streamflow will be sustained by the recharged groundwater. The point where runoff begins is thought to be easy enough to identify: it is the point at which the hydrograph rises. Different techniques use different methods to determine the point at which runoff ends. They differ as well in how they identify the contribution of baseflow to streamflow during the time runoff is occurring. Figure 1 shows the results of three possible methods of baseflow separation. The problem can be visualized as how to draw a line or curve that connects the point runoff begins with the point at which it ends, such that the flow beneath the line represents groundwater's contribution to streamflow, while the flow above the line represents runoff. Techniques differ in how to perform this "baseflow separation," in part because they embody different assumptions about the behavior of runoff and groundwater during a storm event, in part because baseflow separation is to some degree arbitrary. The hydrology of storm events is more complicated than the simple picture given here.

Baseflow techniques were developed to be performed on a well-defined storm, whose effects can be isolated from other storms. The techniques can be extended to treat two storms whose peak flows are distinguishable (Linsley et al., 1958). In order to estimate average annual runoff, however, baseflow separation must be performed on several years of gage record. The effects of multiple storms will not necessarily be able to be isolated. Many storms will be much smaller than the design storms the techniques have been developed for, and their effects will be less pronounced.

Shirmohammadi et al. (1984) developed a technique for baseflow separation that can be used on USGS daily flow records over extended periods. Their method depends on estimating two parameters, the threshold storm and the time base of the runoff event. The threshold storm is the minimum-sized storm which produces runoff. The time base is the length of time runoff occurs for storms larger than the threshold storm. When a threshold storm occurs, baseflow is assumed to linearly increase from the streamflow the day before the storm occurs to the streamflow at end of the time base of the storm event. If another storm above the threshold occurs during the time base period, the end of the second storm is taken as the end of direct runoff. Shirmohammadi et al. tested their method on ten research watersheds in the Coastal Plain of Georgia and found reasonably good agreement between their predictions and the observed data.

The baseflow separation technique of Shirmohammadi et al. formed the point of departure for developing the technique used in this study. It was altered in two respects. First, instead of estimating the time base of the runoff event, the time from the peak of the hydrograph to the end of runoff was estimated. Linsley et al. (1958) provide a formula for approximating N, the time after peak till the end of runoff

$$N = A^{0.2} \tag{18}$$

where A is the area of the watershed (mi^2) and N is in days. Linsley et al. suggest adjusting N by inspection so it fits the hydrograph. Table 3 shows the values of N and the adjusted time-after-peak used in estimation of runoff from gage records for the three watersheds. By using N, the most simple of Linsley et al.'s baseflow separation techniques can used. Baseflow is assumed to linearly increase from the streamflow on the day prior to the storm to the streamflow N days after the peak of the storm. Method 1 in Figure 1 illustrates this technique.

An attempt was made to identify threshold storms for the three watersheds. No well-defined threshold precipitation could be found below which no increase in streamflow was produced. In general, however, storms less than 1 cm do not consistently produce substantial increases in streamflow. The concept of a threshold storm was abandoned, however, for two other reasons. First, threshold storms do not necessarily identify snowmelt-driven runoff. Although storms sometimes cause substantial snowmelt, snowmelt can also occur without precipitation. Second, the weather record for a single gage probably does not identify all runoff-producing storms in the watershed. In the Rock Creek Watershed, warm-weather thunderstorms, which can produce substantial runoff, can be geographically isolated (personal observation).

It was therefore assumed that runoff occurs whenever daily streamflow is larger than the previous day's streamflow. The previous day's streamflow is then identified as the initial baseflow B_i. Runoff stops N days after a peak is reached and streamflow begins to decrease, or the level of the initial baseflow is again reached. The rate of change of baseflow r_b is then calculated as follows:

$$r_b = \frac{S_N - B_i}{\Delta t} \qquad \textbf{(19)}$$

where S_N is the streamflow when runoff ceases and Δt is the time between the beginning and end of runoff. The rate of change of baseflow is either positive or constant. That is, baseflow either linearly increases or remains constant. If baseflow is ever calculated to be larger than streamflow, it is set equal to streamflow and r_b is recalculated over the remaining portion of the event. Figure 2 shows the results of baseflow separation for part of the stream gage record on Rock Creek.

Table 3 shows the average annual runoff calculated by this method for each of the three watersheds. For each watershed, runoff was calculated for different values of N. The best choice of N, determined by equation (18) and the inspection of hydrographs, is marked in bold. As is shown in the Table 3, predicted runoff is not very sensitive to changes in N.

To repeat, it is important not to treat values for runoff calculated by baseflow separation as if it were a direct observation of runoff. There are three reasons to exercise caution in interpreting the estimates of average annual runoff obtained by baseflow, two of which have been touched upon already. First, there is an inherent arbitrariness in the separation method. Second, is the extension of the separation method from design storms with well-defined peaks to all storms, regardless of their size or their proximity to other storms. To these reasons can be added the fact that urbanized watersheds can contain many detention basins or other storm water control structures that delay runoff from reaching the stream. This makes it more difficult to determine where streamflow from direct runoff ends.

GWLF Runoff Estimates
The average annual runoff for each of the three watersheds was estimated using GWLF in two ways. First, the impervious area of each watershed was assigned its own curve number (98--the value recommended by *TR-55)*. The pervious area of each watershed was treated as pasture. This is the distributed parameter approach advocated in the *NEH-4*. Second, the urban land use classifications in *TR-55* were used to estimate curve numbers. To repeat, these curve numbers are the weighted average of the curve numbers of impervious and pervious areas associated with the land use. This approach thus uses lumped urban land uses.

The results for each watershed are discussed below. Appendix A, **Meteorological, Soil, and Land Use Data**, discusses the source of data and how the areal extent of land use and soil type complexes were calculated.

Rock Creek. Runoff was simulated for the 20-year period 1975-1994 using both distributed urban land uses and lumped urban land uses. Table 4 shows the land use and soil groups for Rock Creek with distributed urban land uses. Table 4 also gives the average annual runoff from each land use. These values are on a per area basis. The total runoff volume from each land use is the product of the land use area and the runoff reported. Table 5 shows the same information for lumped urban land uses. The simulation with distributed land uses produces about twice the runoff as the lumped land uses. This is also the case in the other watersheds, and reflects the nonlinearity of the curve number equation (3).

The estimate from baseflow separation for the Rock Creek Watershed falls in between the GWLF predictions for lumped and distributed urban land uses. Several reasons exist for thinking that the GWLF predictions would tend to overestimate, rather than underestimate, the quantity of runoff. First, the land use data reflects conditions in the 1994. Since the amount of urban land increased during the simulation period, the use of 1994 land use data would tend to upwardly bias runoff estimates by upwardly biasing the estimate of impervious surfaces. Second, no attempt has been made to take into account detention storage of stormwater in the basin, or the use of infiltration basins to control stormwater. Montgomery County has not yet been able to estimate the extent of urban areas which are under stormwater controls. Two flood control reservoirs, Lake Bernard Frank and Lake Needlewood, also control flow upstream of the gage. Flood control, detention storage, and the infiltration of runoff diminishes the amount of runoff which contributes to streamflow. Since these factors are not taken into account in the GWLF model, GWLF is, *ceteris paribus*, more likely to overpredict average annual runoff in comparison to the gage estimate. Third, no attempt has been made in the GWLF model to calculate to what extent the impervious areas are hydraulically connected to storm sewers or other drainage. Runoff from roofs, for example, may be diverted across lawns where at least some of the runoff will infiltrate into the soil. *TR-55* suggests adjusting curve numbers to take into account the amount of "effective impervious area," that is, the amount of impervious surface hydraulically connected to drainage. This was not done in this study, because it is difficult to get estimates of effective impervious areas on a large scale. In effect, discharging roofs and gutters across lawns represents a type of stormwater control, and thus is closely related to the second factor for upward bias of the GWLF models .

One factor that may introduce negative bias into the GWLF runoff estimates is the watering of lawns and other grassed areas. Watering keeps the soil wetter than it would be under natural conditions. The infiltration capacity of the soil is therefore lower than would be predicted on the basis of rainfall alone. GWLF does not take watering into account, and therefore underestimates the antecedent soil moisture and the curve numbers under those conditions. On the other hand, the contribution of pervious urban areas to runoff is relatively small, as the simulation with distributed urban land uses shows, and the watering of lawns is thus unlikely to have a major impact on the average annual runoff for the whole watershed.

Beaverdam Run. The gage on Beaverdam Run at Cockeysville has only been operable since October 1982, so the GWLF simulations were run for 12 years, 1983-1994. Table 6 gives the soils, land uses, and predicted average annual runoff for distributed land uses, and Table 7 gives the same information for lumped urban land uses.

The results from Beaverdam Run are similar to the results from Rock Creek. The gage estimate lies between the GWLF estimates for distributed and lumped urban land uses. The land use data for Beaverdam Run represents conditions in 1990. This land use layer is probably more representative of the entire simulation period, so there is less bias introduced in the Beaverdam Run simulation than the Rock Creek simulation. Otherwise, the same factors that make the GWLF predictions upwardly biased in Rock Creek also hold in Beaverdam Run. No attempt was made to take into account detention and infiltration of runoff, and no adjustment was made to the curve numbers so they reflect the amount of effective impervious area in urban land.

Difficult Run. GWLF simulations with lumped and distributed urban land uses were run for the twenty year period 1975-1994. The results for distributed uses is given in Table 8 and the results for lumped uses are given in Table 9.

The GIRAS digital land use data used in the simulation represents land use conditions in the mid-1970's (Mitchell et al., 1977). It therefore underestimates the extent of urban land and impervious surfaces in the simulation period, and most likely tends to underpredict the runoff for this period. This may explain why the estimated average annual runoff from baseflow separation is higher than the predicted values for both GWLF simulations. On the other hand, as in the other simulations, no attempt was made to account for stormwater controls or to estimate the effective impervious area of the watershed.

Summary of GWLF Simulations. Figure 3 compares the baseflow separation estimate of average annual runoff with the predictions of the GWLF simulations. The average annual runoff predicted by GWLF with distributed urban land uses is always twice as large as predictions using the curve numbers recommend by *TR-55*. When impervious surfaces are separated from other land uses, impervious surfaces are responsible for more than half the predicted average annual runoff volume. The rate of runoff, per hectare, for impervious areas is three times the rate of the cropland on D soils, which has the next highest runoff rate.

Several factors potentially biased the GWLF simulations. Detention storage and infiltration from stormwater control was not taken into account. Thus it should be expected that less of the runoff predicted by the GWLF simulations would appear as streamflow. Land use was not adjusted during the simulations to take into account the changes that occurred in the simulation period. This could lead to a positive bias in the prediction of average annual runoff for Rock Creek, and a negative bias in the prediction of average annual runoff for Difficult Run. The use of a single land use was probably not as much of a factor in the Beaverdam Run simulations, due to the shorter simulation period.

On the other hand, no attempt was made to account for the watering of lawns and other grassed areas. Watering use represents an interbasin transfer which can potentially increase runoff by increasing antecedent moisture conditions. The GWLF simulations underpredict runoff from lawns by not taking watering into account.

The estimates of average annual runoff from baseflow separation fell between the two types of GWLF simulations for Rock Creek and Beaverdam Run. The baseflow separation estimate was above both GWLF simulations for Difficult Run. Given that stormwater controls were not represented in the simulations, it should be expected that, *ceteris paribus*, the estimated average annual runoff from the simulations should be higher than the gage estimate, especially in the case of Rock Creek, where a positive bias in the simulation estimate is introduced by using a land use cover representing more recent conditions. If the assumption is made that the bias introduced by using a constant land use has the greatest impact, and the bias introduced by the water of lawns has the least impact, then one tentative conclusion of comparing the GWLF simulations with the baseflow separation estimates is that the curve numbers recommended by *TR-55* underestimate the runoff from urban areas.

EPIC Simulations

EPIC is a field-scale model. It calculates runoff, among other quantities, for a homogeneous field, on a per area basis. To use EPIC on a watershed scale, the per-area estimates of runoff for each land use and soil type complex are multiplied by the area for each complex. An alternative to this procedure would have been to use the Simulator for Water Resources in Rural Basins (SWRRB), which is an ARS watershed-scale model which can simulate different land covers simultaneously. SWRRB uses the same runoff model as EPIC. It is necessary in SWRRB, however, to locate the different land covers and route flows from the covers to the watershed outlet. Routing is appropriate if an accurate prediction of daily flow is required; it is irrelevant to the prediction of runoff on an average annual basis. In addition, SWRRB can only simulate ten different land use coves at one time. Thus there was no advantage to using SWRRB in these simulations.

EPIC and other ARS models are oriented towards representing agricultural land uses. The representation of soil moisture model is obviously irrelevant in modeling runoff from impervious surfaces. Bare soil cannot even be represented in EPIC. There must be a vegetative cover, and the choice of cover is limited to cultivated species. Moreover, soil profiles in urban areas are frequently disturbed by construction and landscaping. The "natural" soil profile, which EPIC uses in its soil moisture model, may be irrelevant for most urban land.

These theoretical reasons might have been sufficient to make EPIC an unsuitable choice for modeling urban runoff. Nevertheless, EPIC was used to estimate the average annual runoff from the three watersheds using the lumped urban land uses recommend by *TR-55*, in order to examine the effects of EPIC's soil moisture model on the runoff estimates. Winter pasture was simulated for lawn turf, using the appropriate curve numbers for commercial, industrial, and residential land uses.

The theoretical justification for using lumped urban land uses is suspect, and runs counter to the suggestion of J. Williams, one of the creators of EPIC, who advised against it (personal communication). Not only is an inhomogeneous land cover represented by a homogeneous one, but the soil water balance in the EPIC model can faithfully represent neither the turf nor the impervious area. The water balance of the soil beneath turf does not represent the water balance of the soil beneath pavement: There is neither infiltration nor transpiration beneath pavement. The water balance beneath turf is not correctly represented either, since the use of the weighted curve number means that less precipitation is represented as infiltrating into the soil. Simulated moisture conditions are thus drier under the turf than would have been the case if turf were simulated separately.

Other adjustments had to be made to simulate runoff from urbanized watersheds using EPIC. Open land was simulated as pasture. Forest were simulated as apple orchards, since the only model parameters available for deciduous trees were for apple trees. To simplify matters, one soil type was chosen to represent each hydrologic group. In almost all cases it was the predominant soil type for a land cover in that hydrologic group, but in a few cases, when another soil type predominated in a watershed, it was chosen to represent the land use-hydrologic group complex.

The soils uses for each land cover, as well as the predicted runoff from that cover and the total average annual runoff for the watershed, are given in Tables 10, 11, and 12 for Rock Creek, Beaverdam Run, and Difficult Run, respectively. The results do not differ markedly from the GWLF simulations using lumped urban land uses. Predicted average annual runoff is higher in the EPIC simulations, by 19%, 6%, and 13% for Rock Creek, Beaverdam Run, and Difficult Run, respectively. The predicted runoff for all three watersheds is still considerably less than the runoff estimate obtained by baseflow separation. Figure 3 shows the predicted average annual runoff from the EPIC simulations, as well as the predictions of the GWLF simulations and the baseflow separation runoff estimate.

EPIC simulations with distributed urban land uses will be discussed in the next section.

Comparison of the Performance of the Runoff Models on Urban Land

A comparison was made of the performance of GWLF, EPIC, the Simple Method, and HSPF in predicting runoff from the urban areas in the three watersheds studied. In contrast to the previous section, only the urban land uses were represented in these calculations; non-urban land uses such as forest and cropland were omitted. This was done for two reasons. First, the Simple Method was never intended to be applied to a watershed with significant forested and agricultural land. It is valid only on urban land uses, such as commercial, industrial, or residential land. While the HSPF Watershed Model output could be used to calculate runoff for the entire gaged watershed, it might not be possible to separate out the contributions from urban and non-urban areas when comparing the predicted runoff to the runoff estimates from baseflow separation. Second, and more importantly, the purpose of this study is to determine the best method for estimating chemical contaminant loads in urban runoff. Only the runoff from urban areas is to be included in the final loading function estimate of chemical contaminant loads. Therefore, it is important to compare the predictions of average annual runoff which the models make on urban land uses alone.

The Calculation of Average Annual Runoff From Urban Land

The average annual runoff from urban land in each of the three watersheds was calculated with HSPF estimates from the Watershed Model, the Simple Model, GWLF with distributed and lumped urban land uses, and EPIC with both distributed and lumped urban land uses. The same land use data was used for each model. The most important parameter, used directly in the Simple Method and indirectly in the HSPF, is the percent of the urban area which is impervious. The calculation of the percent impervious land in a watershed is explained in Appendix A. The percent of urban land that is impervious in each watershed is shown in Table 13. Other details of the calculations are discussed below.

The Simple Method. Beside the percent of impervious land in a watershed, the Simple Method only needs the average annual rainfall to calculate the average annual runoff. The average annual rainfall for the study period was 109.0 cm, 105.4 cm, and 104.1 cm for Rock Creek, Beaverdam Run, and Difficult Run, respectively.

HSPF. Predicted annual runoff from the Watershed Model was obtained from the Chesapeake Bay Program Office. Model output was obtained for urban pervious and urban impervious land uses in model segments 890, 470, and 220, which contain, respectively, Rock Creek, Beaverdam Run, and Difficult Run. Only the years 1984-1991 were available. The average annual runoff from urban land uses was calculated for each watershed as a weighted average (by percent impervious area) of the annual values. It would have been preferable to average over the same period as the GWLF simulations. On the other hand, at best, only output from the years 1984-1994 will be available from the Watershed Model before the 1997 reevaluation.

GWLF and EPIC. Weighted averages of the annual average runoff from urban land uses were calculated for the GWLF simulations, both with lumped urban land uses and distributed urban land uses. These can be derived from the previous tables by weighing the runoff estimates for each urban land use by the area of the watershed occupied by each land use.

The same procedure was used for the EPIC simulations with lumped urban land uses. An estimate of average annual runoff for each watershed with distributed urban land uses was constructed in the following way. Estimates of runoff from turf grass were determined by an EPIC simulation using one soil for each hydrologic group in each watershed. For Difficult Run, these runoff estimates can be found under the pasture values in Table 12. For Rock Creek and Beaverdam Creek, the soils and the prediction of average annual runoff are found in Table 14. The GWLF estimates of runoff from impervious land was used in calculating a weighted average for all the urban land uses in a watershed.

Evaluation of Predictions of Average Annual Runoff

Table 13 shows the predicted average annual runoff from urban land for all of the models tested. Figure 4 shows the same information graphically. The estimates break into two groups. As might be anticipated, the lumped GWLF and the lumped EPIC estimates are closer in value. They are less than half the value of the other estimates. The distributed GWLF and EPIC estimates, as well as the HSPF estimates and the estimates from the Simple Method, are relatively close in value. The coefficient of variation (the ratio of the standard deviation to the mean) is less than 0.1 for both Rock Creek and Beaverdam Run. It is about 0.2 for Difficult Run, primarily because of the large predicted average annual runoff from the HSPF model.

The predictions from HSPF, the Simple Method, and the distributed estimates from EPIC and GWLF all separate the contribution to runoff of impervious areas from the contribution of pervious areas. Their estimates are close in value because runoff from the impervious areas accounts for most of the predicted runoff from urban lands in these watersheds. Table 15 shows the percent of total predicted runoff volume due to impervious areas. Except for the HSPF estimate of runoff in the Difficult Run Watershed, the percent of predicted runoff from impervious areas is greater than 80%. For Difficult Run, the runoff from pervious urban land predicted by HSPF is unusually large, which also explains the large total value for HSPF for Difficult Run and the greater variability among the estimates in that watershed. The HSPF prediction is more than three times the estimates from GWLF and EPIC for urban pervious land in the Difficult Run watershed. At 12.0 cm/yr, it is more than twice as large as the next largest predicted runoff from urban pervious land from any of the models in the study.

In each of these watersheds, the area occupied by urban land does not represent the entire watershed above the gaging station. For this reason, the estimates of average annual runoff from urban land uses cannot be compared to the estimates of average annual runoff from baseflow separation directly. It might be tempting to make the following indirect comparison: Average annual runoff from the Simple Method or the Watershed Model is higher than average annual runoff from the distributed GWLF and EPIC models on urban land uses. Average annual runoff from the distributed GWLF and EPIC models, on all land uses, are higher than the estimates of average annual runoff from baseflow separation. Therefore, the continuous curve number simulations with distributed urban land uses are closer to the baseflow separation estimates than either the Simple Method or HSPF. To put it in other words, if the distributed GWLF and EPIC estimates are too high, when compared to the estimates obtained from baseflow separation, and the estimates of runoff from urban land predicted by the Simple Method and the Watershed Model are higher than the estimates from the distributed GWLF and EPIC modes, then the estimates of annual runoff from the Simple Method and the Watershed Model must not only be too high, relative the baseflow estimates, but also worse estimates, relative to the baseflow estimates, than either of the distributed curve number models.

The temptation to infer that the continuous curve number models are closer to the observed data should be resisted. The factors that bias the continuous curve number models also bias the Simple Method and HSPF in the same way. Changes in the fraction of impervious land cover in the watershed affect all of the models directly. None of the models take into account detention storage, infiltration, and the watering of lawns, and thus their estimates are similarly biased with respect to the amount of runoff that actually reaches the receiving stream. On the other hand, these factors do not affect the runoff estimate derived from baseflow separation. If the biasing factors were somehow taken into account, the size of the estimates from the continuous curve number models, HSPF, and the Simple Method would probably not change relative to each other, while their size relative to the gage estimate might change. It is therefore not possible to say which model would be closer to the gage estimate if these factors were taken into account.

It is interesting to note that the EPIC estimates from urban pervious land show a good deal of variability. As Table 14 shows, the predicted runoff from a C soil (Elioak) can be more than the runoff from a D soil (Dunning). If the contribution from pervious areas were more significant, more care would have to be used in estimating the runoff from these areas using EPIC. A wider variety of soils would have to be represented. Given the dominance of runoff from impervious areas, however, the variability in estimated runoff from different soils on pervious urban land seems less important.

Implications of the Use of CBPLU Land Use Data and STATSGO Soil Data On the Estimation of Urban Runoff

The estimates of average annual urban runoff discussed so far have used the best available land use and soil data for the three watersheds. With the exception of land use for Difficult Run, all the data used came from county-level planning or environmental agencies. County-level data is generally not available for much of the Chesapeake Bay Basin. Even where it is available, it would be beyond the scope of the resources of this current effort to perform GIS analyses on disparate sources of county-level data.

The Modeling Subcommittee of the Chesapeake Bay Program has developed a GIS land use layer, the Chesapeake Bay Program Land Use (CBPLU). Unless an alternative is found, CBPLU is likely to be used to supply the land use information for estimating average annual urban runoff. If a continuous curve number model is used, a GIS layer with soil information will be needed. The only basin-wide soil data layer available is the NRCS's State Soil Geographic Database (STATSGO). These databases are described below, and some of the implications of their use discussed following their description.

The Chesapeake Bay Program Land Use

CBPLU was developed in 1995 for use in Phase III of the Watershed Model. It is based on the GIS land use layer of the Environmental Monitoring and Assessment Program (EMAP). The EMAP land use is derived from remote sensing data from 1990. EMAP was supplemented by data from the National Oceanic and Atmospheric Administration's (NOAA) Coastal Change Assessment Program (C-CAP) to better capture wetland areas. More importantly, at least for the present purposes, EMAP's representation of urban land uses was supplemented by data from the Geographic Information Retrieval and Analysis System (GIRAS), which was developed in the mid-seventies by the USGS from their topographical quadrangle map series and remote sensing data. GIRAS land use data was used to identify herbaceous and woody land cover that fell within urban areas, but were not captured by EMAP. In this way, residential areas with land cover indistinguishable from the surrounding areas could be delineated. In contrast to GIRAS and the county land use layers, EMAP recognizes only two categories of urban land: high intensity urban and low intensity urban. Two additional categories were added to CBPLU, herbaceous urban and woody urban, to identify those urban areas captured by GIRAS that EMAP failed to identify. Details on the construction of CBPLU is given in Neumiller et al., *Watershed Model Appendix E: Watershed Land Uses and Model Linkages to the Airshed and Estuarine Models.*

State Soil Geographic Database

STATSGO is the soil geographic database which the NRCS recommends using for "regional, multistate, river basin, state, and multicounty resource planning, management, and monitoring." (*STATSGO*, p.1) It is less detailed than the standard county soil maps. Where single soil series are delineated on county maps, soils in STATSGO are represented in map units which may contain up to 21 soil series. The percentage of each soil type in the STATSGO map unit is identified, and the associated databases contain detailed information on each soil type. STATSGO map units do not correspond to the soil associations found in county soil surveys, and appear to be coarser classifications than the county soil associations.

Implications of the Use of CBPLU and STATSGO

A cross-tabulation of CBPLU land uses and STATSGO soil data was prepared for the Rock Creek and Beaverdam Run Watersheds. Details of the analyses are provided in Appendix A. Table 16 shows the cross-tabulation of land uses and hydrologic groups for Rock Creek; Table 17 shows the cross-tabulation of land uses and hydrologic groups for Beaverdam Run. This analysis was not performed on Difficult Run because the original analysis of Difficult Run used GIRAS land use data which was incorporated into CBPLU.

There is a noticeable difference between the STATSGO and the county soil maps which appears in the cross-tabulations. STATSGO attributes to both Rock Creek and Beaverdam Run a percentage of soil in hydrologic group A. The county soil survey maps do not. This reinforces a warning made in the STATSGO manual: " percentages [of soil types] do not statistically represent a subset of the delineation such as the county portion." (p. 4) According to the STATSGO database, 77% of the Rock Creek Watershed has B soils, 14% has C soils, and 3% has D soils, whereas, according to the county soil survey, the percentage of B, C, and D soils is 83%, 9%, and 9%, respectively, when those soils rated C/D are divided equally between the C and D soil groups. For Beaverdam Run, according to STATSGO, the percentage of B, C, and D soils is 81%, 11%, and 5%, respectively, compared to 65%, 24%, and 7%, according to the county soil survey.

The differences between STATSGO and the county soil surveys are probably not systemic, but may simply reflect the fact that any portion of a STATSGO map unit will not necessarily have the same percentage of soil types as the map unit as a whole. The differences between the CBPLU and the county land use layers may be more systemic, reflecting the fact that CBPLU has its origin in EMAP remote sensing data. As explained above, the Modeling Subcommittee found that EMAP under-reported the amount of urban land. Areas which according to the GIRAS had urban land uses were not identified as such in EMAP's interpretation of remote sensing data. For that reason, EMAP's delineation of urban areas had to be supplemented by information from GIRAS. GIRAS itself, however, is from the 1970's, and therefore there are likely to exist urban areas which have been developed since GIRAS but are not detectable using the techniques by which EMAP was produced. It is not surprising, then, that CBPLU identifies less urban land in the Rock Creek and Beaverdam Creek Watersheds (57% and 29%, respectively) than counties' land use layers (68% and 40%, respectively).

The differences between CBPLU and the county land use layers in their estimates of the amount of impervious land in the watersheds is not as great as the differences in their estimates of the amount of urban land in the watersheds. The assumptions made in *Watershed Model Appendix E* about the percent of impervious area in each land use category led to higher estimates of the fraction of urban land which is impervious. In *Watershed Model Appendix E,* high intensity urban land is considered 85% impervious, low intensity urban and exposed lands are 40% impervious, and woody urban and herbaceous urban lands are considered 10% impervious. Using CBPLU, 36% of the urban land in the Rock Creek Watershed and 45% of the land in the Beaverdam Run is impervious, compared to 34% and 37%, respectively, using county land use data. Since, for all models except the lumped versions of GWLF and EPIC, runoff predictions depend primarily upon the fraction of the watershed that is impervious, the difference in predicted runoff when CBPLU is used will not be as great as the difference between CBPLU's estimates of urban land and the county-level estimates of urban land. Nonetheless, it should be noted that CBPLU probably underestimates urban land by a factor of about 10%, and that it compensates by classifying a greater percentage of urban land as impervious than is customary.

Summary, Conclusions, and Recommendations

As stated in the Introduction, the performance of the runoff models is to be evaluated according to three criteria: (1) a comparison with the estimate of average annual runoff derived from gage records and baseflow separation, (2) the theoretical soundness of the model, and (3) the availability of input data and the ease of model implementation.

Comparison with the Runoff Estimate From Baseflow Separation

Only the predictions of the continuous curve number models could be compared with the estimates derived by baseflow separation from the gage records. The Simple Method cannot be used if there are substantial non-urban land uses in the watershed, so the comparison was limited to the runoff predictions from GWLF and EPIC.

The comparison shows that the continuous curve number simulations which lumped pervious and impervious urban areas tended to predict lower average annual runoff than the estimate derived from baseflow separation. In the case of Rock Creek and Beaverdam Run, the EPIC and GWLF simulations which separated pervious and impervious surfaces predicted higher runoff estimates than the estimates from baseflow separation. In all three watersheds, the simulations with distributed urban land uses predicted more runoff than the simulations with lumped urban land uses.

Four factors can explain the disagreement between the modeling simulations and the estimates obtained by baseflow separation: (1) Land use at one point in time was used to represent the whole simulation period, (2) the simulation did not take into account detention storage and the use of infiltration as a stormwater control, (3) all impervious areas were assumed to be hydraulically connected to storm sewers or other drainage, and (4) water from outside the basin is used to irrigate lawns and other grassed areas. Only the last factor without qualification would tend to indicate that the model prediction would be lower than the gage estimate. Factors (2) and (3) indicate that the predictions of the models should be higher than the gage estimate. Since the simulations from Rock Creek and Beaverdam Run used more recent land use data, while the simulation for Difficult Run used land used data from the beginning of the simulation period, it should be anticipated, *ceteris paribus*, that model predictions for the former would be higher than the gage estimate, while model predictions form the latter would be lower than the gage estimate. In fact, the use of land use data for Difficult Run from the 1970's may explain the anomaly that the predicted average annual runoff from the distributed GWLF simulation was less than the gage estimate.

Given the information available, it is not possible to quantify the impact of these four factors on the model simulations. Moreover, the estimate of average annual runoff determined from gage records by baseflow separation is itself a somewhat arbitrary estimate of runoff, and not simply an observation. Nonetheless, given the bias introduced by three of the four factors discussed above, it can be tentatively concluded that the continuous curve numbers, used with the lumped urban land uses of *TR-55*, underestimate the average annual runoff.

Average annual runoff was calculated using the Simple Method and the output from the HSPF Watershed Model for the urban land uses in the watersheds only. The predictions from these models therefore cannot be directly compared to the estimates of average annual runoff derived from baseflow separation. When average annual runoff is calculated for only the urban areas of the three watersheds, the Simple Method and the HSPF Watershed Model predicted more runoff from urban land than the distributed curve number models. All of the predictions, however, are relatively close in value, when contrasted to the predictions from the lumped curve number models. It is not tenable to infer that because predicted runoff from the Simple Method or the HSPF Watershed Model is larger than predicted runoff from the distributed curve number models, predicted runoff from Simple Method and the Watershed Model is larger than the runoff estimated by baseflow separation, without attempting to account for the biases in the modeling estimates.

To summarize, the following conclusions can be drawn from comparing modeling predictions with the estimates of runoff from baseflow separation of gage records:

- A simple comparison of the baseflow separation estimate with the predictions from the lumped and distributed curve number models does not determine whether curve numbers should be implemented with impervious and impervious areas lumped or distributed.

- A qualitative analysis of the potential biases in the curve number models suggests that the average annual runoff predicted by the models should be larger, not smaller, than the estimate from baseflow separation, except in the case of Difficult Run. This suggests that lumped curve numbers, such as those described in *TR-55*, underpredict urban runoff.

- The predictions of runoff from the Simple Method and the HSPF Watershed Model are compatible with the estimates obtained by baseflow separation, since their predictions of average annual runoff from urban areas are close in value to those of the distributed GWLF and EPIC models. The Simple Method and HSPF also separate the contribution of pervious from impervious land when calculating runoff.

The Theoretical Soundness of the Runoff Models for Urban Areas

There is no theoretical justification assuming that an urban land use has a curve number which is the weighted average of the curve numbers for pervious and impervious surfaces. Predicted runoff is a nonlinear function of the curve number. This fact alone may make lumping pervious and impervious areas together suspect, and is an additional reason not to use the methods of *TR-55* to determine average annual runoff.

If it is assumed that pervious and impervious areas should be modeled separately, then one fact stands out: the predicted runoff from impervious areas is the dominant source of runoff for all the models tested. Therefore, it is imperative that the runoff model for impervious surfaces be theoretically sound. In this respect the Curve Number Procedure has two strikes against it. First, the curve number assigned to impervious surfaces is not derived from test watersheds with homogeneous land uses, as were the curve numbers for rural land uses. Second, the hypothesis that the initial abstraction $I_a = 0.2$ S is suspect for impervious surfaces. This hypothesis was not well established for agricultural land covers. Even the NRCS, in *TR-55*, expressed its reservations, and explicitly recommended that this hypothesis be tested before it is used on impervious areas. In addition, it must be noted that the Curve Number Procedure was originally formulated to estimate design storms, with return periods great than one year, and that continuous curve number models, which take into account moisture conditions on a daily basis, are still evolving. At the moment, there is no official method for estimating antecedent moisture conditions. The methods used in GWLF no longer have the sanction of the NRCS.

In contrast, the Simple Method is an empirically derived equation, based from data on urban watersheds. The regression explains the variability of average annual runoff with a substantial coefficient of determination (.71). The Simple Method also requires an estimate of the fraction of the volume of annual precipitation that produces runoff. The use of the recommended value, 0.9, as an estimate of the volume of storms that produce runoff may be less well-supported, however, since this was derived for data from the Washington metropolitan area only.

The theoretical soundness of the HSPF model is less easy to characterize. The concepts by which HSPF represents the hydrologic processes of impervious surfaces--such as detention storage or interception capacity--are the standard means by which runoff from impervious surfaces are modeled, but the validity of HSPF simulations depends more upon the choice of model parameters and model calibration than model structure. The Chesapeake Bay Program possesses a HSPF model of the entire Chesapeake Bay Basin, including all of the urban areas for which chemical contaminant loads are to be estimated in the second stage of this project. That model has been calibrated to observed streamflow with great success.

Data Availability and Ease of Implementation

If an HSPF model of urban runoff in the Chesapeake Bay Basin had to be created from scratch, it would be a daunting undertaking, probably requiring a prohibitively high level of resources and effort. The Watershed Model, however, already calculates annual runoff from both pervious and impervious areas for each model segment in the Chesapeake Bay Basin. The hydrology for that model has already been successfully calibrated. Little additional effort is required to obtain estimates of average annual runoff from urban land in the basin.

The Simple Method requires (1) average annual precipitation in each model segment, (2) urban area in each model segment, and (3) the fraction of urban land that is impervious. All of the necessary data is available from the Watershed Model.

The distributed curve number models require, in addition to the information necessary for the Simple Method, a cross-tabulation of pervious urban land with soil type for each model segment. In principle this would not be difficult, but, as discussed previously, the only soil layer that is available is the STATSGO soil layer, which is not accurate at the scales at which the cross-tabulation would have to take place. The lumped curve number models would require a cross-tabulation of soil type with types of urban land--commercial, residential, and industrial. The only bay-wide land use classification that contains urban land types is the GIRAS land use layer, which is over twenty years old. Even after the cross-tabulations are performed, there would still be a considerable effort involved in preparing input files for either EPIC or GWLF.

Conclusions

Table 18 summarizes the evaluation of runoff models according to the three criteria: comparison of the runoff models with the runoff estimate from baseflow separation, the theoretical soundness of applying the runoff models to urban areas, and the availability of data and the ease of implementation.

Only the predictions from the curve number models could be compared directly to the runoff estimates from baseflow separation. Without interpretation, the results of comparing model predictions with baseflow estimates are inconclusive. A qualitative analysis of the expected biases in model prediction, however, led to the conclusion that the lumped curve number models underpredicted runoff. All models were used to calculate average annual runoff from urban areas alone, and it was found that all of the models which calculated runoff from pervious and impervious areas separately--the distributed curve number models, the Simple Method, and the HSPF Watershed Model--had similar predictions, in contrast to the lumped curve number models. The estimate of runoff from the baseflow separation cannot be used to discriminate between the distributed curve number models, the Simple Method, and HSPF.

There is no theoretical justification for calculating the curve numbers for urban land uses as the weighted average of curve numbers for impervious surfaces and curve numbers for grassed areas. The use of curve numbers for impervious surfaces is itself open to question, since conceptually, a curve number is a measure of the infiltration capacity of the soil. Therefore, there is little theoretical justification for using the Curve Number Procedure on urban land. On the other hand, the HSPF Watershed Model uses a more standard conceptual model of runoff from impervious surfaces, and the runoff calculation in the Simple Method is based on a regression equation for urban watersheds.

The HSPF Watershed Model calculates annual runoff from urban pervious and impervious land in each model segment. It is a straightforward task to use this information to calculate the average annual runoff from urban land in each model segment. Average annual runoff can also be easily calculated from Watershed model output using the Simple Method. The curve number models, on the other hand, require more detailed soil and land use information. Soil information is available for the entire basin only at a coarse scale. Recent urban land use data necessary for lumped curve number models is not available basin-wide.

Using the Curve Number Procedure to calculate average annual urban runoff therefore requires more effort but has little empirical or theoretical justification. Either the Simple Method or the HSPF Watershed Model could be used to calculate average annual runoff from urban areas. The HSPF Watershed Model is the means by which the Chesapeake Bay Program calculates nutrient loads from land uses in the Chesapeake Bay Basin. It would be a natural extension of the use of this model, in the context of the Chesapeake Bay Program, to use the model output to calculate chemical contaminant loads in runoff from urban areas. In fact, it would appear that some explanation would be necessary if the model was not used to calculate average annual runoff for the estimation of chemical contaminant loads.

Recommendations

This is not to say that the calculation of runoff by the HSPF Model could not be improved. If it is accepted that the county land use layers are more accurate than the EMAP land use layer used to construct the CBPLU, the GIS land use layer for the Watershed Model, there is reason to believe that CBPLU understimates the amount of urban land in the Chesapeake Bay Basin, and compensates for this by overestimating the fraction of urban land that is impervious. The credibility of the model's estimates of urban nutrient loads could be increased by improving the accuracy of the land use layer for urban areas. An accurate estimate of the amount of impervious land in the basin is the key to improving estimates of urban runoff, urban nutrient loads, and urban chemical contaminant loads. To this end, the following recommendations can be made:

- Use HSPF Watershed Model estimates of annual runoff for urban pervious and impervious areas to calculate the estimates of average annual runoff from urban areas necessary for estimating chemical contaminant loads in urban runoff.

- Improve the representation of urban land uses and impervious areas in the GIS land use layers supporting the Watershed Model.

- Use the runoff estimates from the Simple Method to help guide any recalibration of the runoff from urban areas in the Watershed Model.

In this manner, continued improvements in the Watershed Model's hydrology can lead to improvements in the estimation of average annual runoff used to calculate chemical contaminant loads in urban runoff and therefore to a refinement of the estimate of chemical contaminant loads in urban runoff in the Chesapeake Bay Basin.

Appendix A
Meteorological, Soil, and Land Use Data

Meteorological Data

Meteorological data for all three watersheds was obtained from the National Climate Data Center's Summary of the Day database on CD-ROM at the NOAA library in Silver Spring, MD. Maximum daily temperature, minimum daily temperature, and daily precipitation data was retrieved for the period 1972-1996 for four locations: Baltimore City, Dulles Airport in Herndon, VA, National Airport in Arlington, VA,, and Rockville, MD. The weather records for National Airport, Dulles Airport, and Baltimore City were complete. Rockville, MD, was missing approximately 2% of the observations.

Rockville weather data was used in the GWLF and EPIC simulations of Rock Creek. National Airport data was used whenever there were observations missing in the Rockville record. Dulles Airport data was used in the Difficult Run simulations and Baltimore City data was used in the Beaverdam Run simulations.

Soil and Land Use Data

To run the GWLF model, the area for each combination of land use and soil hydrologic group must be calculated. That is, the number of hectares of commercial land with hydrologic group A, the number of hectares of commercial land with hydrologic group B, the number of hectares of industrial land with hydrologic group B, etc., must be identified. Similarly, to use the EPIC model to simulate average annual runoff in a watershed, a cross tabulation of land use and soil type must be performed.

GIS is the natural tool for calculating the cross tabulation of land use and soil type. With the exception of land use data for Difficult Run, GIS land use and soil layers were available from county-level agencies for the three watersheds studied. Because the GIS layers were not in the same format, different methods were used to process the information for each watershed.

Rock Creek. Montgomery County Department of Environmental Protection supplied ARC/INFO polygon layers of land use, soil types, and watershed boundaries for Montgomery County. Using these layers, it was possible to produce a polygon layer delimiting areas of different land use and soil type. Table A-1 shows the total area for each combination of soil type and land use. The hydrologic group for each soil type was obtained from *TR-55*. Soil types complexed with urban land, such as Glenelg Urban Land and Wheaton Urban Land, were not delineated in the original soil layer. These soils represent areas where the original soil has been disturbed or covered with impervious surfaces. Inspection of the soil survey maps of Montgomery County showed that the vast majority of this land is Glenelg Urban Land. This soil was assumed to belong to hydrologic group B.

The Water Resources Management Division of the Department of Consumer and Regulatory

Affairs in the District of Columbia also supplied ARC/INFO polygon layers of watershed boundaries, land use, and soil types. The watershed boundary layer was edited to delineate the area upstream of the USGS gage at Sherill Drive. A polygon layer showing areas with different combinations of land use and soil type were then produced. Table A-2 shows the total area for each combination of soil type and land use. The hydrologic group for each soil type was again obtained from *TR-55*.

Beaverdam Run. The Department of Environmental Protection and Resource Management supplied IDRISI image files of land use, soil type, and watershed boundaries. A cross-tabulation of land use and soil type in the Beaverdam Run Watershed was produced using IDRISI. Hydrologic soil groups for the soil types were again determined using *TR-55*. Table A-3 shows the results. Table A-3 includes the area downstream of the USGS gage at Route 45 in Cockeysville. The contribution from this area was later eliminated, after the land use downstream of the gage was determined on a site visit, and the soils in this area determined from a soil map of Baltimore County.

Difficult Run. The cross-tabulation of soil type and land use for the Difficult Run Watershed presented several problems. First, no locally-generated land use layer was available for the Difficult Run Watershed. The USGS's GIRAS (Geographic Information Retrieval and Analysis System) land use cover in ARC/INFO GRID format, available from the Chesapeake Bay Program Office, was used as a land use layer. Fairfax County 's Department of Planning supplied an ARC/INFO polygon layer of watershed boundaries in the county. The Planning Department very generously supplied its ARC/INFO polygon layer of soil types, which it was still in the process of completing. All the soil information for the Difficult Run Watershed was available, but the layer was broken into ten pieces.

Attempts to convert the relevant section of the GIRAS land use grid to polygon format proved unsuccessful. To avoid converting the soil layers to GRID format, the cross tabulation of land use and soil type was obtained by another method. One thousand locations were randomly generated in a rectangle encompassing the Difficult Run Watershed. These locations were converted into a ARC/INFO point coverage. Locations which lay outside of the watershed were eliminated. An inspection of the remaining locations eliminated those locations which lay downstream of the USGS gage north of the Georgetown Pike. The first 250 locations generated which were not eliminated were then used to sample the soil layer and the land use grid. The sampling point coverage was intersected with the soil layers to associate a soil type with each sampling point. The point layer was converted to a grid, then intersected with the GIRAS grid coverage, to determine the land use at each sampling point. The percentage of the watershed's area with a given combination of land use and soil type was determined by the fraction of the sampling points which had that combination. The cross-tabulation of land use and soil type for the Difficult Run Watershed is given in Table A-4. Hydrologic groups were determined from information supplied by Fairfax County's Department of Information Technology.

It must be admitted that the GIS analysis of the Difficult Run Watershed was not done with complete rigor. Although the soil layer and the land use layer came from different sources and were in different formats, the layers were not reregistered. In addition, a larger sample size would have given greater statistical validity to the sampling procedure. Nevertheless, it is unlikely that a more rigorous analysis would have affected the conclusions.

Cross-Tabulation of CBPLU and STATSGO Data Layers. The STATSGO geographic data was supplied by the National Soil Survey Center in Lincoln, NE. CBPLU was obtained from the Chesapeake Bay Program Office. The STATSGO geographic data layer is in ARC/INFO vector format, while CBPLU is in ARC/INFO GRID format. The STATSGO coverages clipped to the boundaries of the watersheds. The polygon covers in STATSGO were converted to GRID format. GRID operation "CAND" was used with the STATSGO GRID layer and the CBPLU GRID. This operation preserved both the soil information and the land use information from the component GRIDs. The layers weren't reregistered before the operation. The soil layers do not have very much detail at the watershed scale, however. In Rock Creek, for example, more than 95% of the watershed was a single mapping unit. The coarse detail of the soil maps probably mitigates the potential for error from the registration of the coordinates.

Reduction of Land Use/Soil Type Data

There are too many categories of cross-tabulated land uses and soil types for all of the combinations to be used directly in GWLF. Many categories cover less than 1% of the watershed area. Moreover, some of the land use categories use in the GIS layers do not directly correspond with the land use categories used in *TR-55*.

In all the Beaverdam Run and Rock Creek Watersheds, institutional land use was treated as low-density residential land, orchards were assimilated to forest land, and mined areas treated as open land. The park areas in the Rock Creek Watershed within the District of Columbia were treated as forest land. For Difficult Run, the transportation land use was considered impervious surface, and residential land was considered medium density residential land.

If a combination of land use and hydrologic group (or soil type) occupied less than 1% of the area of a watershed, it was combined with other soil types of the same land use. An area-weighted average of the component soil types was used to represent the curve number of the combined soil types.

Impervious Areas in Urban Land

Unless the methods of *TR-55* are used, in which curve numbers are assigned on the basis of a land use type, it is necessary to know the amount of impervious land in a watershed. *TR-55* gives estimates of the percent of impervious area in each land use. It also gives estimates of the number of dwellings per acre for residential land uses. The residential land use classifications used in the land use layers for Rock Creek and Beaverdam Run assume the same number of dwellings per acre as the classifications of *TR-55*. Impervious areas were therefore calculated on the basis of estimates used in *TR-55* for each land type. Those estimates are shown in Table A-5. In the

Difficult Run Watershed, residential land was considered to be 30% impervious.

Figure 1
Methods of Baseflow Separation

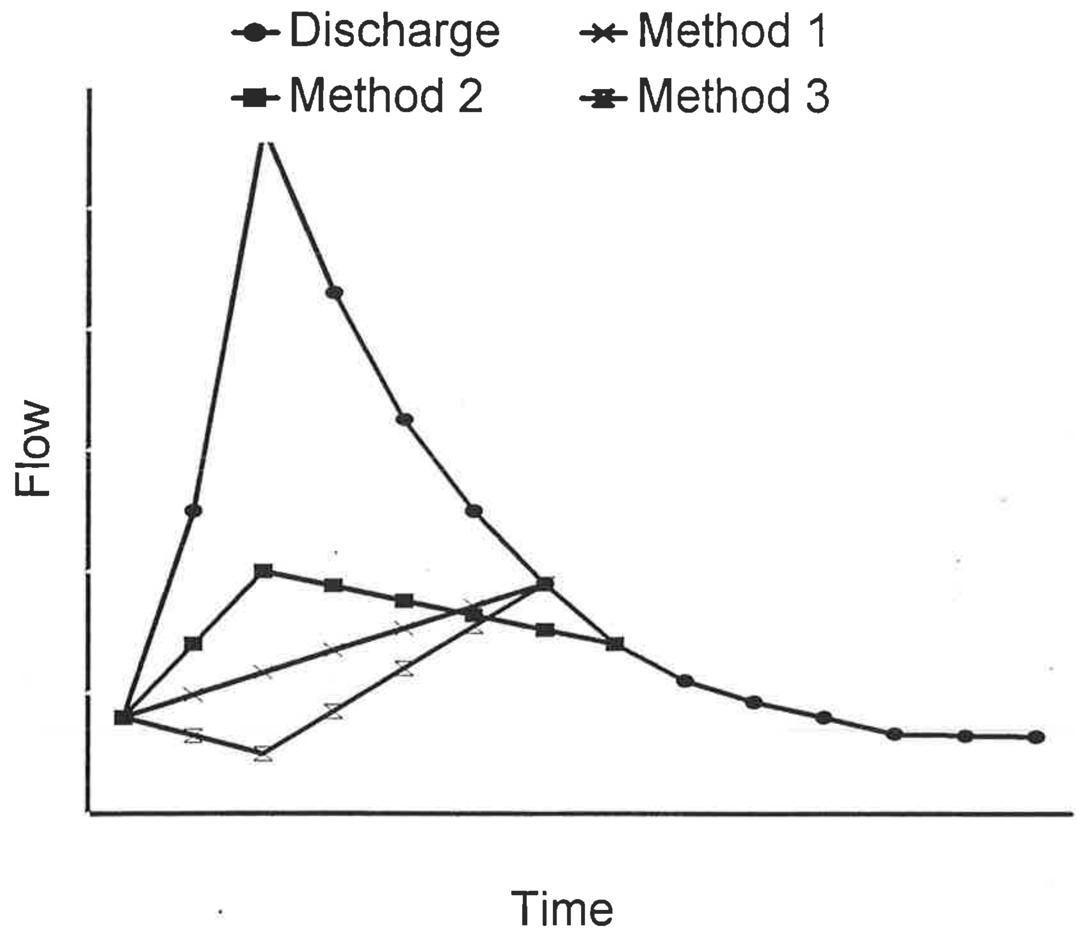

Figure 2
Streamflow and Baseflow
Rock Creek
March, 1972

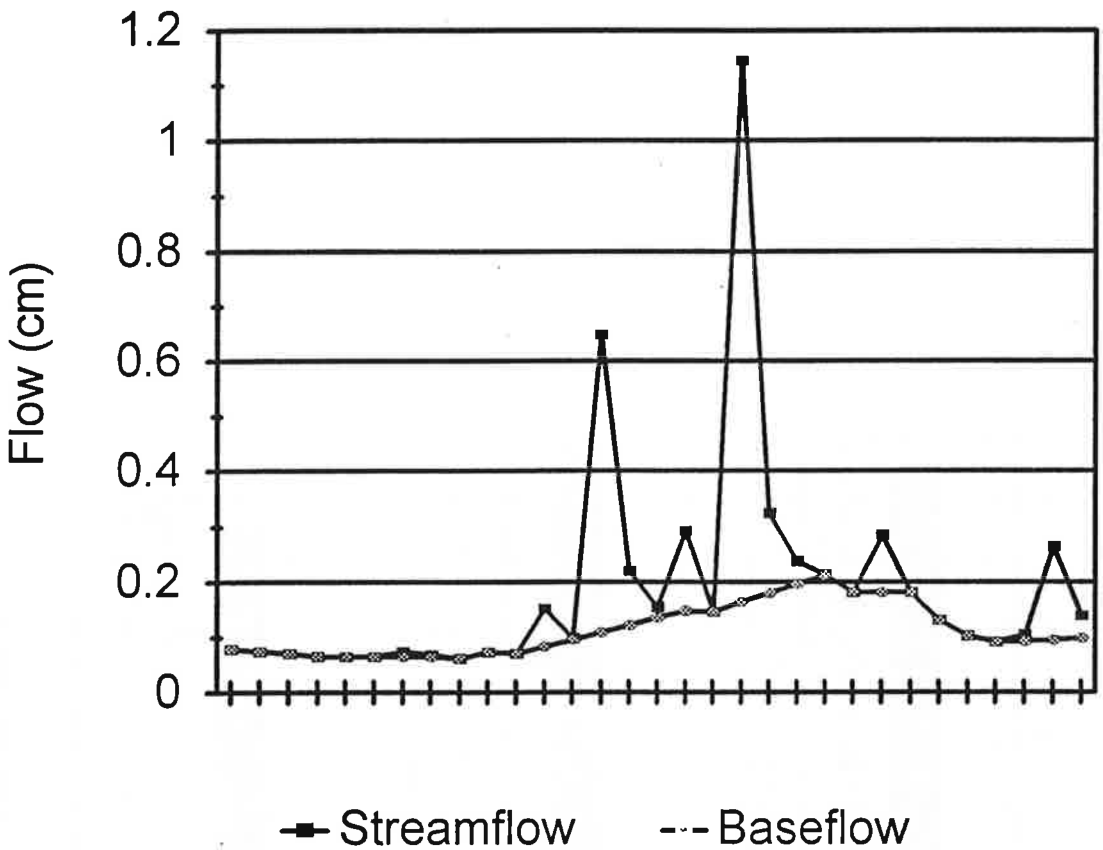

Figure 3
Average Annual Runoff From Gaged Watersheds (cm)

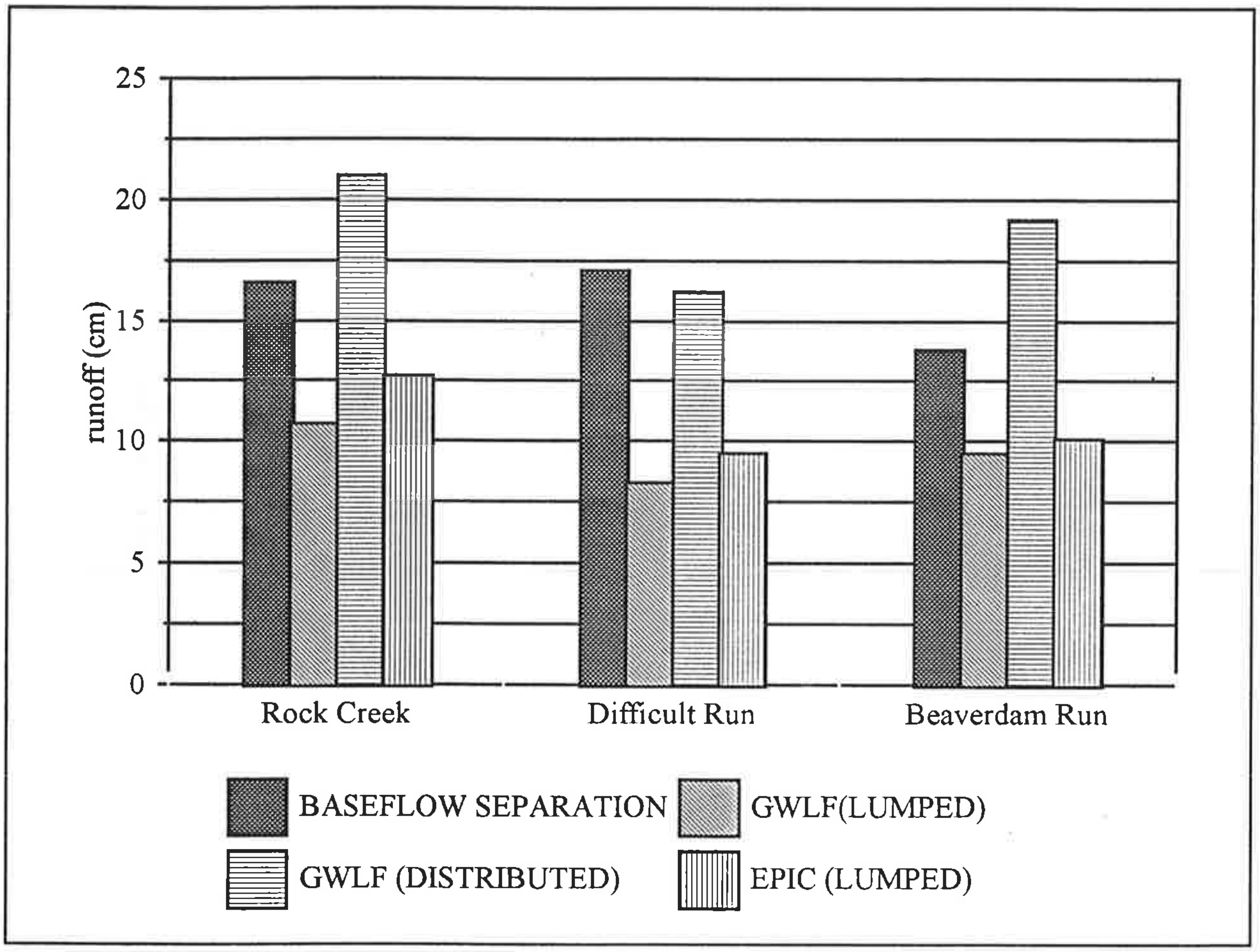

Figure 4
Predicted Average Annual Runoff
From Urban Areas

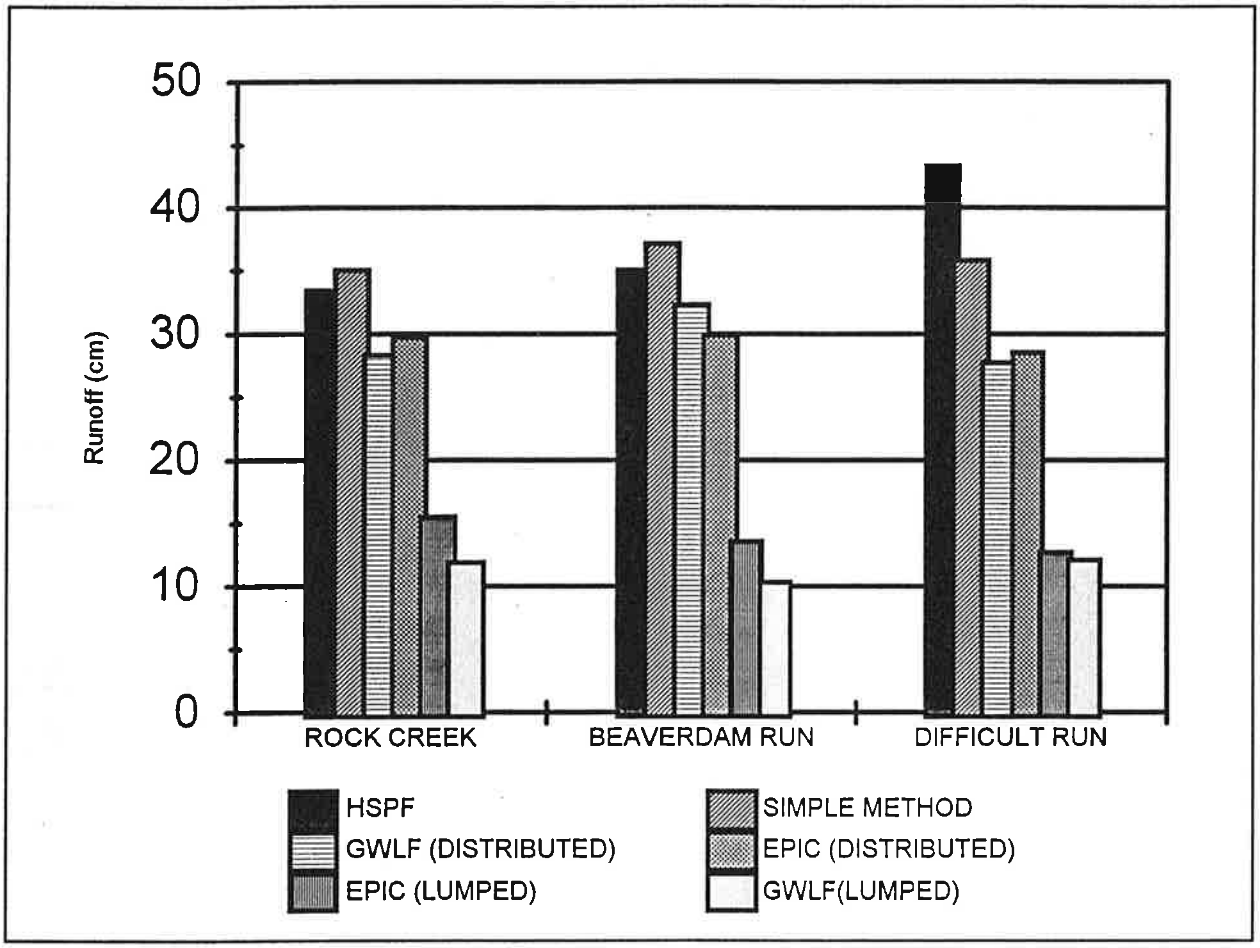

Table 1
Anteceedent Moisture Conditions
National Engineering Handbook (1985)

	Total Five-Day Anteceedent Rainfall (in)	
Antecedent Moisture Condition	Dormant Season	Growing Season
AMC I	< .5	< 1.4
AMC II	0.5 to 1.1	1.4 to 2.1
AMC III	Over 1.1	Over 2.1

Table 2
Watersheds and Gaging Stations

Watershed	Gage Number	Location
Rock Creek	01648000	7.5 mi. upstream of mouth Downstream from Sherrill Drive Bridge
Beaverdam Run	01583600	0.45 upstream of mouth Left bank of bridge on State Route 45 at Cockeysville
Difficult Run	01646000	0.7 mi. upstream of mouth Downstream of bridge on State Highway 193

Table 3
Runoff Estimates From USGS Gage Records

	Area		Runoff (cm) For Values of N			
Watershed	**(mi^2)**	**N=A$^{0.2}$**	**1**	**2**	**3**	**4**
Rock Creek	62.2	2.28		14.6	**16.6**	18.2
Difficult Run	57.9	2.25		15.3	**17.1**	18.4
Beaverdam Run	20.9	1.83	10.1	**13.8**	15.4	

The runoff for the best estimate of N are in bold.

Table 4
GWLF Runoff Model Results
Distributed Land Uses
Rock Creek

Land Use	Hydrologic Group	Curve Number	Area (ha)	Runoff (cm)
Pasture/Turf	B	61	6222	3.28
Pasture/Turf	C	74	513	7.85
Pasture/Turf	C/D	77	158	9.65
Pasture/Turf	D	80	393	11.93
Cropland	B	78	1204	10.35
Cropland	C	85	84	17.4
Cropland	C/D	87	17	20.48
Cropland	D	89	173	24.35
Forest	B	55	1729	2.15
Forest	C	70	255	6
Forest	C/D	74	255	7.85
Forest	D	77	343	9.65
Open Land	W	87	811	20.48
Brush	W	53	378	1.85
Impervious		98	3764	70.43
Total			16299	21
Baseflow Separation Estimate				16.6

Hydrologic Group "W" is a weighted average of other hydrologic groups.

Table 5
GWLF Runoff Model Results
Lumped Land Uses
Rock Creek

Land Use	Hydrologic Group	Curve Number	Area (ha)	Runoff (cm)
Commercial	W	92	1244	32.41
Industrial	W	89	57	24.35
Low Density Residential	B	68	2598	5.25
Low Density Residential	C	79	210	11.11
Low Density Residential	D	84	180	16.09
Medium Density Residential	B	72	4637	6.86
Medium Density Residential	C	81	326	12.84
Medium Density Residential	D	86	255	18.86
High Density Residential	W	86	716	18.86
Brush	W	53	378	1.85
Open Land	W	80	811	20.48
Pasture	W	80	816	11.93
Cropland	W	82	1297	13.82
Cropland	D	89	182	24.35
Forest	B	55	1729	2.15
Forest	C	70	383	6
Forest	D	77	471	9.65
Total			16290	10.7
Baseflow Separation Estimate				16.6

Hydrologic Group "W" is a weighted average of other hydrologic groups.

Table 6
GWLF Runoff Model Results
Distributed Land Uses
Beaverdam Run

Land Use	Hydrologic Group	Curve Number	Area (ha)	Runoff (cm)
Pasture/Turf	B	61	720	1.99
Pasture/Turf	C	74	297	5.73
Pasture/Turf	D	80	62	9.33
Cropland	B	78	580	7.9
Cropland	C	85	578	14.49
Cropland	D	89	93	21.33
Forest	B	55	1291	1.13
Forest	C	70	196	4.19
Forest	D	77	95	7.29
Open Land	W	88	362	19.29
Brush	W	61	138	1.99
Impervious		98	897	67.64
Total			5309	19.2
Baseflow Separation Estimate				13.8

Hydrologic Group "W" is a weighted average of other hydrologic groups.

Table 7
GWLF Runoff Model Results
Lumped Land Uses
Beaverdam Run

Land Use	Hydrologic Group	Curve Number	Area (ha)	Runoff (cm)
Commercial	W	92	249	29.43
Industrial	B	88	229	19.29
Industrial	C	91	59	26.33
Industrial	D	93	50	33.05
Low Density Residential	B	68	565	3.58
Low Density Residential	W	79	342	8.58
Medium Density Residential	W	74	323	5.73
High Density Residential	W	86	242	15.9
Brush	W	61	138	1.99
Open Land	W	88	362	19.29
Cropland	B	78	570	7.9
Cropland	C	85	573	14.49
Cropland	D	89	93	21.33
Forest	B	55	1233	1.13
Forest	C	70	186	4.19
Forest	D	77	95	7.29
Total			5309	9.5
Baseflow Separation Estimate				13.8

Hydrologic Group "W" is a weighted average of other hydrologic groups.

Table 8
GWLF Runoff Model Results
Distributed Land Uses
Difficult Run

Land Use	Hydrologic Group	Curve Number	Area (ha)	Runoff (cm)
Pasture/Turf	B	61	4764	2.87
Pasture/Turf	C	74	1591	7.38
Pasture/Turf	D	80	623	11.38
Forest	B	55	3287	1.78
Forest	C	70	1066	5.55
Forest	D	77	471	9.15
Open Land	W	86	118	18.07
Impervious		98	2786	67.29
Total			14706	16.2
Baseflow Separation Estimate				17.1

Hydrologic Group "W" is a weighted average of other hydrologic groups.

Table 9
GWLF Runoff Model Results
Lumped Land Uses
Difficult Run

Land Use	Hydrologic Group	Curve Number	Area (ha)	Runoff (cm)
Pasture	B	61	1293	2.87
Pasture	C	74	707	7.38
Pasture	D	80	294	11.38
Forest	B	55	3287	1.78
Forest	C	70	1066	5.55
Forest	D	77	471	9.15
Open Land	W	86	118	18.07
Commercial	B	92	647	31.11
Commercial	C	94	118	38.6
Residential	B	72	4820	6.4
Residential	C	81	1239	12.26
Residential	D	86	471	18.07
Transportation	W	98	177	67.29
Total			14708	8.3
Baseflow Separation Estimate				17.1

Hydrologic Group "W" is a weighted average of other hydrologic groups.

Table 10
EPIC Runoff Modeling Results
Lumped Land Uses
Rock Creek

Land Use	Soil Type	Curve Number	Area (ha)	Runoff (cm)
Commerical	Glenelg	92	1369	42.14
Cropland	Glenelg	78	1483	9.38
Forest	Glenleg	55	1382	3.02
Forest	Brinklow	55	346	4.28
Forest	Blocktown	74	261	16.65
Forest	Hatboro	77	342	11.50
Forest	Codorus	70	261	7.05
High Density Residential	Glenelg	85	717	24.74
Low Density Residential	Glenelg	65	2999	6.13
Medium Density Residential	Glenelg	72	4446	9.92
Medium Density Residential	Brinklow	72	183	10.43
Medium Density Residential	Baile	86	228	21.19
Medium Density Residential	Glenville	81	293	12.39
Open Land	Glenelg	87	815	28.65
Pasture	Glenelg	61	1190	4.67
Total			16314	12.70
Baseflow Separation Estimate				16.60

Table 11
EPIC Runoff Modeling Results
Lumped Land Uses
Beaverdam Run

Land Use	Soil Type	Curve Number	Area (ha)	Runoff (cm)
Forest	Manor	55	1371	1.62
Forest	Codorus	70	186	7.76
Forest	Hatboro	77	95	13.84
Cropland	Glenelg	78	570	8.34
Cropland	Hagerstown	85	573	15.63
Cropland	Hatboro	89	93	20.48
Open	Manor	88	362	13.21
Industrial	Conestoga	88	229	17.13
Industrial	Codorus	91	59	30.45
Industrial	Dunning	93	50	27.21
Commercial	Conestoga	92	249	24.64
Low Density Residential	Manor	68	565	4.92
Low Density Residential	Elioak	78	342	13.05
Medium Density Residential	Manor	72	323	7.16
High Density Residential	Manor	86	242	21.73
Total			5309	10.06
Baseflow Separation Estimate				13.8

Table 12
EPIC Runoff Modeling Results
Lumped Land Uses
Difficult Run

Land Use	Soil Type	Curve Number	Area (ha)	Runoff (cm)
Residential	Glenelg	72	4820	8.14
Residential	Elioak	81	1239	13.24
Residential	Orange	86	471	13.40
Commercial	Manor	92	824	34.64
Commercial	Elioak	94	118	37.20
Open Land	Glenelg	86	118	20.94
Pasture	Glenelg	61	1293	4.08
Pasture	Elioak	74	707	7.80
Pasture	Wehadkee	80	294	12.91
Forest	Glenelg	55	3287	3.35
Forest	Chewacla	70	1066	8.59
Forest	Wehadkee	77	471	13.78
Total			14708	9.51
Baseflow Separation Estimate				17.1

Table 13
Comparison of Model Predictions of Runoff From Urban Land

Model	Runoff (cm) Rock Creek	Beaverdam Run	Difficult Run
GWLF (lumped)	11.9	10.3	12.1
GWLF (distributed)	28.3	32.3	27.8
EPIC (lumped)	15.5	13.6	12.7
EPIC (distributed)	29.7	29.9	28.5
HSPF	33.4	35	43.3
Simple Method	35	37.1	35.8
Percent Impervious*	34.1%	38.4%	37.3%

* The method by which impervious area is calculated is given in Appendix A.

Table 14
Average Annual Runoff From Turf Grass/Pasture
EPIC Model
Rock Creek and Beaverdam Run

Rock Creek

Soil	Curve Number	Runoff (cm)
Glenelg	61	4.67
Glenville	74	7.03
Blocktown	77	12.51
Baile	80	13

Beaverdam Run

Soil	Curve Number	Runoff (cm)
Manor	61	2.41
Elioak	74	8.66
Dunning	80	8.46

Table 15
Percent of Predicted Runoff Volume
Contributed By Impervious Surfaces

Model	Rock Creek	Beaverdam Run	Difficult Run
GWLF	85%	85%	90%
EPIC	81%	86%	88%
HSPF	87%	93%	72%

Table 16
Cross Tabulated Areas
CBPLU Land Uses and STATSGO Hydrologic Groups
Rock Creek

	Area of Hydrologic Group (ha)				
Land Use	**A**	**B**	**C**	**D**	**Total**
Herbaceous	157	2039	347	79	2622
Herbaceous Urban	50	644	108	25	826.1
Herbaceous Wetland	0	3	1	0	3.7
High Intensity Urban	74	960	170	38	1242
Low Intensity Urban	409	5336	988	211	6944
Woody	181	2349	406	91	3026
Woody Urban	89	1163	212	46	1510
Water	3	44	7	2	56.5
Total	962	12537	2239	491	16229

Table 17
Cross Tabulated Areas
CBPLU Land Uses and STATSGO Hydrologic Groups
Beaverdam Run

	Area of Hydrologic Group (ha)				
Land Use	**A**	**B**	**C**	**D**	**Total**
Exposed	2	183	19	14	217
Herbaceous	54	1060	147	61	1322
Herbaceous Urban	9	223	29	14	275
Herbaceous Wetland	0	5	1	0	6
High Intensity Urban	2	274	28	22	325
Low Intensity Urban	17	663	78	45	803
Woody	114	1820	275	90	2298
Woody Urban	7	161	22	9	200
Water	0	1	0	0	2
Total	205	4390	598	255	5448

Table 18
Summary of Criteria For Evaluating Runoff Models

Model	Comparison with Baseflow Separation Estimate	Theoretical Soundness	Data Availability/Ease of Implementation
Lumped Curve Number Models	Understimates runoff, given model biases.	No theoretical justification for calculating curve numbers for urban land uses as a weighted average of curve numbers for impervious surfaces and grassed areas.	No recent basin-wide land use data available with necessary urban land categories.
Distributed Curve Number Models	Compatible with baseflow separation estimate.	The assignment of a curve number to impervious surface is problematic, since curve number is a measure of soil infiltration capacity.	Basin-wide soil data is available only at a coarse resolution valid at level of state-wide analysis.
The Simple Method	Compatible with baseflow separation estimate.	Uses statically-supported regression equation relating runoff to precipitation, watershed area, and impervious fraction of watershed.	Can be implemented using data assembled by Chesapeake Bay Program for Watershed Model.
The HSPF Watershed Model	Compatible with baseflow separation estimate.	Uses standard conceptual model of runoff from impervious surfaces.	Annual runoff for urban pervious and impervious areas calculated by Watershed Model.

Table A-1
Land Use and Soil Types For the Rock Creek Watershed
Maryland

Land Use	Soil Type	Hydrologic Group	Area (ha)
Med Density Residential	Urban	U	3235.4
Low Density Residential	Glenelg	B	1123.0
Cropland	Glenelg	B	950.4
Med Density Residential	Glenelg	B	885.1
Commercial	Urban	U	815.2
Deciduous	Glenelg	B	733.5
Hi Density Residential	Urban	U	386.1
Deciduous	Urban	U	337.0
Institutional	Urban	U	332.9
Low Density Residential	Urban	U	307.6
Open Urban Land	Glenelg	B	306.5
Deciduous	Blocktown	C/D	255.1
Pasture	Glenelg	B	231.5
Commercial	Glenelg	B	227.5
Deciduous	Hatboro	D	225.6
Institutional	Glenelg	B	207.9
Hi Density Residential	Glenelg	B	184.8
Med Density Residential	Brinklow	B	181.7
Deciduous	Brinklow	B	176.1
Deciduous	Gaila Silt Loam	B	174.8
Open Urban Land	Wheaton	B	168.5
Open Urban Land	Urban	U	143.9

Table A-1 (Cont.)
Land Use and Soil Types For the Rock Creek Watershed
Maryland

Land Use	Soil Type	Hydrologic Group	Area (ha)
Brush	Glenelg	B	129.9
Cropland	Baile	D	128.5
Med Density Residential	Baile	D	125.5
Deciduous	Baile	D	117.7
Med Density Residential	Gaila Silt Loam	B	110.9
Med Density Residential	Glenville	C	109.0
Deciduous	Codorus	C	106.8
Low Density Residential	Gaila Silt Loam	B	104.8
Med Density Residential	Codorus	C	103.5
Cropland	Gaila Silt Loam	B	102.2
Med Density Residential	Wheaton	B	91.9
Low Density Residential	Baile	D	86.3
Low Density Residential	Brinklow	B	75.9
Low Density Residential	Gaila	B	75.1
	Glenelg	B	73.4
Med Density Residential	Blocktown	C/D	70.3
Med Density Residential	Hatboro	D	69.9
Pasture	Gaila Silt Loam	B	66.7
Deciduous	Gaila	B	66.4
Cropland		U	63.8
Institutional	Brinklow	B	54.9
Brush		U	52.2

Table A-1 (Cont.)
Land Use and Soil Types For the Rock Creek Watershed
Maryland

Land Use	Soil Type	Hydrologic Group	Area (ha)
Deciduous	Glenville	C	51.8
Commercial	Glenville	C	48.8
Low Density Residential	Glenville	C	44.4
Pasture	Baile	D	44.0
Cropland	Hatboro	D	42.7
Deciduous	Wheaton	B	42.5
Cropland	Glenville	C	42.2
Low Density Residential	Hatboro	D	41.4
Low Density Residential	Wheaton	B	41.1
Open Urban Land	Baile	D	39.9
Pasture	Gaila	B	38.9
Brush	Gaila Silt Loam	B	37.0
Open Urban Land	Gaila Silt Loam	B	35.7
Low Density Residential	Neshaminy	B	34.5
Low Density Residential	Blocktown	C/D	34.0
Med Density Residential	Gaila	B	31.6
Or/Vin/Hort/Aqu	Glenelg	B	31.5
Cropland	Brinklow	B	31.5
Brush	Blocktown	C/D	30.9
Commercial	Baile	D	30.3
Pasture	Elioak	C	29.4
Deciduous	Elioak	C	28.8

Table A-1 (Cont.)
Land Use and Soil Types For the Rock Creek Watershed
Maryland

Land Use	Soil Type	Hydrologic Group	Area (ha)
Low Density Residential	Chrome	C	27.7
Institutional	Wheaton	B	27.6
Industrial	Urban	U	26.5
Deciduous	Occoquan	B	25.5
Brush	Hatboro	D	25.0
Commercial	Gaila	B	24.9
Open Urban Land	Hatboro	D	24.3
Deciduous	Elsinboro	B	24.0
	Water	U	23.4
Mixed	Urban	U	23.2
Cropland	Chrome	C	23.2
Institutional	Gaila Silt Loam	B	22.3
Med Density Residential	Chrome	C	22.2
Hi Density Residential	Brinklow	B	22.2
Hi Density Residential	Baile	D	22.0
Institutional	Blocktown	C/D	21.9
Cropland	Gaila	B	21.7
Open Urban Land	Brinklow	B	21.4
Low Density Residential	Codorus	C	21.2
Pasture	Glenville	C	21.0
Commercial	Brinklow	B	20.8
Pasture	Hatboro	D	20.5

Table A-1 (Cont.)
Land Use and Soil Types For the Rock Creek Watershed
Maryland

Land Use	Soil Type	Hydrologic Group	Area (ha)
Brush	Baile	D	19.9
Deciduous	Water	U	19.5
Brush	Brinklow	B	19.4
	Blocktown	C/D	19.1
Commercial	Blocktown	C/D	19.0
Cropland	Elioak	C	18.7
Mixed	Gaila Silt Loam	B	18.7
Med Density Residential	Elioak	C	18.0
Institutional	Glenville	C	17.9
Mixed	Gaila	B	17.7
Mixed	Chrome	C	17.6
Hi Density Residential	Glenville	C	17.6
Open Urban Land	Glenville	C	17.5
Cropland	Blocktown	C/D	17.3
Low Density Residential	Elioak	C	17.3
Open Urban Land	Blocktown	C/D	16.5
Institutional	Codorus	C	16.4
Pasture		U	16.3
Institutional	Baile	D	16.3
Industrial	Glenelg	B	15.9
Hi Density Residential	Chrome	C	15.3
Commercial	Gaila Silt Loam	B	15.3

Table A-1 (Cont.)
Land Use and Soil Types For the Rock Creek Watershed
Maryland

Land Use	Soil Type	Hydrologic Group	Area (ha)
Open Urban Land	Codorus	C	15.1
	Gaila Silt Loam	B	14.9
Hi Density Residential	Codorus	C	14.1
Cropland	Occoquan	B	14.1
Pasture	Brinklow	B	14.0
Low Density Residential	Occoquan	B	13.9
Brush	Wheaton	B	13.6
Cropland	Wheaton	B	13.3
Commercial	Hatboro	D	12.8
Mixed	Glenelg	B	11.6
Mixed	Blocktown	C/D	11.4
Mixed	Baile	D	11.4
Brush	Occoquan	B	11.2
	Baile	D	11.1
Hi Density Residential	Elioak	C	10.6
Pasture	Chrome	C	10.5
	Brinklow	B	10.1
Hi Density Residential	Blocktown	C/D	9.8
Brush	Water	U	9.8
Or/Vin/Hort/Aqu	Wheaton	B	9.5
Med Density Residential	Neshaminy	B	9.3
Med Density Residential	Conowingo	C	9.2

Table A-1 (Cont.)
Land Use and Soil Types For the Rock Creek Watershed
Maryland

Land Use	Soil Type	Hydrologic Group	Area (ha)
Brush	Glenville	C	8.9
Or/Vin/Hort/Aqu	Elioak	C	8.3
Open Urban Land	Gaila	B	8.3
Brush	Elioak	C	8.3
Hi Density Residential	Gaila Silt Loam	B	8.3
Or/Vin/Hort/Aqu	Baile	D	8.1
Commercial	Wheaton	B	7.8
Institutional	Elioak	C	7.7
Pasture	Blocktown	C/D	7.7
Commercial	Elioak	C	7.6
Deciduous	Legore	B	7.6
Med Density Residential	Elsinboro	B	7.4
Hi Density Residential	Wheaton	B	7.4
Or/Vin/Hort/Aqu	Glenville	C	7.2
Institutional	Hatboro	D	7.2
	Wheaton	B	7.2
Brush	Gaila	B	6.9
Deciduous	Chrome	C	6.0
Institutional	Gaila	B	5.8
Hi Density Residential	Neshaminy	B	5.7
Open Urban Land	Elioak	C	5.6
Mixed	Hatboro	D	5.5

Table A-1 (Cont.)
Land Use and Soil Types For the Rock Creek Watershed
Maryland

Land Use	Soil Type	Hydrologic Group	Area (ha)
Mixed	Wheaton	B	5.1
	Elioak	C	5.0
Med Density Residential	Occoquan	B	4.9
Brush	Neshaminy	B	4.9
Cropland	Neshaminy	B	4.8
Pasture	Neshaminy	B	4.6
Industrial	Brinklow	B	4.2
Pasture	Watchung	D	4.0
		U	4.0
Med Density Residential	Travilah	C	3.9
Open Urban Land	Water	U	3.8
Commercial	Codorus	C	3.5
Institutional	Neshaminy	B	3.5
Deciduous	Travilah	C	3.4
Open Urban Land	Travilah	C	3.4
Deciduous	Neshaminy	B	3.4
Hi Density Residential	Travilah	C	3.3
	Glenville	C	2.9
Industrial	Blocktown	C/D	2.8
Commercial	Neshaminy	B	2.8
Commercial	Water	U	2.8
Industrial	Codorus	C	2.5

Table A-1 (Cont.)
Land Use and Soil Types For the Rock Creek Watershed
Maryland

Land Use	Soil Type	Hydrologic Group	Area (ha)
Low Density Residential	Montalto	C	2.4
Hi Density Residential	Gaila	B	2.4
Pasture	Occoquan	B	2.2
Cropland	Watchung	D	1.9
	Hatboro	D	1.9
Pasture	Legore	B	1.9
Pasture	Codorus	C	1.9
Commercial	Travilah	C	1.8
Industrial	Hatboro	D	1.8
Mixed	Watchung	D	1.8
Pasture	Wheaton	B	1.7
Industrial	Glenville	C	1.7
Med Density Residential	Water	U	1.5
Commercial	Elsinboro	B	1.5
Commercial	Chrome	C	1.5
Hi Density Residential	Water	U	1.4
Industrial	Elioak	C	1.4
Med Density Residential	Montalto	C	1.4
Cropland	Water	U	1.3
Pasture	Conowingo	C	1.3
Low Density Residential	Water	U	1.1
Hi Density Residential	Hatboro	D	1.1

Table A-1 (Cont.)
Land Use and Soil Types For the Rock Creek Watershed
Maryland

Land Use	Soil Type	Hydrologic Group	Area (ha)
Low Density Residential	Watchung	D	1.0
Pasture	Water	U	0.9
Or/Vin/Hort/Aqu	Water	U	0.9
Institutional	Montalto	C	0.9
Hi Density Residential	Conowingo	C	0.6
Open Urban Land	Elsinboro	B	0.6
Hi Density Residential	Watchung	D	0.5
Cropland	Legore	B	0.5
Hi Density Residential	Montalto	C	0.5
	Gaila	B	0.4
Commercial	Occoquan	B	0.4
Mixed	Neshaminy	B	0.3
Mixed	Brinklow	B	0.2
Mixed	Codorus	C	0.2
Industrial	Water	U	0.1
Industrial	Gaila Silt Loam	B	0.1
Pasture	Travilah	C	0.1
Mixed	Conowingo	C	0.0
Industrial	Baile	D	0.0
Mixed	Glenville	C	0.0
Pasture	Montalto	C	0.0
Deciduous	Montalto	C	0.0

Table A-1 (Cont.)
Land Use and Soil Types For the Rock Creek Watershed
Maryland

Land Use	Soil Type	Hydrologic Group	Area (ha)
Med Density Residential	Legore	B	0.0
5-20 Ac.		U	0.0

Hydrologic Group "U" means the hydrologic group is unknown. It is usually urban land, considered "B" for purposes of analysis.

Table A-2
Land Use and Soil Types in Rock Creek Watersehed
Distict of Columbia

Land Use	Soil Type	Hydrologic Group	Area (ha)
Low density residential	Urban Land - Manor-Glenelg	B	131.8
Parks	Manor-Glenelg Deep	B	93.8
Parks	Luka-Lindside-Codorus Deep	C	47.3
Parks	Urban Land - Manor-Glenelg	B	25.0
Low density residential	Urban Land - Brandywine	C	23.8
Low density residential	Urban Land - Sassafras-Chillum	B	23.1
Parks	Urban Land - Brandywine	C	11.0
Federal	Urban Land - Sassafras-Chillum	B	3.3
Institutional	Urban Land - Manor-Glenelg	B	2.7
Low density residential	Luka-Lindside-Codorus Deep	C	2.6
Federal	Urban Land - Manor-Glenelg	B	1.3
Low density commerical and residential	Urban Land - Sassafras-Chillum	B	1.2
Federal	Manor-Glenelg Deep	B	1.1
Low density residential	Manor-Glenelg Deep	B	0.8
Parks	Urban Land - Sassafras-Chillum	B	0.0

Table A-3
Land Use and Soil Types in the Beaverdam Run Watershed

Land Use	Soil Type	Hydrologic Group	Area (ha)
Deciduous Forest	Manor	B	652.86
Deciduous Forest	Glenelg	B	285.51
Low-Density Residential	Manor	B	247.38
Cropland	Hagerstown	C	227.85
Low-Density Residential	Elioak	C	225.06
Low-Density Residential	Glenelg	B	200.88
Cropland	Elioak	C	197.16
Cropland	Glenelg	B	191.58
Cropland	Manor	B	165.54
Industrial	Baltimore	B	134.85
Cropland	Chester	B	100.44
Deciduous Forest	Elioak	C	88.35
Commercial	Baltimore	B	82.77
Deciduous Forest	Chester	B	82.77
Med-Density Residential	Baltimore	B	80.91
Med-Density Residential	Manor	B	79.05
Extractive	Mine dumps		68.82
High-Density Residential	Manor	B	64.17
Cropland	Codorus	C	50.22
Cropland	Glenville	C	48.36
Cropland	Baltimore	B	46.5

Table A-3 (Cont.)
Land Use and Soil Types in the Beaverdam Run Watershed

Land Use	Soil Type	Hydrologic Group	Area (ha)
Deciduous Forest	Hatboro	D	46.5
Low-Density Residential	Chester	B	46.5
Commercial	Conestoga	B	44.64
Deciduous Forest	Glenville	C	44.64
Large Lot Subd.-Forest	Manor	B	44.64
High-Density Residential	Baltimore	B	39.99
Extractive	Conestoga	B	38.13
High-Density Residential	Conestoga	B	38.13
Industrial	Hollinger	B	38.13
Industrial	Dunnning	D	38.13
Commercial	Hagerstown	C	36.27
Cropland	Hatboro	D	36.27
Deciduous Forest	Baile	D	32.55
Med-Density Residential	Glenelg	B	30.69
Open Urban	Chester	B	30.69
Open Urban	Glenelg	B	30.69
Commercial	Hollinger	B	27.9
Cropland	Melvin	D	27.9
Deciduous Forest	Codorus	C	27.9
Pasture	Manor	B	27.9
Deciduous Forest	Baltimore	B	26.04

Table A-3 (Cont.)
Land Use and Soil Types in the Beaverdam Run Watershed

Land Use	Soil Type	Hydrologic Group	Area (ha)
Open Urban	Manor	B	26.04
Cropland	Baile	D	22.32
Industrial	Conestoga	B	22.32
Industrial	Captina	C	20.46
Low-Density Residential	Baltimore	B	20.46
Med-Density Residential	Baile	D	20.46
Bare Ground	Manor	B	18.6
Deciduous Forest	Mine dumps		18.6
Extractive	Baltimore	B	18.6
Brush	Hagerstown	C	17.67
Deciduous Forest	Hollinger	B	17.67
Industrial	Codorus	C	17.67
Industrial	Made land		17.67
Large Lot Subd.-Forest	Chester	B	17.67
Low-Density Residential	Glenville	C	17.67
Med-Density Residential	Conestoga	B	17.67
Deciduous Forest	Made land		15.81
Institutional	Baltimore	B	15.81
Brush	Hollinger	B	13.95
Brush	Codorus	C	13.95
Deciduous Forest	Alluvial		13.95

Table A-3 (Cont.)
Land Use and Soil Types in the Beaverdam Run Watershed

Land Use	Soil Type	Hydrologic Group	Area (ha)
High-Density Residential	Hollinger	B	13.95
Med-Density Residential	Alluvial		13.95
Mixed Forest	Glenelg	B	13.95
Open Urban	Elioak	C	13.95
Commercial	Mine dumps		12.09
Cropland	Hollinger	B	12.09
Extractive	Dunnning	D	12.09
High-Density Residential	Glenelg	B	12.09
Large Lot Subd.-Forest	Glenville	C	12.09
Low-Density Residential	Hatboro	D	12.09
Open Urban	Dunnning	D	12.09
Orchard/Vineyard	Manor	B	12.09
Orchard/Vineyard	Glenelg	B	12.09
Bare Ground	Glenelg	B	10.23
Cropland	Conestoga	B	10.23
Extractive	Hollinger	B	10.23
High-Density Residential	Glenville	C	10.23
Low-Density Residential	Hagerstown	C	10.23
Med-Density Residential	Lindside	C	10.23
Med-Density Residential	Hatboro	D	10.23
Brush	Dunnning	D	8.37

Table A-3 (Cont.)
Land Use and Soil Types in the Beaverdam Run Watershed

Land Use	Soil Type	Hydrologic Group	Area (ha)
Cropland	Captina	C	8.37
High-Density Residential	Brandywine	C	8.37
High-Density Residential	Baile	D	8.37
Industrial	Hagerstown	C	8.37
Institutional	Captina	C	8.37
Large Lot Subd.-Ag	Baltimore	B	8.37
Med-Density Residential	Captina	C	8.37
Open Urban	Glenville	C	8.37
Ag. Buildings	Elioak	C	6.51
Commercial	Alluvial		6.51
Commercial	Manor	B	6.51
Institutional	Hatboro	D	6.51
Low-Density Residential	Baile	D	6.51
Med-Density Residential	Hollinger	B	6.51
Mixed Forest	Manor	B	6.51
Bare Ground	Elioak	C	5.58
Bare Ground	Baltimore	B	5.58
Brush	Mine dumps		5.58
Brush	Conestoga	B	5.58
Brush	Glenelg	B	5.58
Deciduous Forest	Conestoga	B	5.58

Table A-3 (Cont.)
Land Use and Soil Types in the Beaverdam Run Watershed

Land Use	Soil Type	Hydrologic Group	Area (ha)
Deciduous Forest	Dunnning	D	5.58
Extractive	Melvin	D	5.58
High-Density Residential	Codorus	C	5.58
High-Density Residential	Lindside	C	5.58
High-Density Residential	Chester	B	5.58
Industrial	Lindside	C	5.58
Industrial	Hatboro	D	5.58
Institutional	Manor	B	5.58
Large Lot Subd.-Ag	Captina	C	5.58
Large Lot Subd.-Forest	Glenelg	B	5.58
Low-Density Residential	Hollinger	B	5.58
Low-Density Residential	Codorus	C	5.58
Med-Density Residential	Edgemont	B	5.58
Med-Density Residential	Chester	B	5.58
Open Urban	Hatboro	D	5.58
Pasture	Baltimore	B	5.58
Bare Ground	Chester	B	3.72
Brush	Melvin	D	3.72
Brush	Manor	B	3.72
Commercial	Glenelg	B	3.72
Commercial	Codorus	C	3.72

Table A-3 (Cont.)
Land Use and Soil Types in the Beaverdam Run Watershed

Land Use	Soil Type	Hydrologic Group	Area (ha)
Commercial	Melvin	D	3.72
Commercial	Hatboro	D	3.72
Deciduous Forest	Hagerstown	C	3.72
Deciduous Forest	Montalto		3.72
Evergreen Forest	Glenelg	B	3.72
Evergreen Forest	Chester	B	3.72
Extractive	Alluvial		3.72
High-Density Residential	Elioak	C	3.72
High-Density Residential	Hatboro	D	3.72
High-Density Residential	Mine dumps		3.72
Industrial	Alluvial		3.72
Institutional	Glenelg	B	3.72
Large Lot Subd.-Ag	Manor	B	3.72
Low-Density Residential	Captina	C	3.72
Med-Density Residential	Glenville	C	3.72
Open Urban	Lindside	C	3.72
Pasture	Conestoga	B	3.72
Brush	Captina	C	1.86
Brush	Baltimore	B	1.86
Brush	Lindside	C	1.86
Brush	Made land		1.86

Table A-3 (Cont.)
Land Use and Soil Types in the Beaverdam Run Watershed

Land Use	Soil Type	Hydrologic Group	Area (ha)
Brush	Baile	D	1.86
Cropland	Alluvial		1.86
Deciduous Forest	Captina	C	1.86
Deciduous Forest	Lindside	C	1.86
Deciduous Forest	Sassafras	B	1.86
Deciduous Forest	Melvin	D	1.86
Evergreen Forest	Baile	D	1.86
Evergreen Forest	Manor	B	1.86
Extractive	Glenelg	B	1.86
Extractive	Manor	B	1.86
High-Density Residential	Captina	C	1.86
High-Density Residential	Made land		1.86
Industrial	Glenelg	B	1.86
Industrial	Manor	B	1.86
Institutional	Conestoga	B	1.86
Institutional	Glenville	C	1.86
Institutional	Baile	D	1.86
Large Lot Subd.-Forest	Melvin	D	1.86
Low-Density Residential	Melvin	D	1.86
Mixed Forest	Elioak	C	1.86
Mixed Forest	Baile	D	1.86

Table A-3 (Cont.)
Land Use and Soil Types in the Beaverdam Run Watershed

Land Use	Soil Type	Hydrologic Group	Area (ha)
Mixed Forest	Chester	B	1.86
Mixed Forest	Hagerstown	C	1.86
Open Urban	Brandywine	C	1.86
Orchard/Vineyard	Glenville	C	1.86
Orchard/Vineyard	Baltimore	B	1.86
Orchard/Vineyard	Hatboro	D	1.86
Pasture	Brandywine	C	1.86
Pasture	Glenelg	B	1.86
Pasture	Lindside	C	1.86
Pasture	Elioak	C	1.86
Row & Garden Crops	Manor	B	1.86

Table A-4
Land Use and Soil Types in the Difficult Run Watershed

Land Use	Soil Type	Hydrologic Group	Area (ha)
Residential	Glenelg	B	3059.2
Forest	Glenelg	B	2039.5
Forest	Manor	B	899.8
Cropland	Glenelg	B	779.8
Residential	Elioak	C	719.8
Residential	Meadowville	B	719.8
Forest	Chewacla	C	599.8
Residential	Manor	B	599.8
Forest	Mixed Alluvial	D	419.9
Residential	Unknown	U	419.9
Commercial	Unknown	U	419.9
Cropland	Elioak	C	359.9
Forest	Glenville	C	359.9
Forest	Meadowville	B	299.9
Cropland	Chewacla	C	299.9
Cropland	Manor	B	299.9
Residential	Glenville	C	239.9
Residential	Mixed Alluvial	D	239.9
Residential	Beltsville	C	180.0
Cropland	Meadowville	B	180.0
Residential	Orange	D	180.0
Cropland	Mixed Alluvial	D	180.0

Table A-4 (Cont.)
Land Uses and Soil Types in the Difficult Run Watershed

Land Use	Soil Type	Hydrologic Group	Area (ha)
Transportation	Impervious	I	120.0
Built-up	Manor	B	120.0
Cropland	Wehadkee	D	120.0
Residential	Chewacla	C	120.0
Built-up	Elioak	C	120.0
Forest	Elioak	C	120.0
Forest	Fairfax	B	60.0
Residential	Manassas	B	60.0
Construction	Manor	B	60.0
Built-up	Unknown	U	60.0
Built-up	Glenelg	B	60.0
Construction	Unknown	U	60.0
Cropland	Unknown	U	60.0
Forest	Unknown	U	60.0
Cropland	Glenville	C	60.0
Water	Water	W	60.0
None	Glenville	C	60.0
Forest	Wehadkee	D	60.0
Residential	Wehadkee	D	60.0

Hydrologic Group "U" means the hydrologic group is unknown.

Table A-5
Impervious Fraction of Urban Land Uses
(SCS, 1986--*TR55*)

Land Use	Lot Size (acres)	Percent Impervious
Commercial		85%
Industrial		72%
High Density Residential	0.125	65%
High Density Residential	0.25	38%
Medium Density Residential	0.333	30%
Medium Density Residential	0.5	25%
Low Density Residential	1	20%
Low Density Residential	2	12%

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