

AN EXAMINATION OF THE REFERENCE WATERSHED APPROACH  
FOR TMDLS WITH BENTHIC IMPAIRMENTS

by

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## ABSTRACT

An Examination of the Reference Watershed Approach for TMDLs with  
Benthic Impairments

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The Clean Water Act is the primary water quality legislation in the United States. Within the Clean Water Act is a provision to uphold the biological integrity of the nation's waters. The most commonly used tool to meet this provision is biological monitoring. In Virginia, benthic macroinvertebrates are used as the primary indicator of the health of stream biota. Benthic macroinvertebrates are animals without backbones that are visible to the naked eye. When the biota of a given waterbody is unhealthy or impaired, the Total Maximum Daily Load (TMDL) process is initiated. A TMDL represents the loading of a pollutant that a stream can assimilate and still meet water quality standards. Through the TMDL process, the primary stressor(s) on the biota is determined and the necessary reductions to the stressor(s) are calculated. Once the stressor(s) is identified, the reductions of the stressor that are necessary to restore the benthic macroinvertebrate assemblage must be determined. For many of the stressors affecting the benthic macroinvertebrate assemblage, such as nutrients and sediment, no water quality criteria have been established in Virginia. Therefore a method other than criteria-based reductions is required to determine pollutant reductions. The method that is most commonly used for TMDLs developed for benthic impairments in Virginia is the Reference Watershed Approach. In this method, a watershed is located that has similar characteristics to the impaired watershed but does not exhibit a benthic impairment. The unit-area loading of a stressor(s) in the reference watershed is established as the target level for the stressor(s) in the impaired watershed. It is expected that if the stressor load(s) in the impaired watershed can be reduced to the level(s) in the reference watershed, then the benthic community in the impaired watershed will be restored over time.

This research addresses the Reference Watershed Approach aspect of the TMDL process for benthic impairments and the impacts of alternative land use sources, reference watersheds, and water quality model used on the final TMDL. Questions considered in this research include: Do the different land use sources (DOQQ and NLCD) result in different stressor loadings? Does the use of alternative water quality models (GWLF and SWAT) result in different stressor loadings? Is there a difference in stressor loadings when different reference watersheds are used? To answer these questions, Stroubles Creek, a benthically-impaired waterbody on Virginia's 1998 303d list, was selected for study. Sediment is the primary benthic stressor and therefore the target for stressor reductions. Stroubles Creek is located in the Town of Blacksburg in Montgomery County, Virginia.

Study results showed that the land use source used for determining land use parameters, the model used to determine sediment loads, and the reference watershed selected to determine the target load may all have marked effects on resulting stressor load reduction requirements. Using different land use sources, regardless of the reference watershed used, resulted in required stressor reductions that were different by greater than 10%. In one scenario (a given reference watershed being modeled with a single water quality model), the application of one of the land use sources results in 3.5 times greater reductions than application of the other land use source. With respect to water quality model selection, in two of the three scenarios considered (a single reference watershed being modeled using parameters derived from a single land use source) a difference in stressor load reduction requirements of greater than 10% resulted from using different water quality models. In one scenario, 2.8 times greater reductions were required with GWLF modeling than with SWAT modeling. Finally, differences in stressor load reduction requirements are seen when different reference watersheds are used, regardless of the water quality model chosen for load calculation or the land use source applied for parameter development. Different reference watersheds result in a difference of as much as 73% in required reductions of sediment in the impaired watershed. In one scenario, the required reductions from using a particular reference watershed are 6.2 times as great as the required reductions resulting from using a different reference watershed. Since TMDL reports become legal documents, it is crucial to be able to consistently and scientifically determine the required reductions of stressor loading in an impaired watershed.

As a result of the differences revealed in this research, alternatives to the current use of the Reference Watershed Approach must be considered. Possible alternatives include a more objective process for determining the best reference watershed for an impaired watershed, or the development of water quality standards to set the target level for many of the common stressors on the benthic assemblage. Additional options involve the use of regression equations that relate benthic stressors to the RBP II (a biological assessment score) value of a stream, or the averaging of load reduction requirements obtained from using the Reference Watershed Approach on several different reference watersheds for a single impaired watershed.

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*Dedicated to my grandfather*

*Mr. Carl Chapin Osgood*

## *Chapter 1*

### INTRODUCTION

#### **Background**

##### **The Clean Water Act**

In 1972, the United States Congress passed the Federal Water Pollution Control Act (PL92-500; USEPA, 2002). This act and subsequent amendments (collectively referred to as the Clean Water Act or CWA) drastically changed U.S. water quality legislation. Several very important legal structures for water quality protection were established by this law, including the focus of this research: total maximum daily loads or TMDLs. The concept behind TMDLs is the focus of water quality controls on ambient water measurements; that is, attainment of water quality goals is based on measurements of water in a stream or lake, rather than on technology-based controls applied to point sources.

Initial execution of the CWA focused on point sources of pollution such as industrial and municipal wastes, and the quality of the water within the waterbodies themselves was essentially ignored. In the mid-1980's, citizen groups began to sue the Environmental Protection Agency (EPA) for its failure to uphold the ambient water quality goals outlined by the TMDL portion of the CWA. According to the CWA, states are required to develop water quality standards (CWA Section 303a; USEPA, 2002). These standards, which must receive EPA approval, are composed of the designated uses of a water body (such as recreation), the water quality criteria (such as  $6 \leq \text{pH} \leq 9$ ), and the allowable frequency of exceedence that can determine compliance with that designated use. Each state must list waters within their boundaries that do not meet standards and they must develop TMDLs to determine the necessary reductions in pollutants for the waterbody to meet its water quality standard (CWA Section 303d; USEPA, 2002).

The TMDL process involves the following steps:

1. Selection of the pollutant to consider for TMDL development.
2. Estimation of the waterbody assimilative capacity.
3. Estimation of the pollutant load from all sources to the waterbody.
4. Predictive analysis of pollution in the waterbody and determination of total allowable pollution load.
5. Allocation (with a margin of safety) of the allowable pollution among the different pollution sources in a manner that water quality standards are achieved. (USEPA, 1991)

In Virginia, the TMDL process does not end with the allocation of necessary pollutant load reductions (step 5 in the above list) and the production of the TMDL report. Virginia also requires the development and execution of an implementation plan through its 1997 Water Quality Monitoring, Information, and Restoration Act (Code of Virginia 62.1-44.19:4-8; Virginia General Assembly, 1997). During implementation, the methods and locations for the most effective and efficient reductions are determined, and a plan is developed to make the physical changes within the watershed (such as restricting cattle access to a stream or planting vegetative filter strips) that are necessary to achieve the stressor reductions. Following implementation, continued monitoring must occur to determine if the TMDL process and its implementation have successfully brought the waterbody into compliance with the standard. Implementation plan development is not considered in this research.

Along with numerical water quality criteria for specific parameters, the Commonwealth of Virginia has a narrative (qualitative) general standard for water quality, which reads in part as follows (9-VAC-25-260-20; Virginia General Assembly, 1998):

*“All state waters... shall be free from substances...which are inimical or harmful to human, animal, plant, or aquatic life.”*

The Virginia Department of Environmental Quality (DEQ) examines the benthic macroinvertebrate assemblage in an effort to determine if Virginia's streams meet the general standard. Benthic macroinvertebrates are the invertebrate subset (mainly insect larvae, crustaceans, and worms) of the community living on a stream bottom. The characteristics of this community subset (or assemblage) change measurably when a stream is impaired by pollutants or environmental stressors. Therefore, when the benthic macroinvertebrate assemblage in a waterbody has the characteristics of an unhealthy assemblage, the general

standard is not met. As of May 2004, a stream in Virginia is designated as “benthically impaired” when comparison of the benthic macroinvertebrate assemblage from the stream in question to the benthic macroinvertebrate assemblage in a non-impaired reference site reveals an impaired assemblage. A benthically-impaired stream shows differences in the number, diversity, and pollution tolerance of the macroinvertebrate taxa compared to the reference stream.

A biological assessment of a waterbody, such as an assessment of the benthic macroinvertebrate assemblage, demonstrates a broader temporal picture than a chemical assessment, since the effects of pollution on the biological community are longer-lived. It is not surprising, therefore, that the biological community is considered “one of the best indicators of potential for beneficial use of a water resource” (Karr, 1989). Biological indicators can serve as “sentinels” for a water quality problem that is not defined by chemical or physical water quality criteria or detected by commonly measured water quality parameters. Non-native species, flow regime changes, and sedimentation are examples of pollutants and environmental stressors with no criteria (USEPA, 2000). These and other stressors can have detrimental effects on native biota. A stream with an impaired biological community fails to comply with the biological requirements of the CWA.

### **The Benthic TMDL Process**

The process to develop TMDLs for benthic impairments (hereafter referred to as benthic TMDLs) in Virginia is relatively new, with the first benthic TMDL approved in June 2002. As of February 2004, the EPA had approved twenty benthic TMDLs for Virginia (VADEQ, 2004). A full half of those reports were approved very recently, in 2003 or in January of 2004. The process of developing a benthic TMDL is inherently different from the process of developing other TMDLs. A TMDL based on a specific pollutant with a numeric water quality criterion, such as fecal coliform, has already identified the pollutant that must be reduced. In the benthic case, however, an unhealthy benthic assemblage is the indication of a problem, not the problem itself.

The main components of the benthic TMDL process are defined below in relation to the EPA list of steps in the TMDL process.

1. *Selection of the pollutant to consider for TMDL development.* An impaired benthic assemblage is an indicator that a pollutant(s) is “stressing” the stream, but the biota does not pinpoint the problem itself (USEPA, 2000). Sometimes the number and type of organisms present in an assemblage (the “metrics”) can offer clues to the cause of the impairment, but they do not reveal a definitive answer. This part of the benthic TMDL process, in which the cause(s) of the benthic impairment is determined, is called the Stressor Analysis. Stressor Analysis is used to compile data from the benthic metrics, the chemical ambient water quality measurements, and the physical habitat evaluations to determine the most likely stressor(s) and the stressor(s) that will be targeted in the TMDL. Available water quality data, such as dissolved oxygen, habitat quality, and nutrient information must be analyzed in conjunction with the benthic metrics in order to relate pollutants and environmental stressors to the impairment revealed in the benthic samples. Although multiple stressors may be contributing to the benthic impairment, Stressor Analysis is used to select the primary stressor(s) that will become the basis for the TMDL (USEPA, 2000).
2. *Estimation of the waterbody assimilative capacity.* For many of the stressors on the benthic assemblage, no numeric water quality criteria exist. In the absence of numeric criteria, one method to determine the target stressor loadings is the Reference Watershed Approach. In this method, a watershed is selected that is unimpaired, but otherwise similar to the impaired watershed. The calculated stressor loadings from this reference watershed establish the target load for the stressor in the impaired watershed.
3. *Estimation of the pollutant load from all sources to the waterbody.* Stressor loadings are typically determined using computer models. These models estimate loads using parameters based on land use, soil type, and other watershed characteristics. Both point sources and nonpoint sources are considered.
4. *Predictive analysis of pollution in the waterbody and determination of total allowable pollution load.* Required reductions of stressor loads necessary to meet the TMDL are calculated.

5. *Allocation (with a margin of safety) of the allowable pollution among the different pollution sources in a manner that water quality standards are achieved.* A number of scenarios are determined to provide different options for source reductions. (USEPA, 1991).

The final goal of the benthic TMDL is the restoration of a healthy benthic assemblage in the waterbody, which brings the waterbody back into compliance with the Virginia general standard for water quality (Benham et al., 2003).

### **Goals and Objectives**

The goal of this study was to examine the estimation of the “waterbody assimilative capacity” of a benthically-impaired stream. For a TMDL based on a benthic impairment, this estimation is determined using the Reference Watershed Approach. The specific objectives were to:

1. Assess the variability in stressor reduction requirements for the impaired watershed based on different sources of land use information.
2. Assess the variability in stressor reduction requirements for the impaired watershed based on the use of alternative water quality models.
3. Assess the variability in stressor reduction requirements for the impaired watershed based on the use of different reference watersheds.

## *Chapter 2*

### LITERATURE REVIEW

#### **The Clean Water Act and Virginia Water Quality Standards**

An important legal structure established by the Federal Water Pollution Control Act is the concept of total maximum daily load (TMDL) (CWA Section 303d; USEPA, 2002), which seeks to control nonpoint sources of pollution in cases where control of point sources did not result in attainment of water quality standards. The TMDL for a waterbody considers ambient water quality, taking into account point sources (National Permitted Discharge Elimination System, or NPDES, permitted discharges), unpermitted nonpoint sources, and natural background sources of contaminants, as well as a margin of safety.

From the implementation of the Clean Water Act (CWA) until the mid-1980s, states focused their attention on point sources of pollution. Point source pollution enters a stream or waterbody mainly from pipes. Such sources are relatively easy to monitor and remedy, in comparison to their nonpoint source counterparts, because the direct effluent from the pipe can be quantified, and the source of the pollutant can be managed where it is produced. Sewage treatment plant effluent and industrial wastewater are two examples of point source pollution.

The mid-1980s through the 1990s saw a series of lawsuits brought by citizen groups against the United States Environmental Protection Agency (EPA), the organization responsible for upholding the CWA, based on the continuing poor quality of the nation's waters. Although pollutant levels of effluents entering waterbodies had been reduced through regulatory focus on point sources of pollution using the National Pollutant Discharge Elimination System (NPDES), the actual quality of the water within the waterbodies themselves had largely been ignored (USEPA, 1992). Based on the CWA, states are required to develop water quality standards which must be approved by the EPA (CWA Section 303a; USEPA, 2002). These standards are composed of 1) the designated uses of a water body (such as shellfish production or swimming) and 2) the water quality criteria (such as  $6 \leq \text{pH} \leq 9$  or dissolved oxygen  $\geq 4\text{mg/L}$ ) that determine compliance with the designated use. The agency responsible for

environmental quality in each state (e.g. Virginia Department of Environmental Quality, DEQ) must list waters within state boundaries that do not meet the designated standards. They then must develop a plan to determine the necessary reductions of each pollutant in a waterbody to meet the standard (CWA Section 303d; USEPA, 2002). This plan is called a TMDL, or total maximum daily load. The lawsuits brought against the EPA were settled with consent decrees through which EPA was required to show progress toward improved water quality through the TMDL process. Although states are responsible for their own standards, if the states fail to meet the requirements of the CWA, the CWA requires the EPA to assume this responsibility and to develop TMDLs.

The term “Total Maximum Daily Load” refers to two distinct but related entities (USEPA, 1991). The first is a number: the maximum pollutant load (for a single specific pollutant) that a waterbody can receive without violating water quality standards. The second definition of a TMDL is the process used to develop the numeric TMDL: watershed analysis, determination of the sources and quantity of the pollutant(s) causing the impairment, and calculation of the changes needed to reach the water quality standard. The latter process generates the TMDL report.

The Commonwealth of Virginia makes the following statement regarding designated uses of the waters in Virginia (9-VAC-25-260-10; Virginia General Assembly, 1998):

*“All state waters, including wetlands, are designated for the following uses: recreational uses, e.g., swimming and boating; the propagation and growth of a balanced, indigenous population of aquatic life, including game fish, which might reasonably be expected to inhabit them; wildlife; and the production of edible and marketable natural resources, e.g., fish and shellfish.”*

In order to support these designated uses, Virginia adopted both numeric and narrative (qualitative) water quality criteria. Numeric criteria exist for parameters such as dissolved oxygen, pH, temperature, fecal coliform, and a number of toxic substances. In addition to these water quality criteria, Virginia also has a narrative general standard for water quality (9-VAC-25-260-20; Virginia General Assembly, 1998):

*“All state waters, including wetlands, shall be free from substances attributable to sewage, industrial waste, or other waste in concentrations, amounts, or combinations which contravene established standards or interfere directly or indirectly with designated uses of such water or which are inimical or harmful to human, animal, plant, or aquatic life.”*

This general standard specifies that the biological integrity of a waterbody is as crucial as its chemical integrity, reflecting ideas delineated in the CWA. The DEQ examines the integrity of the benthic macroinvertebrate assemblage to determine compliance with the general standard.

For some impairments, such as pathogen indicators (e.g. *E. coli*) or toxics, the goal of the TMDL process is to determine the pollutant reductions required to bring the waterbody back into compliance with applicable water quality standards. The goal of a benthic TMDL is to restore the benthic assemblage to a non-impaired state; however, the process is more complicated because the cause of the impairment is not specified. Consequently, the TMDL process for a benthic impairment includes an analysis to first determine the cause(s) of the impairment and then to calculate the necessary reductions in the parameter(s) causing the impairment.

### **Biomonitoring**

Scientists have long recognized the advantages of assessing the biological integrity of a water body. Chemical or physical assessment of a stream takes a snapshot of the water quality at the moment sampled, while a biological assessment demonstrates a more extensive temporal picture, since the effects of pollution on the biological community are longer-lived (Karr, 1989). Consider a stream that receives an episodic slug of a highly toxic chemical pollutant, but the pollutant is quickly washed downstream. Chemical monitoring after the pollutant is washed downstream will not indicate a problem, but the biological community may still show the effects (Walker et al., 2002). The goal of biological monitoring “should be to detect significant changes in ecosystems, not minor fluctuations that are quickly dampened” (Cairns and Pratt, 1993). In addition to being a better indicator of long-term water quality, the health of the biological community is useful in detecting pollutants and environmental stressors that do not have defined water quality criteria. In these instances, stream biota can indicate water quality

problems caused by chemical and physical stressors with or without defined water quality criteria. The National Research Council, in their 2001 assessment of the TMDL process, writes that “in general, biological criteria are more closely related to the designated uses of waterbodies than are physical or chemical measurements.” (NRC, 2001) These “designated uses” are related to the ecological services provided by a waterbody – fish for consumption, clean drinking water, waste assimilation, wildlife habitat – which are available for the cost of appropriately managing the ecosystem containing the waterbody (Cairns and Pratt, 1993). Biological monitoring of benthic macroinvertebrates helps ensure that these designated uses are maintained. An additional advantage to monitoring the biological integrity of a water body is the connection that can be made to the public, who ultimately must support watershed management changes. People without a scientific background may not relate to certain chemical parameters, but the benefits of a water body that supports healthy animal and plant communities is understood by many individuals (USEPA, 1999).

The CWA includes phrasing that requires information-gathering of “factors necessary to restore and maintain the chemical, physical, and biological integrity of all navigable waters, ground waters, waters of the contiguous zone, and the oceans” (CWA Section 304a(2); USEPA, 2002). By including “biological integrity” in its wording, the CWA necessitates biological monitoring. Current practices for biological monitoring of aquatic systems are based on the early twentieth century work of Kolkwitz and Marsson (1908). These ecologists described the biological communities found in waters with varying degrees of organic pollutants. They concluded that species composition was affected by water quality and developed the Saprobien System, which describes the distribution of species across a gradient of contamination. From this early index of biological monitoring, other systems and formulas have been developed for qualitative and quantitative measurements of the biotic condition. (Voshell, 2002)

The most commonly used biological monitoring approach in the United States is the Rapid Bioassessment Protocol (RBP), developed by the EPA in the late 1980s (Plafkin et al., 1989). The RBP outlines methods for selecting monitoring procedures for different types of waterbodies, describes data analysis options, and includes methods for evaluating results. In a 1999 biomonitoring guidance document (Barbour et al., 1999), the EPA no longer provides an

exact “recipe” for a biological monitoring study, but rather suggests that the monitoring organization select an appropriate option for the study site in question. As a result of this second edition regarding the rapid bioassessment protocol, this method is currently known as RBP II. The most common design for sampling is single habitat sampling of a riffle with a D-frame dip net. Macroinvertebrate identification is done in the laboratory to the family or lowest possible identification level. Analysis usually involves comparison of region-appropriate metrics between an impaired site and an unimpaired reference site. As of Spring 2004, the DEQ used the RBP II method for sampling and assessment of the biological integrity of Virginia waters. (Voshell, 2002)

### **The Reference Watershed Approach**

When a series of benthic macroinvertebrate samples from a watershed are moderately or severely impaired, the watershed is listed as required by the CWA with a benthic impairment. Before a target pollutant load can be determined, the target pollutant (or stressor) must be determined. Examination of possible stressors with the objective of linking these possible stressors to the benthic assemblage health is called stressor analysis. During this stage of benthic TMDL development, data from the benthic metrics, the chemical ambient water quality measurements, and the physical habitat evaluations are compiled to determine which stressor(s) will be targeted for the TMDL.

Once the stressor(s) is identified, individual sources are identified, the existing total stressor load is calculated, and then the stressor reductions necessary to restore the benthic assemblage must be determined. For many potential stressors, such as sediment and nutrients, Virginia currently has no water quality criteria, and an indirect method is therefore necessary to determine required reductions in stressor loads or conditions. Most of the approved benthic TMDLs in Virginia have used the Reference Watershed Approach to determine the target stressor load, and this approach is one of the options suggested by the EPA (USEPA, 1999). In this approach, an unimpaired “reference watershed” is identified that has similar characteristics (e.g. ecoregion and climate) to the impaired watershed except that it does not exhibit a benthic impairment (USEPA, 1999). The stressor loading in the reference watershed is used to establish the target load for the stressor(s) in the impaired watershed. Since the reference watershed is non-

impaired, its relative stressor load is somewhat less than, and therefore a conservative estimate of, a threshold at which the benthic assemblage becomes impaired. Based, therefore, on the concept that the same level of stressor loading in a different stream will also not affect the benthic assemblage, it is assumed that if the stressor load(s) in the impaired watershed is reduced to the level(s) in the area-adjusted reference watershed, then the benthic assemblage in the impaired watershed will be restored (Benham et al., 2003).

### **Modeling and Benthic Impairments**

Calculating the loadings of the stressor(s) in an impaired watershed and in reference watersheds is usually accomplished using computer models. A model is “a way of capturing some aspects of a particular reality within the framework of a mathematical apparatus that provides... a means for exploring the properties of the reality mirrored in the model.” (Casti, 1992) Computer modeling of nonpoint source pollution and water quality allows for estimation of pollutant loadings into a waterbody and pollutant processes within a waterbody. A number of models exist with different data requirements, computational complexity, and processes simulated. For TMDL development, a single model is typically selected and used to determine the existing and allowable stressor loading to the waterbody.

In an assessment of watershed-scale models, the EPA (USEPA, 1992) categorized models into “simple,” “mid-range,” and “detailed” models according to the complexity of processes employed and the level of detail within the model. Simple models use empirical equations and describe a limited number of processes. Their application is limited to the areas with similar characteristics to the location in which they were developed. Mid-range models are usable for watershed-level planning. The Generalized Watershed Loading Functions model (GWLF) is an example of a mid-range model. Detailed models include degradation and transformation processes, unlike the simple and mid-range models. Their equations are more physically-based, attempting to actually simulate hydrologic and pollutant transport processes. In addition to watershed-level planning, these models may be useful for design of pollution control systems. Detailed models require greater detail of input parameters. The Soil and Water Assessment Tool (SWAT) model is an example of a detailed model. (USEPA, 1992)

Characteristics of the watershed being modeled, such as land use, soil type, and climate, are used to develop model input parameters. These parameters are then used by the equations that describe the processes such as hydrology and pollutant movement. Hydrologic simulation models can be classified as lumped or distributed. In lumped models, the parameters are aggregated across heterogeneous areas. That is, the watershed is considered as a homogeneous unit with a single value assigned to each necessary parameter. Lumped parameter models may consider a variety of land use-soil combinations, called hydrologic response units or HRUs, but the spatial arrangement of these areas are not considered. In a distributed model, the values of each parameter vary across the landscape and the spatial distribution of the parameters is relevant. Distributed models are more realistic, taking into consideration the natural variability in a watershed; the model calculations, however, are more complex and data requirements are greatly increased. In an effort to combine the realistic spatial variability in a watershed with the simplicity and practicality of lumped parameter models, semi-distributed models divide watersheds into subbasins, within which parameters are lumped. A semi-distributed model simulates processes in and pollutant losses from each subbasin and then the subbasin outputs are integrated to simulate overall watershed response. When using a lumped parameter model or when considering a single subbasin in a semi-distributed model, spatial variability within the HRU is not simulated.

In Virginia, 15 of the 22 benthic TMDL reports approved by EPA, and 19 of the 20 draft (awaiting EPA approval) benthic TMDL reports (as of March 2004) identified sediment as the primary stressor (VADEQ, 2004). Consequently, models that simulate sediment loadings have been required to develop the majority of benthic TMDLs in Virginia. The following sections describe two watershed-scale models that have been used to estimate sediment loadings to and within streams for the development of benthic TMDLs.

### **Generalized Watershed Loading Functions Model (GWLF)**

The Generalized Watershed Loading Functions model (GWLF) was developed at Cornell University (Haith, 1985). The sediment component of this model was developed to predict sediment loading into streams using parameters that do not require calibration and that are obtainable from readily accessible data sources. GWLF uses sediment delivery ratios and the

parameters required by the USLE. The soil erosion process modeled in GWLF is based on 1) soil detachment by rainfall, 2) transport by rainfall, 3) soil detachment by runoff, and 4) transport by runoff (Meyer and Wischmeier, 1969). GWLF has been used in many TMDLs in Virginia (VADEQ, 2004) and has also been used in TMDL development in other states (such as Ohio and Mississippi; Ohio EPA, 2002 and TetraTech, 2003). This model was used in Virginia's "Biennial Nonpoint Source Pollution Water Quality Assessment Report: September, 2002" (Yagow et al., 2002). The EPA (USEPA, 1992) categorizes GWLF as a mid-range model. The model calculations are based on a daily time step, it includes both urban and rural land use types, and it simulates runoff and baseflow with a tolerable degree of accuracy (USEPA, 1992).

#### Use and Limitations

The GWLF sediment component is designed for evaluating short-term (several months to several years) sediment yields. The model does not consider flow routing, and therefore is inappropriate for large heterogeneous watersheds. However, if a large heterogeneous watershed can be broken down into reasonably homogeneous subbasins, these smaller subbasins can be modeled individually and the overall watershed yield can be obtained by summing the subbasin yields after adjusting yields with subbasin-based sediment delivery ratios. Since GWLF uses a daily time step in evaluating the water balance, sediment yield calculations are also daily. However, since flow routing is not considered, the monthly aggregation of daily yields is more accurate than the individual daily yields, and the daily yields are not included in output. (Haith, 1985)

The original GWLF model developed by Haith (1985) does not consider channel erosion. A channel erosion component was added to AVGWLF (a version of GWLF interfaced with the GIS program ArcView™ by ESRI) by researchers at Penn State (Evans et al., 2003). Although the AVGWLF interface was developed with data specific to Pennsylvania, the channel erosion equations are not state-specific. These equations were modified and incorporated into the GWLF model by Dr. Gene Yagow at Virginia Tech (Yagow, 2003). The addition of a channel erosion module improves model usefulness, particularly in areas where channel erosion is a significant contributor to overall sediment loads in a stream (Haith, 1985).

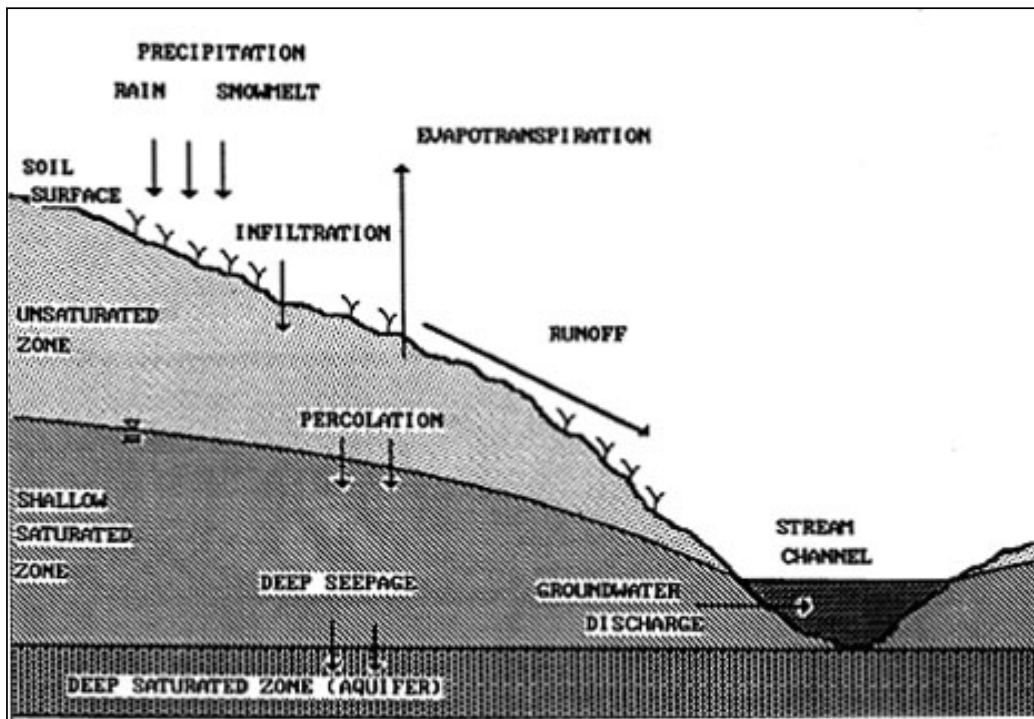
### Accuracy and Validation

The sediment component of the GWLF model was validated by Haith (1985) on the 850-km<sup>2</sup> West Branch Delaware River watershed in southern New York. The watershed was lumped as one unit and parameter values were aggregated by techniques such as area-weighting. Observed monthly sediment yields were compared to modeled monthly sediment yields. The modeled yields are approximately 18% higher than the observed yields, and the standard deviation for the modeled values was slightly higher than for the observed values. However, the correlation coefficient was very high, 0.945, indicating that the model explained 94.5% of the variability in the observed data. (Haith, 1985) Results from modeled streamflow explain 88% of the variability in the observed data, with the poorest accuracy during low flows (Haith et al., 1992).

Although GWLF was developed for use in ungaged watersheds, some users recommend calibration (Dai et al., 2000). Mostaghimi et al. (2003) reduced percent error between simulated and observed monthly runoff by 18% through calibration on Linville Creek. GWLF has been used for sediment load calculations without calibration in numerous TMDLs for ungaged watersheds including the Stroubles Creek TMDL in Virginia and the Lake Washington TMDL in Mississippi (VADEQ, 2003; TetraTech, 2003).

### GWLF Hydrology Submodel

The hydrology simulation in the GWLF model is driven by precipitation. Figure 2.1 demonstrates the fate of precipitation transfer in and out of the available water storage zones as modeled in GWLF.



(Haith et al., 1992)

Figure 2.1. GWLF Hydrology and Storage Zones.

Surface runoff volume for both urban and rural areas is determined using the Soil Conservation Service (SCS) curve number method (USDA, 1986) as:

$$Q_{\text{surf}} = \frac{(R_{\text{day}} - 0.2S)^2}{(R_{\text{day}} + 0.8S)}$$

where  $R_{\text{day}}$  = rainfall depth (plus snowmelt) for the day, and

$$S = 25.4 \left( \frac{1000}{\text{CN}} - 10 \right)$$

where CN = the curve number for the day.

Eq. 2.1

The curve number, a function of soil type and land use, is adjusted for antecedent soil moisture (determined by antecedent rainfall), and snowmelt is determined based on temperature and

considered in the total rainfall depth. The water that does not runoff of the surface infiltrates into the unsaturated soil zone. The water balance in this upper soil zone is determined by the addition of infiltrated water and the subtraction of water due to evapotranspiration and/or percolation into the shallow saturated soil zone. Evapotranspiration is a function of potential evapotranspiration, land cover, and the available soil moisture in the unsaturated soil zone. Potential evapotranspiration is calculated using an equation from Hamon (1961) requiring daylight hours, saturated water vapor pressure, and air temperature. Percolation into the saturated soil zone occurs when available water is greater than the water holding capacity of the unsaturated zone. Other factors in the water balance for the saturated soil zone include groundwater discharge into the stream (based on a recession coefficient) and flow to the deep seepage zone (based on a seepage coefficient). Water that enters the deep seepage zone is lost from the system. The stream channel is fed by groundwater discharge from the shallow saturated zone and by surface runoff. (Haith et al., 1992)

*GWLF Erosion Model*

Erosion from pervious land surfaces is calculated using the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). The USLE calculates average annual soil loss and GWLF converts that average annual value to a daily value, such that (Haith, 1992):

$$X_{\text{day}} = RE \times K_{\text{USLE}} \times LS_{\text{USLE}} \times C_{\text{USLE}} \times P_{\text{USLE}} \times A$$

where

$X_{\text{day}}$  = sediment generated per day

RE = Rainfall erosivity factor for a given day,

$K_{\text{USLE}}$  = USLE soil erodibility factor,

$LS_{\text{USLE}}$  = USLE topographic factor,

$C_{\text{USLE}}$  = USLE cover and management factor,

$P_{\text{USLE}}$  = USLE support practice factor, and

A = source area.

Eq. 2.2

The rainfall erosivity factor is a function of daily rainfall and varies with location. Monthly sediment loss generated by the land surface in the watershed is determined by multiplying monthly erosion (sediment potentially available for transport) estimated using the USLE and a

sediment delivery ratio (SDR), a user-generated input parameter, based on watershed area, representing the fraction of detached sediment that will exit the watershed (Haith, 1992). The calculation for SDR is shown in Equation 2.3.

$$\begin{aligned} \text{SDR} &= 5 \times 10^{-6} (\text{area}^2) - 1.4 \times 10^{-3} (\text{area}) + 0.198 && \text{for area} < 50 \\ \text{SDR} &= 0.4518 (\text{area}^{-0.298}) && \text{for area} > 50 \end{aligned} \quad \text{Eq. 2.3}$$

where SDR = sediment delivery ratio

and area = watershed area (km<sup>2</sup>)

A runoff transport factor, equivalent to the runoff to the 5/3 power, determines monthly distribution of sediment transport to the watershed outlet (Meyer and Wischmeier, 1969).

Sediment generation from impervious land sources is determined by a build-up/wash-off routine (Haith, 1992). Sartor and Boyd (1972) developed exponential equations describing both build-up and wash-off of sediment on impervious surfaces that are used by the GWLF model. Alterations were made by Yagow (2003) to the original GWLF model to include the sediment produced from impervious areas in the total sediment load generated by the watershed, rather than only using this information for calculating nutrient loads.

Although channel (stream bank) erosion was not considered in the original GWLF model, a channel erosion component has been added to later versions of the model. This calculation, developed at Penn State (Evans et al., 2003), determines lateral erosion rate of a stream bank, which is a function of the mean monthly stream flow, percent urban land, animal density, curve number, soil erodibility, and slope. The lateral erosion rate is multiplied by the length of stream with livestock access, the average channel depth, and an average soil bulk density to determine the average sediment load produced by stream bank erosion.

The final monthly sediment yield generated by GWLF considers the soil detached from the land surface (USLE and build-up/wash-off), the potential for that soil to travel across the land surface and reach a stream (SDR and transport factor), and stream bank erosion.

### **The Soil and Water Assessment Tool (SWAT)**

The Soil and Water Assessment Tool (SWAT), was developed by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) at the Grassland, Soil, and Water Research Laboratory in Temple, Texas (Neitsch et al., 2002b). The SWAT model descended primarily from two simpler models: the Simulator for Water Resources in Rural Basins (SWRRB) model and the Routing Outputs to Outlet (ROTO) model. ROTO's primary function was to allow multiple SWRRB runs to be linked together; SWRRB is "a continuous time step model that was developed to simulate nonpoint source loadings from watersheds." (USEPA, 1992) In addition to these two parent models, SWAT contains components of CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Leonard et al., 1987), and EPIC (Erosion-Productivity Impact Calculator) (Williams et al., 1984). The first version of SWAT was released in the early 1990s and has since undergone numerous revisions (Neitsch et al., 2002b). The SWRRB predecessor to SWAT was classified as a detailed model by EPA (USEPA, 1992).

SWAT is a semi-distributed-parameter model developed for simulating large, complex watersheds over a long time period (Neitsch et al., 2002b). Like GWLF, SWAT is a continuous-simulation model with a daily time-step. Unlike GWLF, SWAT is semi-distributed, allowing for the simulation of multiple subbasins and their interactions. SWAT has the capacity to calculate outputs for each subbasin and then to route water from the subbasins and through the channel system. Output is summarized on a daily, monthly, or annual basis. An additional benefit of SWAT over GWLF is that SWAT considers in-stream processes. The sediment, nutrients, pesticides, and water that get to the channel from the land surface can then undergo processes within the channel itself (Neitsch et al., 2002a).

AVSWAT is an interface of the SWAT model with ArcView 3.x (ESRI™) Spatial Analyst (DiLuzio et al., 2002). Use of a geographic information system (GIS) software is valuable in determining model parameters, and the AVSWAT interface allows the user to evaluate values for the necessary parameters and creates the model input files automatically.

### Use and Limitations

The SWAT model was developed to “predict the effect of management decisions on water, sediment, nutrient and pesticide yields with reasonable accuracy on large, ungaged river basins” (Arnold et al., 2002). It has been used to evaluate management decisions in a number of studies, including a study of Best Management Practices (BMPs) for dairy waste and municipal wastewater on the water quality in the impaired North Bosque River Watershed in central Texas (Santhi et al., 2001). A study in the Rock River Basin in southern Wisconsin successfully used SWAT to evaluate two specific BMPs: change from conventional tillage to conservation tillage and change of fertilizer application rates from a high level to a recommended level (Kirsch et al., 2002).

SWAT is not effective for modeling individual storms, but rather for providing long-term analysis of watershed processes (Neitsch et al., 2002b). The model is applicable to medium sized watersheds (of a few hundred square miles) to large watersheds (thousands of square miles) (Neitsch et al., 2002a; Neitsch et al., 2002b). Although no limit is imposed for the number of subbasins created in a watershed, the subbasins should be large enough to be suitable for the equations employed by SWAT but small enough to show the variability within a watershed. The SWAT development team recommends between 1 and 10 hydrologic response units (HRUs) in a subbasin (Neitsch et al., 2002a). An HRU is a unique soil-land use combination.

SWAT is intended for use in ungaged watersheds and therefore without calibration (Neitsch et al., 2002a). However, in many studies where observed data is available, hydrologic calibration is used to improve model performance. Both studies referenced above (Santhi et al., 2001 and Kirsch et al., 2002) calibrated SWAT to improve model performance.

### Accuracy and Validation

The SWRRB component of the SWAT model was used (before SWAT was developed) to model the effects of urbanization on water yields, peak flow rates, and sediment yields in the White Rock Lake watershed in Dallas, Texas. Based on observed data from five sediment surveys over the course of 50 years, a comparison between simulated and observed values show

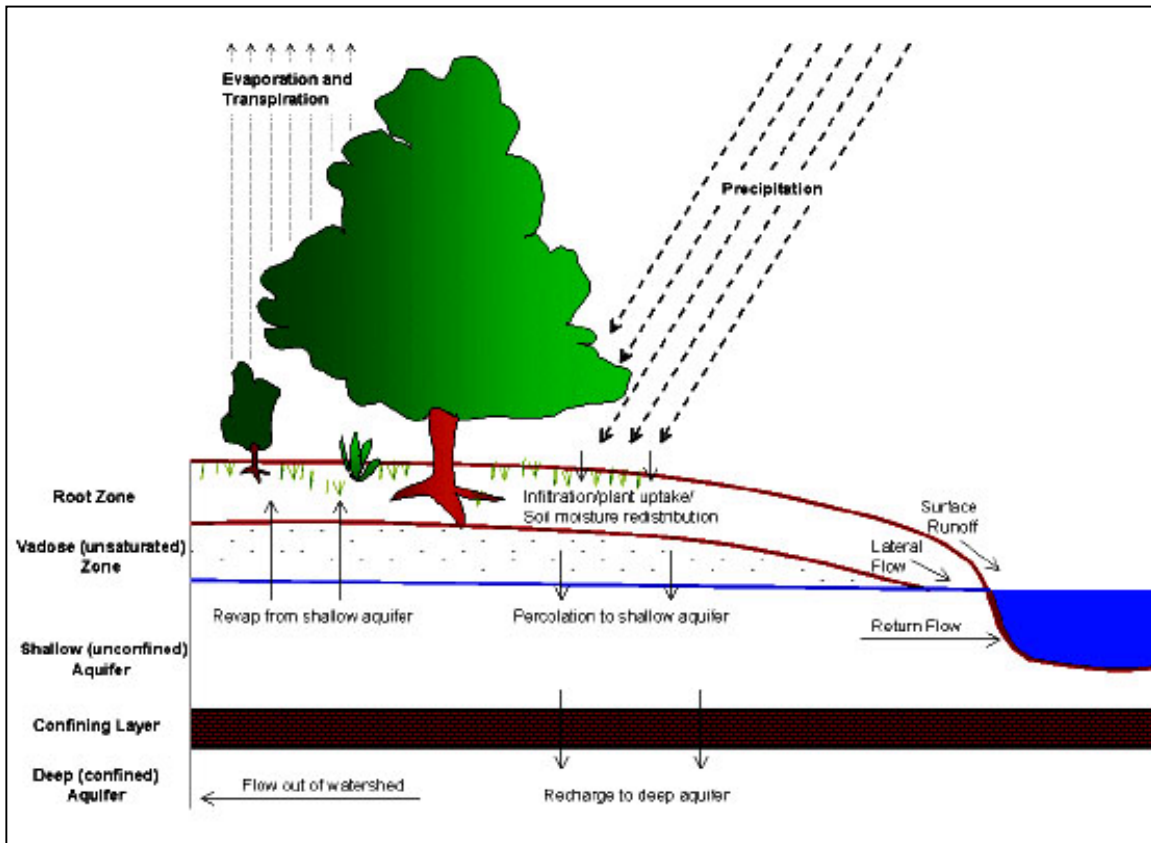
that the model did “a reasonable job predicting the effect of urbanization on these variables” (Arnold and Williams, 1995).

Two studies of SWAT considered the effects of the number of subbasins. The first (Bingner et al., 1997) reported that total annual runoff was not significantly affected by the number of subbasins delineated in a single watershed, but that the annual sediment yield did increase significantly as the number of subbasins delineated increased (that is, as the area in each subbasin decreased). The sediment variation plateaus at a high number of subbasins, such that further increase in subbasin numbers does not increase the sediment yield. Bingner et al. attributed the increase in sediment yield to two major factors. First, as the number of subbasins increases, the average subbasin slopes increase; second, as the number of subbasins increases, the number of subbasins with crop land area, which contributes relatively high sediment yields, as a significant contributor to overall land use increases. Since the cropland area, although significant, is distributed in small parcels across the watershed, it is averaged out in the larger subbasins. These conclusions conflict with those of a second study (FitzHugh and Mackay, 2000) that found that while sediment *generation* varies with the number of subbasins (sediment generation with more subbasins is 44% lower than with fewer subbasins), sediment *reaching the outlet* was not significantly different. Their rationale for this is that the watershed in their study is “transport-limited,” that is, the stream channel cannot transport all the sediment generated on the land. FitzHugh and Mackay explain that the reason their results differ from Bingner et al.’s results is probably due to the difference in channel transport equations between the versions used by the two different research teams. Regardless of specific results, it is notable that subbasin delineation may affect sediment yield results.

#### SWAT Hydrology Model

In SWAT, runoff is divided into two phases: the land phase, which controls runoff to channels, and the routing phase, which controls routing in channels. The land phase is based on a water balance. Precipitation can either be intercepted by vegetation or reach the land surface. Water that reaches the land surface can runoff or infiltrate into the root zone and the unsaturated zone. Water can be exchanged between this upper soil layer and the unconfined aquifer layer below, or it can move as lateral flow into the main channel. From the unconfined aquifer, water can be

transported into the main channel as return flow or recharge the deep aquifer. As in the deep saturated zone in GWLF, water in SWAT's deep aquifer is lost from the system (Neitsch et al., 2002b). The processes of the land phase of the hydrologic cycle are illustrated in Figure 2.2. During the channel routing phase water may be lost via evaporation or seepage, or added via rainfall and baseflow.



(Neitsch et al., 2002b)

**Figure 2.2. SWAT Hydrologic Cycle: Land Phase.**

SWAT offers two procedures for determining runoff volume: the SCS curve number method, and the Green and Ampt infiltration method (Neitsch et al., 2002a). The Green and Ampt method requires break-point precipitation data, which is not as widely available as the daily precipitation data required by the SCS curve number method. The SCS curve number method for determining surface runoff volume is described in the hydrology section of the GWLF

model (Eq. 2.1). As in the GWLF model, SWAT adjusts the curve number based on antecedent precipitation.

Peak runoff rate, used in estimating erosion and sediment yield, is calculated with a modified rational method as a function of area, runoff volume, time of concentration, and the fraction of daily rainfall that occurs during the time of concentration. In the model, the surface runoff volume and the peak runoff rate are determined for each HRU. (Neitsch et al., 2002b)

#### SWAT Erosion Model and Channel Transport

Erosion in SWAT is computed using the Modified Universal Soil Loss Equation (MUSLE) (Neitsch et al., 2002b), shown below:

$$X_{\text{day}} = (Q_{\text{surf}} \cdot q_{\text{peak}} \cdot \text{area}_{\text{hru}})^{0.56} \times K_{\text{USLE}} \times C_{\text{USLE}} \times P_{\text{USLE}} \times LS_{\text{USLE}} \times \text{CFRG}$$

where

$X_{\text{day}}$  = sediment generated per day,

$Q_{\text{surf}}$  = surface runoff volume,  
 $q_{\text{peak}}$  = peak runoff rate,  
 $\text{area}_{\text{hru}}$  = area of the HRU, } runoff factor

Eq. 2.4

$K_{\text{USLE}}$  = USLE soil erodibility factor,

$C_{\text{USLE}}$  = USLE cover and management factor,

$P_{\text{USLE}}$  = USLE support practice factor, and

CFRG = the coarse fragment factor.

MUSLE (Williams, 1975) determines sediment yield using the same parameters as the original USLE except that the rainfall erosion factor is replaced by a runoff factor. The energy that governs the transport of eroded sediment in flow across the land surface is dependent on runoff variables in MUSLE, while this energy is a function of rainfall in the original USLE (Williams, 1995). With this method, the sediment delivery ratio is incorporated into the equation and does not need to be specified separately.

In SWAT, sediment in the main channel can be deposited or the stream channel can degrade (Neitsch et al., 2002b). The transport capacity of the channel is simplified from the stream

power equation proposed by Bagnold (1977), and is a function of the peak channel velocity (which in turn is a function of the peak flow rate and channel cross-sectional area). The maximum sediment concentration that can be transported by water, based on the transport capacity, is compared to the sediment concentration in the channel at the beginning of the time step to determine whether sediment is being deposited or the channel is degrading (Neitsch et al., 2002b). The sediment at the watershed outlet is therefore a function of soil loss from the land surface (determined by MUSLE) and sediment processes within the channel (based on transport capacity).

### **Literature Review Summary**

The benthic TMDL process is an important process for protecting the biological integrity of waterbodies as required by the Clean Water Act. The process uses biomonitoring data and ambient chemical and physical water conditions to determine the most likely stressor(s) of an impaired waterbody. Next, the processes by which the stressor(s) is generated and transported within the watershed are simulated. Finally, the loads of the stressor(s) simulated in the impaired watershed are compared with those in a reference watershed with similar characteristics to the impaired watershed but with no benthic impairment. A review of the literature found no research on the effects of reference watershed selection or on the effects of the use of alternative watershed models in the development of benthic TMDLs.

## *Chapter 3*

### METHODS

The first objective of this research was to investigate the effects of selecting different sources of land use information for developing input parameters on stressor reduction requirements in a benthically-impaired watershed. The second objective was to investigate the use of different computer models and their impacts on required stressor reductions. The third objective of this research was to investigate the use of different reference watersheds on resulting stressor reduction requirements.

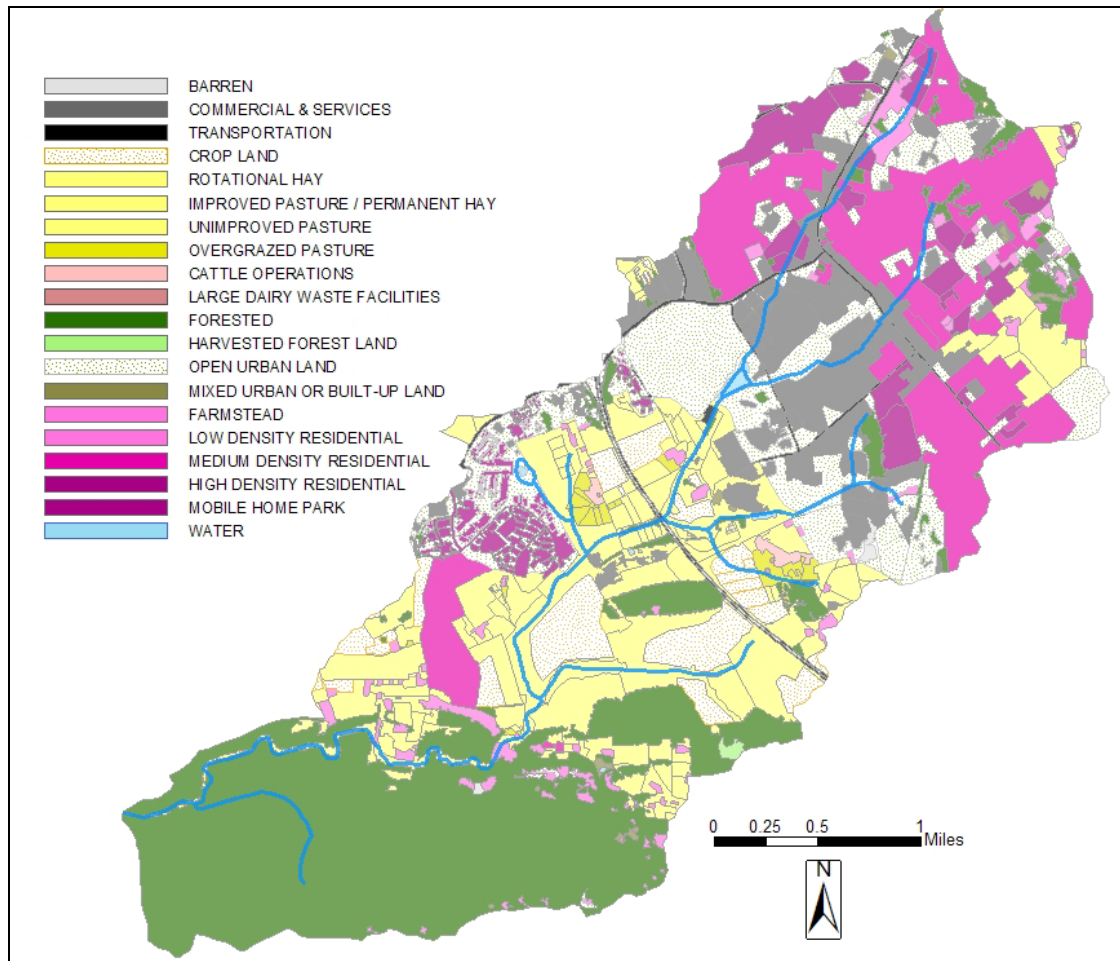
#### **Impaired Watershed Selection**

Stroubles Creek, a benthically-impaired stream on Virginia's "303d list," was selected as the impaired watershed for this research. Stroubles Creek was selected because the primary stressor was identified as sediment, which was preferred since sediment has been the most common stressor on the benthic assemblage for TMDLs developed in Virginia. In addition, the Virginia Tech (VT) TMDL Development Group had the contract to develop the Stroubles Creek Benthic TMDL and Stroubles Creek is a local watershed (it flows through the Virginia Tech campus).

Stroubles Creek's headwaters are located in residential areas in the Town of Blacksburg. It flows through downtown Blacksburg and the Virginia Tech campus and then through agricultural and forest land. The watershed and land uses within the watershed (based on digital ortho quarter-quad aerial photography) are shown in Figure 3.1.

The impairment was defined as originating in the headwaters and continuing downstream from the biological monitoring station to the confluence with the Wall Branch tributary. Since biological monitoring is not conducted on Wall Branch or below the confluence, the impairment cannot be confirmed below that point (VADEQ, 2003). The impairment is 8.02 km in length and the contributing watershed area is approximately 24.8 km<sup>2</sup>.

The Stroubles Creek Benthic TMDL was completed by the Virginia Tech TMDL Development Group and approved by EPA in January 2004. The adjacent Tom's Creek watershed was used as the reference watershed for estimating the target sediment load.



**Figure 3.1. Stroubles Creek Watershed and Land Uses.**

**Reference Watershed Selection**

To evaluate the variability of stressor reductions in the impaired watershed to the selection of reference watershed, it was decided to develop the Stroubles Creek TMDL using three different reference watersheds. Candidate reference watersheds were selected from the available reference watersheds in Virginia. Selection of the reference watersheds for benthic TMDL development, and therefore for this research, was based on similarities in ecoregion and among

the following watershed characteristics in the impaired and candidate reference watersheds: area, land use distribution, soil erodibility factor, slope, elevation, and proximity to the impaired watershed.

Approximately 25 biological reference streams are available in the Central Appalachian Ridges and Valleys ecoregion of Virginia (TetraTech, 2002), the ecoregion in which Stroubles Creek resides. These unimpaired streams are available for use as reference watersheds in benthic TMDL development. Through recommendations from the Virginia Tech TMDL Development Group based on similarities in characteristics to the Stroubles Creek Watershed, three of these watersheds were selected for use in this study as reference watersheds for the impaired Stroubles Creek: Tom's Creek, Upper Opequon Creek, and Upper Quail Run.

Upper Opequon Creek and Upper Quail Run have been used as reference watersheds for other TMDLs with benthic impairments in Virginia. Tom's Creek is an unimpaired watershed, but had not been used as a reference watershed before the development of the Stroubles Creek TMDL. Originally, the selected reference watershed for the Stroubles Creek TMDL was the Upper Opequon Creek, approximately 300km from Stroubles Creek in Frederick and Clarke Counties. However, after the first public meeting, it became obvious that the public preferred a closer reference watershed and Tom's Creek was selected. Stroubles Creek drains the southern part of the town of Blacksburg, while Tom's Creek drains the northern part of the town. Stakeholders in the Stroubles Creek basin are familiar with Tom's Creek and have a sense of the environment in which each stream is located. The use of Tom's Creek required the relocation of an ambient monitoring station and the collection of an additional year's worth of water quality data, but it was necessary for public acceptance of the reference watershed (Mostaghimi et al., 2003). In addition, Tom's Creek is the biological reference stream<sup>1</sup> for Stroubles Creek.

The parameter values for the characteristics used in evaluating these possible reference watersheds are listed in Table 3.1. Note that with characteristics such as "percent urban," no reference watershed is available with a similar value to the impaired Stroubles Creek; somewhat

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<sup>1</sup> The biological reference stream is the stream used when comparing the Rapid Biological Assessment (RBP II) metrics to calculate a score and determine impairment status. The watershed based on this stream can be used as the reference watershed to determine sediment loads in the Reference Watershed Approach or a different watershed can be used.

dissimilar values, therefore, are considered “reasonably” close to the Stroubles Creek value for this characteristic. There are no reference watersheds in the state that have significant urban land use. All watersheds assessed in Virginia with greater than 15% impervious area (based on 1992 NLCD land use information) are benthically impaired (Dillaha, 2004).

**Table 3.1. Comparison of Impaired Stroubles Creek and Unimpaired Reference Watershed Characteristics.**

CODE	NAME	Area (ha)	Land Use Distribution (1992 NLCD)			Non-Forested Soil Erodibility Factor	Slope (%)	Elev. (m)	Proximity (km from STE)
			% Urb	% For	% Agr				
STE	<i>Stroubles Creek</i>	2470	29%	39%	32%	0.34	6.2	641.0	
OPE	Upper Opequon Creek	14840	5%	35%	60%	0.31	7.1	224.1	290
QAL	Upper Quail Run	300	13%	81%	6%	0.26	10.9	452.9	200
TOM	Tom’s Creek	2070	3%	68%	29%	0.30	10.5	688.8	7

### **Reference Watershed Approach**

The Reference Watershed Approach compares a single unimpaired reference watershed to the impaired watershed. The loads of the primary stressor are determined in both watersheds. Since a reference watershed does not have the same area as the impaired watershed, certain adjustments, such as multiplying land use areas by a ratio of the watershed areas, must be made to allow direct comparison of resultant stressor loads. The required reduction of the stressor in the impaired watershed is calculated as the difference in loads between the impaired and reference watershed as a percentage of the impaired watershed load. In a TMDL report, the final target reduction requirement also includes point sources in each watershed as well as a margin of safety. For this research, however, only the nonpoint source loads are compared in order to avoid introducing unwanted complexity into the comparisons; the margin of safety is left out also, since it would have no effect on the comparisons.

### **Alternative Land Use Sources Used in TMDL Development**

Land use information was derived from two different sources – digital ortho quarter-quads (DOQQs) and the National Land Cover Dataset (NLCD). The DOQQs are aerial photographs of one quarter of a USGS 7.5-minute quadrangle map. Using these images, the outlines of distinct land use areas were traced in a GIS environment such as ArcMap™ (by ESRI). Each outlined area was designated with a specific land use, first by looking at the photograph and then confirmed through a visual assessment of the watershed. For this research, some of the DOQQ-based land use was prepared by Virginia Department of Conservation and Recreation (DCR) and some was prepared by the VT TMDL Development group. Areas digitized by VT were checked and approved by DCR. Table 3.2 shows the DCR land uses assigned to each delineated polygon area of the DOQQ. These land use categories were used consistently when DOQQs were digitized for TMDL development.

**Table 3.2. DCR Land Use Categories Used in Stroubles Creek and Reference Watershed DOQQ Digitization.**

LU Code	Classification
3	RANGELANDS
4	FORESTED
5	WATER
6	WETLANDS
7	BARREN
12	COMMERCIAL & SERVICES
13	INDUSTRIAL
14	TRANSPORTATION
15	INDUSTRIAL/COMMERCIAL COMPLEXES
16	MIXED URBAN OR BUILT-UP LAND
17	OTHER URBAN OR BUILT-UP LAND
18	OPEN URBAN LAND
22	ORCHARDS
44	HARVESTED FOREST LAND
111	LOW DENSITY RESIDENTIAL
112	MEDIUM DENSITY RESIDENTIAL
113	HIGH DENSITY RESIDENTIAL
115	MOBILE HOME PARK
118	WOODED RESIDENTIAL
211	CROP LAND
231	CATTLE OPERATIONS
233	OTHER FEEDING OPERATIONS
241	FARMSTEAD
242	LARGE DAIRY WASTE FACILITIES
2114	ROTATIONAL HAY
2121	IMPROVED PASTURE / PERMANENT HAY
2122	UNIMPROVED PASTURE
2123	OVERGRAZED PASTURE
2431	MANAGED GRASSLANDS
2432	UNMANAGED GRASSLANDS

The VT TMDL Development group has a standard set of land uses for the GWLF model that does not correspond exactly with the DCR list. In order to use available look-up tables in spreadsheets containing parameters previously determined for the Virginia 2002 Biennial Nonpoint Source Pollution Water Quality Assessment of nonpoint source pollution loads (VADCR, 2002), it was useful to translate the DCR land uses into those on the VT list. As seen in Table 3.3, several of the land uses correspond directly (e.g. “forest”); several of the VT land uses are created by combining some of the DCR land uses (e.g. VT land use, “transitional”); and one of the DCR land uses, “cropland,” is divided into two VT land uses, “high-till” and “low-till.” In several cases, a land use is divided into pervious and impervious areas by percentage. These percentages were developed from numerous sources, including the NLCD classification system and the Chesapeake Bay Watershed Program land use scheme (USEPA, 2004a; Hopkins et al., 2000). Best professional judgment of the VT TMDL Development Group determined the final percentage breakdown between pervious and impervious areas.

The division of DCR’s “cropland” category into VT’s “high-till” and “low-till” categories was based on data developed for DCR’s statewide non-point source pollution assessment in 2002 (Yagow et al., 2002). For this statewide assessment, nine land uses were used, including both high-till and low-till cropland. Assessments of land use were made by state hydrologic unit, of which there are 493 in Virginia. To quantify cropland categories for this research, the corresponding state hydrologic unit was identified for each watershed and the fraction of each type of cropland (for a given hydrologic unit) in the 2002 assessment was used to divide the cropland into “high-till” and “low-till” in each watershed.

**Table 3.3. Land Use Consolidation and Disaggregation.**

<b>VADCR Land Use Categories (code)</b>	<b>TMDL Land Use Categories (code)</b>	<b>Pervious/Impervious (percentage)</b>
Cropland (211)	Cropland - high till (1) Cropland - low till (2)	Pervious (100%)
Improved pasture (2121)	Pasture 1 (3)	Pervious (100%)
Unimproved pasture (2122)	Pasture 2 (4)	Pervious (100%)
Overgrazed pasture (2123)	Pasture 3 (5)	Pervious (100%)
Open urban (18)	Urban Grass (6)	Pervious (100%)
Rotational Hay (2114) Orchards (22) Managed Grasslands (2431) Unmanaged grasslands (2432)	Hay (7)	Pervious (100%)
Forest (4) Wetlands (6)	Forest (8)	Pervious (100%)
Barren (7) Urban transition (16) Harvested forest (44) Confined cattle (231) Rangeland (3)	Transitional (9)	Pervious (100%)
LDR (111) Wooded residential (118)	Low Density Residential (LDR) (10, 11)	Pervious (88%) Impervious (12%)
MDR (112) Mobile homes (115) Farmstead (241) Dairy Waste Facilities (242)	Medium Density Residential (MDR) (12, 13)	Pervious (70%) Impervious (30%)
HDR (113)	High Density Residential (HDR) (14, 15)	Pervious (35%) Impervious (65%)
Commercial (12) Industrial (13) Transportation/Utilities (14) Industrial/Commercial Complexes (15) Other Urban/Built-Up (17)	Commercial (COM) (16, 17)	Pervious (21%) Impervious (79%)

### **Quail Run Land Use Categorization**

Unlike the other watersheds, the land use digitization from the DOQQ for the Quail Run watershed had been developed prior to this research by the VT TMDL Development Group using categories that did not correspond exactly to the categories in Table 3.2. An explanation

of the adjustment from the original Quail Run categories into the categories used in this research can be found in Appendix A.

### **Alternative Models Used in TMDL Development**

Based on the literature review of the models commonly used in the development of sediment TMDLs for benthically-impaired streams, the Generalized Watershed Loading Functions Model (GWLF) and the Soil and Water Assessment Tool (SWAT) were selected as the models for evaluation in this study. The approach used to apply these models in this study is described below.

### **GWLF**

#### ***Parameter Development***

GWLF inputs are relatively straightforward compared to many hydrologic simulation models. The model requires three input files: “weather” (climate data), “transport” (sediment generation and transport parameters such as land use), and “nutrient” (nitrogen and phosphorus parameters). Climate data required by GWLF are average daily precipitation and average daily temperature. Transport parameters include Universal Soil Loss Equation (USLE) parameters as well as curve number and evapotranspiration cover coefficients. The nutrient file is required for GWLF to run properly, but for this research, only the sediment buildup rate was a necessary input for this file, since only sediment was being examined. The other values in the nutrient files are dummy values. All the GWLF parameters are described in Appendix B.

With the development of Geographic Information Systems (GIS), extensive data has become available for determining necessary model inputs such as land use and land cover, elevation and slope, and soil type and characteristics. Using GIS, the boundaries of the impaired and reference watersheds were delineated based on elevation. The routines available within the ESRI ArcMAP™ hydrology extension were used to calculate flow direction and flow accumulation; the raster calculator operation “watershed” was then used to determine the watershed rasters. The boundaries of each watershed were checked by comparison to the digital raster graphics (DRGs), which are the GIS layers containing the 7.5-minute United States Geological Survey (USGS) quadrangle topographic maps. If the watershed boundary created

from the digital elevation model (DEM) did not agree with the DRG contour lines, the boundary was adjusted to follow boundary suggested by the DRG's contour lines. The watershed outlet for the impaired stream was the downstream limit of the impaired stream segment as specified by DEQ. The watershed outlets for the reference watersheds were determined based on tributary confluences in relation to biological monitoring stations.

#### *Land Use Data*

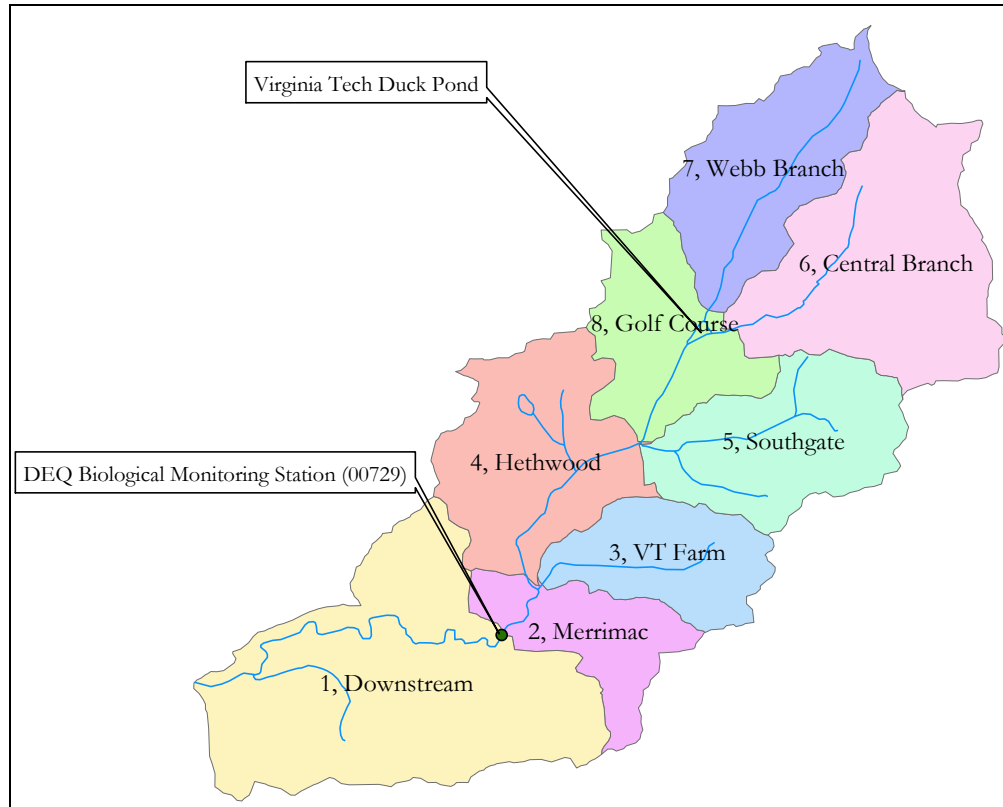
GWLF uses the term “rural” for land uses that are modeled as pervious areas and the term “urban” for land uses that are modeled as impervious areas. Since it is desirable to model some land uses as having both a pervious and an impervious component, each is represented as two land uses – one pervious and one impervious – in GWLF. Therefore based on the VT land uses and the breakdown into pervious and impervious areas, there are 13 rural land uses (those with a pervious component) and 4 urban land uses (those with an impervious component). Parameters were developed for both rural and urban land uses.

#### *Subbasin Delineation*

GWLF does not have the capacity to route water through different subbasins. However, breakdown of an impaired watershed into subbasins is beneficial for TMDL development because a subbasin provides more specific information to target pollutant sources for TMDL implementation (Yagow, 2003). Since source allocation of pollutants is not a concern for reference watersheds, and since substantial differences in load production are not seen when subbasins are delineated in GWLF, only impaired watersheds are divided into subbasins. Parameter development for headwater subbasins is performed as described above. However, in cases where the subbasin is not a headwater, the parameters must be developed for the area that includes the subbasin plus all the subbasins that route water to the downstream subbasin.

Subbasins for the GWLF model were developed using the same procedures used in the Stroubles Creek Benthic TMDL (Mostaghimi et al., 2003). Subbasins in Stroubles Creek, shown in Figure 3.2, were determined based on the confluence of tributaries to the main branch, using the same outlets that had been used in the Stroubles Creek Benthic TMDL (Mostaghimi et al.,

2003). An additional subbasin was created with the biological monitoring station (labeled in Figure 3.2 as “DEQ Biological Monitoring Station 00729”) as an outlet.



**Figure 3.2. Stroubles Creek Subbasins and Reservoir for GWLF modeling.**

#### *Sediment Detention Basins*

One of the benefits of dividing a watershed into subbasins in GWLF is the ability to incorporate sediment reductions from impoundments. For example, sediment detention basins may trap sediment from part of a watershed. By dividing a large watershed into subbasins, the total sediment from the upstream subbasins is reduced before combining the sediment with the sediment loads from the rest of the subbasins to obtain an overall total sediment yield from the watershed.

#### *Area Adjustment*

Area adjustment is made prior to running the GWLF model. The ratio of the impaired watershed area to the reference watershed area is calculated. This ratio is then multiplied by

each land use area in the reference watershed. The stream length in the reference watershed is also multiplied by this value. Since the sediment delivery ratio (SDR) is a function of the watershed area, the SDR from the impaired watershed is used in the area-adjusted reference watershed modeling. In addition, the mean channel depth from the impaired watershed is used in the area-adjusted reference watershed modeling.

#### Input File Construction

To facilitate determination of many GWLF parameters and construction of the GWLF input files, the VT TMDL Development Group developed two Microsoft Excel<sup>TM</sup> spreadsheets and several macros to process the data (Yagow, 2003). The first spreadsheet, “WATERSHED” contains watershed-related parameters; the second, “LANDUSE,” contains land use-related parameters. The spreadsheets contain lookup tables with values for most of the required GWLF parameters. The lookup tables are based on characteristics such as Virginia ecoregions, Virginia soils, the 17 land use categories used by Virginia Tech in TMDL development, and watershed locations. When a given land use has both pervious and impervious components, both types of parameters are available. Use of these tables provides consistency in GWLF parameter development among all Virginia watersheds being examined by the VT TMDL Development Group. These tables insure that reference watershed values and impaired watershed values are based on the same decisions during TMDL development.

Once the spreadsheet inputs were completed for the impaired and reference watersheds with parameters developed from both land use sources, they were processed using scripts to produce GWLF input files in the proper format. The spreadsheet/macro production and the subsequent processing for input file production were developed for the DCR state-wide nonpoint source assessment mentioned above in the description of land use category development (Yagow et al., 2002). Descriptions of those parameters, and an example of the lookup tables from the parameter development spreadsheets (“LANDUSE” and “WATERSHED”) are available in Appendix C. GWLF parameters and sample files can be found in Appendix D.

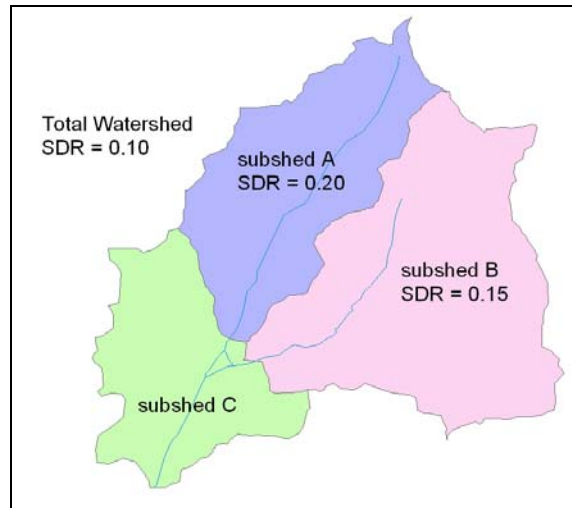
## Post-Processing

### *Subbasins*

During post-processing of model results, upstream subbasins loads are subtracted from downstream subbasin loads to estimate loads from within the downstream subbasin itself. This method of combination and subtraction is important for accurate evaluation of parameters such as sediment delivery ratio, in which the parameter is dependent on stream length or watershed area and cannot be calculated accurately without considering contributions from upstream areas.

When a watershed is divided into subbasins for GWLF modeling, the sediment delivery ratio (SDR) must be adjusted. Since this parameter is based on watershed size, it initially must be calculated for the subbasin in question plus any subbasins that flow into the subbasin. Consider the example watershed shown in Figure 3.3. To calculate the load from a downstream subbasin such as subbasin C, the upstream subbasins' contribution (subbasins A and B) must be subtracted from the load of the combined subbasin ABC. However, to insure that the total watershed output is the sum of the combined subbasin outputs, each upstream subbasins' contribution must be multiplied by the ratio of the total watershed SDR (0.10 in the figure) to the individual subbasin SDR (0.20 for subbasin A and 0.15 for subbasin B). In other words, the calculation for determining the sediment load from subbasin C :

$$Load_C = Load_{ABC} - Load_A \frac{SDR_{ABC}}{SDR_A} - Load_B \frac{SDR_{ABC}}{SDR_B} \quad \text{Eq. 3.1}$$



**Figure 3.3. Subbasin SDR calculation.**

#### *Sediment Detention Basins*

In the Stroubles Creek Benthic TMDL (Mostaghimi et al., 2003), a pond, labeled as the Virginia Tech Duck Pond in Figure 3.2, was estimated to be trapping 50% of the sediment entering the pond from upstream subbasins. After modeling with GWLF, the total sediment load from the upstream subbasins (subbasins 6 and 7 in Figure 3.2) in the Stroubles Creek watershed was therefore reduced by 50% before combining the sediment with the sediment loads from the rest of the subbasins to obtain an overall total sediment yield from the watershed.

#### GWLF Model: Version Specifications

The GWLF Model used for this research is derived from the original GWLF model (Haith, 1985). Alterations have been made by a research group at Penn State (PS) and by Dr. Gene Yagow at Virginia Tech (VT). These changes include:

1. Inclusion of a channel erosion routine. (PS)
2. Calculation of sediment loads by land use. (PS)
3. Use of a “response file” to allow for batch runs of multiple watersheds. (VT)
4. Allowing a variable urban sediment build-up rate. (VT)
5. Inclusion of the urban sediment load in total sediment loads. (VT)
6. Allowing a variable mean channel depth. (VT)

For this research, the GWLF model was modified to eliminate some of the previously hard-coded file locations. The modified model and user interface allow users to specify filenames and locations and to output additional parameters from the model. The model is called “GWLF2003E\_sumfile” and is available from the Center for TMDL and Watershed Studies at Virginia Tech (<http://www.tmdl.net/>).

## **SWAT**

### *Parameter Development*

The SWAT model requires numerous input files. Five input files are databases, housing lookup tables of parameters related to plant growth, tillage practices, pesticides, fertilizers, and urban land uses. These database files are provided in the SWAT2000 program, and can be modified if necessary. The rows from the plant growth and urban land use databases that are applicable to this research can be found in Appendix E. Four input files are watershed based, containing routing information, watershed parameters, and the names of the files that will be inputs to and outputs from the model. Three files describe parameters at the subbasin level, and four files describe parameters at the hydrologic response unit (HRU) level.

The model can simulate precipitation and temperature, but for this study observed data were used. The same period of record was used for temperature and precipitation data for both SWAT and GWLF. Other weather parameters required by SWAT, such as solar radiation, were simulated.

The SWAT model has been incorporated into an ArcView<sup>TM</sup> GIS interface. The interface, called AVSWAT, was used in this study to develop parameters and to create input files for running the model. The impaired watershed and the selected reference watersheds were delineated from elevation data using the automatic delineation routine in AVSWAT. The same digital elevation models and the same watershed outlets were used for both SWAT and GWLF. Since subbasin delineation may affect SWAT outputs, as described in the literature review, all the watersheds were modeled in SWAT with the same number of subbasins.

### Land Use Data

The SWAT model databases were developed for the categories in the NLCD land cover layer. However, since the DOQQ-based land use was available, this layer was chosen for land use parameter development for the SWAT model. Conversion of the land use types used in the DOQQ land use development to the land uses in the SWAT databases is shown in Table 3.4. These decisions were based on best professional judgment and on advice from the SWAT User's Manual (Neitsch et al., 2002a).

**Table 3.4. Land Use Recategorization for use in SWAT.**

DOQQ Classification	DOQQ Land Use Code	SWAT Land Use Tag	SWAT Land Use Description
RANGELANDS	3	RNGE	Range-grasses
FORESTED	4	FRST	Forest-mixed
WATER	5	WATR	Water
WETLANDS	6	WETL	Wetlands
BARREN	7	UINS	Urban-Institutional
COMMERCIAL & SERVICES	12	UCOM	Urban-Commercial
INDUSTRIAL	13	UIDU	Urban-Industrial
TRANSPORTATION	14	UTRN	Urban-Transportation
INDUSTRIAL & COMMERCIAL COMPLEXES	15	UCOM	Urban-Commercial
MIXED URBAN OR BUILT-UP LAND	16	URHD	Urban-Residential High Density
OTHER URBAN OR BUILT-UP LAND	17	URMD	Urban-Residential Medium Density
OPEN URBAN LAND	18	URLD	Urban-Residential Low Density
ORCHARDS	22	ORCD	Orchard
HARVESTED FOREST LAND	44	URLD	Urban-Residential Low Density
LOW DENSITY RESIDENTIAL	111	URLD	Urban-Residential Low Density
MEDIUM DENSITY RESIDENTIAL	112	URMD	Urban-Residential Medium Density
HIGH DENSITY RESIDENTIAL	113	URHD	Urban-Residential High Density
MOBILE HOME PARK	115	URHD	Urban-Residential High Density
WOODED RESIDENTIAL	118	URLD	Urban-Residential Low Density
CROP LAND	211	AGRR	Agricultural Land-Row Crops
CATTLE OPERATIONS	231	AGRL	Agricultural Land-Generic
OTHER FEEDING OPERATIONS	233	AGRL	Agricultural Land-Generic
FARMSTEAD	241	URLD	Urban-Residential Low Density
LARGE DAIRY WASTE FACILITIES	242	URLD	Urban-Residential Low Density
ROTATIONAL HAY	2114	WPAS	Winter pasture
IMPROVED PASTURE / PERMANENT HAY	2121	WPAS	Winter pasture
UNIMPROVED PASTURE	2122	WPAS	Winter pasture
OVERGRAZED PASTURE	2123	WPAS	Winter pasture
MANAGED GRASSLANDS	2431	RNGE	Range-grasses
UNMANAGED GRASSLANDS / CRP	2432	RNGE	Range-grasses

After the reclassification of land uses into the categories in the SWAT databases, an overlay of the land use and soil layers created the HRUs. AVSWAT offers the user a choice of using only the dominant land use and soil classes or of creating multiple HRUs. For this research, all land

use and soil combinations, regardless of how small their contribution to the watershed area, were used to construct HRUs.

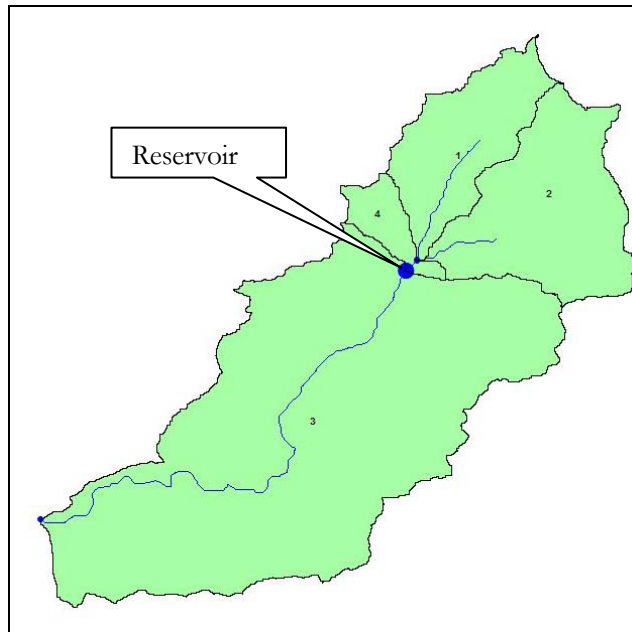
### *Subbasins*

As discussed in the literature review, the number of subbasins used in a SWAT simulation can affect sediment generation and sediment loads at a watershed outlet. Therefore it was decided that all the watersheds being examined should have the same number of subbasins. Since delineating four subbasins was useful for simulating the sediment detention basin in the Stroubles Creek watershed, four subbasins were delineated in all watersheds.

In all cases (Stroubles Creek watershed and the three reference watersheds), the sediment load resulting from modeling with subbasins was less than the sediment load resulting from modeling without subbasins. In order to avoid interference from this discrepancy, all the watersheds were divided into the same number of subbasins for modeling.

### *Sediment Detention Basins*

The SWAT model has a module for creating a reservoir. Since SWAT simulates the reservoir at the inlet of a subbasin, the pond on Stroubles Creek was modeled in SWAT by creating four subbasins in the watershed as shown in Figure 3.4. This arrangement allows both the upstream tributaries to feed into the reservoir. The parameters of the reservoir are shown in Appendix F. The reservoir created in the SWAT model traps approximately 72% of the sediment from the upstream basins, resulting in a 7% overall sediment load reduction from the entire watershed.



**Figure 3.4. Stroubles Creek Subbasins and Reservoir for SWAT Modeling.**

#### *Area Adjustment*

In SWAT, as in GWLF, area adjustment of the reference watersheds was made prior to running the model. This required area adjustment of parameters in the basin input file (“.bsn”) and the subbasin file (“.sub”) for each subbasin. The adjustments are shown in Appendix G. Since the individual HRU areas were calculated as fractions of the total watershed area, only the total watershed area of the reference watershed needed to be changed to the area of the impaired watershed in the basin input (“.bsn”) file, rather than changing all the individual HRU areas. The channel length and channel width parameters were adjusted by the ratio of the impaired to the reference watershed ratio in each subbasin general input (“.sub”) file. These changes could not be made using the AVSWAT interface; they had to be made directly to the files themselves. After these adjustments were made, the model was run outside of the AVSWAT interface. Output files were then returned to the AVSWAT interface for automated conversion into user-friendly tables using the “Read Results” command.

### Input File Construction

The automatic file creation feature of AVSWAT was used to create all the necessary input files for the model. Defaults were selected for the offered options (Manning's roughness factor and plant heat unit estimation). SWAT sample input files can be found in Appendix H.

### SWAT Model: Version Specifications

The version of SWAT used for this research was version 2000. The version of AVSWAT used for this research was also version 2000. Both are available by download from the SWAT website, <http://www.brc.tamus.edu/swat/index.html>.

### Comparison of Sediment Loads

In development of a TMDL with sediment as the primary stressor, the loads calculated by the model are translated into the percent of the load in the impaired watershed that must be eliminated to meet the TMDL target load established by the reference watershed. This is referred to as the required percent reduction, and is calculated as:

$$\text{Reduction} = \frac{Y_{\text{imp}} - Y_{\text{ref}}}{Y_{\text{imp}}} \times 100$$

where Reduction = required sediment reduction in impaired watershed, % Eq. 3.1

$Y_{\text{imp}}$  = total sediment, impaired watershed

$Y_{\text{ref}}$  = total sediment, reference watershed

It is this value, the percent required reduction in the impaired watershed, which is evaluated throughout this research. These values, obtained from different combinations of land use source, water quality model, and reference watershed are compared in three ways: 1) the value of the required percent reductions are compared, 2) the ratio of required percent reductions are compared, and 3) the required percent reduction values are compared to the averaged required percent reduction values across a given scenario (when comparing more than two values).

RESULTS AND DISCUSSION

**Load Reductions as a Function of Land Use Source**

The first objective of this study was to determine if different sources of land use information used for input parameter development produce different stressor reduction requirements for the impaired watershed. Sediment loads in the impaired Stroubles Creek are shown in Table 4.1. These loads are based on modeling in GWLF using both DOQQ-based and NLCD-based land use information. The percent reductions required by each reference watershed are shown in Table 4.2. When the results from GWLF modeling of reference watersheds using DOQQ-based and NLCD-based land uses for parameter development are compared, there are notable differences between the required reductions from each land use type. Tom’s Creek has the largest difference in required sediment reduction due to land use source: the DOQQ-based modeling requires a 50% reduction while the NLCD-based modeling requires only 14% reduction, a difference of 36% reductions. As indicated by the ratio (in Table 4.2), this means that the reductions required are 3.48 times greater when the DOQQ is used as the source of land use information than when the NLCD is used as the source of land use information. In contrast, the other two reference watersheds, Upper Opequon Creek and Upper Quail Run had only 15% and 14% differences, respectively, in required sediment reductions due to DOQQ-based and NLCD-based land use model runs. For Upper Opequon Creek, reductions required from the DOQQ modeling are 1.38 times greater than reductions required from the NLCD modeling. For Upper Quail Run this difference is reversed between the two land use sources: the reductions are 1.19 times greater when the NLCD is used than when the DOQQ is used.

**Table 4.1. Sediment Loads in the Impaired Stroubles Creek based on different sources of Land Use Information.**

	<i>DOQQ</i>	<i>NLCD</i>
	<i>Stroubles Creek</i>	<i>Stroubles Creek</i>
Sediment Yield (Mg/yr)	5349	5974
Streambank Erosion (Mg/yr)	4085	2117
Total Sediment (Mg/yr)	9434	8090

**Table 4.2. Comparison of Required Sediment Reductions from DOQQ and NLCD Land Use Modeling.**

	DOQQ Upper Opequon Creek	NLCD Upper Opequon Creek	DOQQ Upper Quail Run	NLCD Upper Quail Run	DOQQ Tom's Creek	NLCD Tom's Creek
Sediment Yield (Mg/yr)	3406	4554	953	1066	4469	6796
Streambank Erosion (Mg/yr)	934	381	1616	4	262	134
Total Sediment (Mg/yr)	4341	4935	2569	1070	4730	6930
Required Sediment Reductions (Mg/yr)	5094	3155	6865	7021	4704	1160
Percent of STE Total Sediment Required for Reductions	<b>54%</b>	<b>39%</b>	<b>73%</b>	<b>87%</b>	<b>50%</b>	<b>14%</b>
Reduction Requirement Difference between Land Uses	15%		14%		36%	
Ratio of DOQQ based reductions to NLCD based reductions	1.38		0.84		3.48	

### Discussion of Land Use Source Comparison

The modeling developed with the NLCD-based land use produces smaller channel erosion loads than the modeling developed with the DOQQ-based land use. (See the second row of Table 4.2.) Since channel erosion is a function of stream length, curve number, and percent urban land, these parameters were compared in Table 4.3. In all watersheds, the NLCD-based land use demonstrates lower percent urban area, which contributes to a smaller a-factor (see Eq. B.4). The a-factor is used in determining channel erosion and is a function of animal density, curve number, soil erodibility, and percent developed land (urban area). The changes in the parameters that contribute to the a-factor, particularly percent urban area, clearly contribute to reduced stream bank erosion from modeling with NLCD-based land use.

While modeling from DOQQ-based land use has higher sediment yield from channel erosion, NLCD-based land use modeling results in higher sediment yields from land surfaces, as seen in the first row of Table 4.2. Two factors should be considered regarding this difference. First, the percent urban area (and, therefore, the impervious area modeled in GWLF) is higher in all watersheds when the DOQQ is the source of land use information (Table 4.4) than when the NLCD is the source of land use information. This is likely because the DOQQ is a more recent source of land use information, and these watersheds may have experienced urbanization not reflected in the NLCD data. Another reason for the higher percent urban area in DOQQ-based land use may be the distance from which the original imagery is captured. Since the aerial photographs (DOQQs) are taken at a much closer range than the satellite imagery from which the NLCD is derived, the DOQQs show areas such as “wooded residential” as residential areas (which are part of the percent urban category), while the NLCD sometimes translates these

areas into forest. The result of higher urbanized area is that less land is available for erosion (as simulated in GWLF). Although the urban build-up and wash-off component of GWLF contributes to the overall sediment generated, it does not contribute as much as pervious areas that simulate erosion based on the USLE. A second contributing factor to the higher sediment yields from land surfaces from NLCD-based land use modeling is the distribution of different types of agricultural land, shown in Table 4.5. When NLCD is the land use source, the percentage of agricultural land in the more erosive types of use such as cropland, pasture 2 (unimproved pasture), and pasture 3 (overgrazed pasture), is much greater, leading to increased sediment generation from the land surface.

The DOQQ-based land use is preferred over the NLCD-based land use for several reasons. First, the DOQQs available for most areas, including the areas modeled in this study, reflect more current land use than the NLCD layers available. Since TMDLs are developed for current conditions, not past conditions, use of the most up-to-date data available is best. An additional reason that DOQQ-based land use is preferred is that DOQQ-based land use is more resolved than the NLCD-based land use. Since the land use categorization for DOQQs is based on a vector rather than a grid, the areas are more accurately delineated. Finally, the process of developing the land use based on the DOQQs requires checking the assigned land use classes by a visual assessment of the watershed; the NLCD-based land use classes are often assumed to be correct and not checked.

**Table 4.3. Channel Erosion Parameter Comparison.**

		References			
		Stroubles Creek	Upper Opequon Creek	Upper Quail Run	Tom's Creek
Percent Urban Land Use	DOQQ	16.92%	4.95%	3.26%	4.11%
	NLCD	8.40%	0.03%	1.44%	1.59%
	<b>Difference</b>	<b>8.52%</b>	<b>4.92%</b>	<b>1.81%</b>	<b>2.52%</b>
Curve Number	DOQQ	79.6	76.0	79.5	78.4
	NLCD	77.5	75.9	72.8	73.3
	<b>Difference</b>	<b>2.02</b>	<b>0.11</b>	<b>6.68</b>	<b>5.08</b>
a-factor	DOQQ	1.68E-04	5.43E-05	4.01E-05	4.54E-05
	NLCD	9.59E-05	2.31E-05	1.00E-07	6.90E-06
	<b>Difference</b>	<b>7.21E-05</b>	<b>3.12E-05</b>	<b>4.00E-05</b>	<b>3.85E-05</b>

**Table 4.4. Land Use Source Comparison of General Land Use Types.**

Watershed	Land Use Source	% Urban / Residential	% Forest	% Agriculture
Stroubles Creek	DOQQ	47%	28%	26%
	NLCD	29%	39%	32%
	Difference (DOQQ-NLCD)	18%	-11%	-6%
	Ratio (DOQQ/NLCD)	1.61	0.71	0.80
Upper Opequon Creek	DOQQ	14%	28%	58%
	NLCD	5%	35%	60%
	Difference (DOQQ-NLCD)	9%	-7%	-2%
	Ratio (DOQQ/NLCD)	2.84	0.81	0.96
Upper Quail Run	DOQQ	28%	70%	2%
	NLCD	13%	81%	6%
	Difference (DOQQ-NLCD)	15%	-11%	-4%
	Ratio (DOQQ/NLCD)	2.14	0.86	0.39
Toms Creek	DOQQ	21%	58%	21%
	NLCD	2%	72%	26%
	Difference (DOQQ-NLCD)	19%	-14%	-5%
	Ratio (DOQQ/NLCD)	10.61	0.81	0.79

**Table 4.5. Distribution of Agricultural Land in DOQQ-based land use versus NLCD-based land use.**

Percent of agricultural land in:		References			
		Stroubles Creek	Upper Opequon Creek	Upper Quail Run	Tom's Creek
P1, Hay	DOQQ	74.67%	78.97%	56.00%	77.89%
	NLCD	34.47%	41.53%	55.76%	35.97%
P2, P3, crop	DOQQ	25.33%	21.03%	44.00%	22.11%
	NLCD	65.53%	58.47%	44.24%	64.03%
<b>Difference between land use sources</b>		<b>40.20%</b>	<b>37.44%</b>	<b>0.24%</b>	<b>41.92%</b>

P1 is improved pasture; P2 is unimproved pasture, P3 is overgrazed pasture, and crop is both high- and low-till cropland.

### **Load Reductions as a Function of Model**

The second objective of this research was to determine if different computer models produce different stressor reduction requirements for the impaired watershed. The sediment loads in Stroubles Creek calculated using GWLF and SWAT are shown in Table 4.6. As shown in Table 4.7, a range of differences in required percent reductions is produced by the different models. The smallest difference between models is a difference of only 9% in required sediments reductions, with Upper Opequon Creek. The reductions in GWLF are only 1.19 times greater than the reductions required by SWAT. The largest difference in required reductions is 32%

with Tom’s Creek. In this case the reductions required by GWLF are 2.75 times greater than those required by SWAT. Upper Quail Run shows a difference of 16% between the two model results. For Upper Quail Run, the required reductions are 1.22 times greater in SWAT than in GWLF. The difference seen in the Upper Opequon Creek modeling is not substantial considering the uncertainty in the input data and model. The difference in the results from the two models when Tom’s Creek is the reference, 32%, is notable. These results are based on modeling with DOQQ-based land use parameters. In general, TMDLs developed for benthic impairments in Virginia usually include a 10% margin of safety due to uncertainties associated with model input data used and with the models themselves. Consequently, differences in required reductions of around 10% are probably to be expected.

**Table 4.6. Sediment Loads in the Impaired Stroubles Creek from Different Models.**

	SWAT	GWLF
	Stroubles Creek	Stroubles Creek
Total Sediment (Mg/yr)	15850	9434

**Table 4.7. Comparison of Required Sediment Reductions between Models.**

	SWAT	GWLF	SWAT	GWLF	SWAT	GWLF
	Upper Opequon Creek	Upper Opequon Creek	Upper Quail Run	Upper Quail Run	Tom's Creek	Tom's Creek
Total Sediment (Mg/yr)	8647	4341	1850	2569	12980	4730
Required Sediment Reduction (Mg/yr)	7203	5094	14000	6865	2870	4704
Percent of Total Sediment Required for Reduction	45%	54%	88%	73%	18%	50%
Reduction Requirement Difference between Models	9%		16%		32%	
Ratio of GWLF reductions to SWAT reductions	1.19		0.82		2.75	

### Discussion of Water Quality Model Comparison

The use of different models when Tom’s Creek is the reference watershed results in a noteworthy difference in required sediment reduction in Stroubles Creek. Table 4.8 shows the percent of sediment coming from different general land use source classes with the percent of the total land use area of those land use source areas. While the scenarios using Upper Opequon Creek and Upper Quail Run both have relatively similar percent contributions from agricultural land between the two models, the scenario using Tom’s Creek has a three-fold

greater contribution from agricultural land using the SWAT model than from agricultural land using the GWLF model. Since agricultural contributions are greater (per unit area) than either urban or forest contributions in any scenario (either model or any reference watershed), this difference between models in contributions from agricultural land in the Tom's Creek scenario may account for the difference in required sediment reductions in Stroubles Creek between the two models. Further investigation shows that one explanation for the difference in the sediment contribution by the different land uses in the Tom's Creek scenario may be soil type. Approximately one-third of the area in the Tom's Creek watershed has a soil type identified as "VA003" in the State Soil Geographic Database (STATSGO; USDA, 1994). This soil, a Frederick-Carbo-Timberville silty loam, has a relatively high K-factor (a component of the USLE and MUSLE, see Eq. 2.4), and therefore when this soil type is part of an HRU, sediment yields are consistently higher than with the other soil types in the Tom's Creek basin. In Tom's Creek, 84% of the agricultural land has this erosive soil type, while only 45% of urban land has this soil type. In the other reference watersheds, no soil type has characteristics that dominate the results to such an extent. In modeling with GWLF, the K-factor is averaged across each land use from all the soil types that overlap that land use. In addition, the GWLF modeling used the Soil Survey Geographic Database (SSURGO; USDA, 1995) for generating soil information. This database is much more resolved than STATSGO, and therefore no area is dominated by one soil type and its characteristics. The AVSWAT interface has not been developed to incorporate information from SSURGO. In SWAT modeling, the HRUs are based on unique soil-land use combinations and therefore the influence of parameters such as the high K-factor this particular soil type ("VA003") is not averaged out. Although Upper Opequon Creek also has considerably higher contribution of sediment from agriculture land than from urban land, this trend is consistent across both models, since no unusual soil type is dominating erosion.

**Table 4.8. Comparison of Required Sediment Reductions between Models.**

Upper Quail Run				Upper Opequon Creek				Tom's Creek			
Land Use	% of watershed area (DOQQ)	% of sediment contribution		Land Use	% of watershed area (DOQQ)	% of sediment contribution		Land Use	% of watershed area (DOQQ)	% of sediment contribution	
		SWAT	GWLF			SWAT	GWLF			SWAT	GWLF
Urban	27.8	30.5	53.9	Urban	14.2	3.1	20.3	Urban	21.2	6.7	70.4
Forested	69.9	46.6	28.6	Forested	28.3	1.5	1.2	Forested	58.2	9.0	4.4
Agriculture	2.3	22.9	17.5	Agriculture	57.5	95.4	78.5	Agriculture	20.5	84.3	25.2

Water quality models are chosen based on professional and personal preference, expertise using the model, and software availability, and the ability of the models to simulate the desired processes and watershed conditions. For example, the ability of SWAT to simulate sediment detention in ponds and reservoirs is superior to GWLF, since the SWAT model's simulation is based on observed characteristics of a reservoir and the simulation considers hydrologic changes affecting the downstream portion of the watershed as well as sediment detention. The GWLF model's simulation is based only on the estimation of sediment detained in the pond, without the ability to consider any hydrologic changes caused by the reservoir. Consequently, SWAT would be expected to provide better results in watersheds in which ponds and reservoirs considerably affect sediment transport processes. However, if a modeler is more familiar with GWLF (and has adequate information about the reservoir in their watershed to make appropriate decisions in post-processing of the GWLF outputs), the modeler may prefer to use GWLF, as an expert, rather than SWAT, as a novice. In addition, if a modeler does not have the channel erosion component incorporated in their version of GWLF, they may want to consider a different model such as SWAT that does include this component, particularly if they suspect that channel erosion is a significant contributor to overall sediment loads. On the other hand, if a user does not have the ArcView<sup>TM</sup> software to facilitate parameter development and input file construction for SWAT, time may dictate that a model with fewer input parameters, such as GWLF, be used.

Since different models sometimes produce different results for required sediment reduction in an impaired watershed, model choice also needs to consider the characteristics of the given watersheds, and the modeler must be aware that the model choice may affect the outcome of the TMDL development. The SWAT model may be preferred in situations where the hydrology simulation can be calibrated or in areas where the SWAT model has been tested

previously, since it has more complex simulation of urban areas and since it has a well-developed channel simulation component. However, there is no historical use of the SWAT model in the Stroubles Creek watershed region, and observed data was not available for calibration. Since GWLF has been used in the Central Appalachian Ridges and Valleys ecoregion of Virginia and is considered suitable for this region, GWLF may be preferred for Stroubles Creek, since no calibration data is available.

### **Load Reductions as a Function of Reference Watershed**

The third objective of this research was to determine if different reference watersheds produce different stressor reduction requirements for an impaired watershed when using the Reference Watershed Approach for a benthic impairment in which sediment is the primary stressor. In order to compare the Reference Watershed Approach in different settings, the impaired watershed was compared with three potential reference watersheds using the results of two different water quality models and using model results from land use distributions based on two different sources. The Reference Watershed Approach for the Stroubles Creek benthic TMDL revealed that the required reduction in sediment load from the Stroubles Creek watershed varies greatly depending on the reference watershed chosen to calculate the target sediment load. These differences between reference watersheds exist regardless of the model used.

#### *GWLF with DOQQ-based land use*

For GWLF modeling with land use based on DOQQ digitization, the highest required reductions in sediment loading are 73% using the Upper Quail Run watershed as the reference for the impaired Stroubles Creek; the other required reductions are 54% using the Upper Opequon Creek watershed and 50% using the Tom's Creek watershed (Table 4.9). The required reductions based on Upper Quail Run, which has the highest required reductions, are only 1.46 times as great as those required using Tom's Creek, which has the lowest required reductions. The average required reductions from these three references is 59%, with Upper Quail Run having the greatest deviation from this average. The Stroubles Creek values are

based on modeling the watershed with eight subbasins and including the sediment detention basin described above. The reference watersheds are modeled as single watersheds.

**Table 4.9. GWLF Sediment Yields and Percent Reductions Required, DOQQ-Based Land Use.**

Parameter	Reference Watersheds			
	<i>Stroubles Creek</i>	Upper Opequon Creek	Upper Quail Run	Tom's Creek
Sediment Yield (Mg/yr)	5349	3406	953	4469
Streambank Erosion (Mg/yr)	4085	934	1616	262
Total Sediment (Mg/yr)	9434	4341	2569	4730
Required Sediment Reduction (Mg/yr)		5094	6865	4704
Required Sediment Reduction		<b>54%</b>	<b>73%</b>	<b>50%</b>
Deviation of Required Reduction from Average Reduction		<b>5%</b>	<b>14%</b>	<b>9%</b>
Ratio to Lowest Required Reductions		<b>1.08</b>	<b>1.46</b>	<b>1.00</b>

*GWLF with NLCD-based land use*

For GWLF modeling with land use based on the NLCD, different reference watersheds produce notably different required sediment load reductions in the impaired Stroubles Creek watershed. The highest required reductions, 87%, were again produced using the Upper Quail Run reference watershed; with the other reference watersheds requiring reductions of 39% and 14% using the Upper Opequon Creek and Tom's Creek reference watersheds, respectively (Table 4.10). Upper Quail Run, which has the highest required reductions, required 6.05 times higher reductions than Tom's Creek, which required the lowest required reductions, and 2.23 times higher reductions than Upper Opequon Creek. Upper Opequon Creek requires 2.72 times the reductions required by Tom's Creek. The average required reductions from these three references is 47%, with Upper Quail Run having the greatest deviation from this average. The Stroubles Creek values are based on modeling of the watershed delineated in eight subbasins and including the sediment detention basin described above. The reference watersheds are modeled as single watersheds.

**Table 4.10. GWLF Sediment Yields and Percent Reductions Required, NLCD-Based Land Use.**

	Stroubles Creek	References		
		Upper Opequon Creek	Upper Quail Run	Tom's Creek
Sediment Yield (Mg/yr)	5974	4554	1066	6796
Streambank Erosion (Mg/yr)	2117	381	4	134
Total Sediment (Mg/yr)	8090	4935	1070	6930
Required Sediment Reduction (Mg/yr)		3155	7021	1160
Required Sediment for Reduction		39%	87%	14%
Deviation of Required Reduction from Average Reduction		8%	40%	32%
Ratio to Lowest Required Reductions		2.72	6.05	1.00

*SWAT with DOQQ-based land use*

When the SWAT model is used to determine sediment loads, reference watershed selection once again produces notably different required reductions for the impaired Stroubles Creek. With the SWAT model, parameters were developed using only the DOQQ-based land use. The required reductions are 88%, 45%, and 18% using the Upper Quail Run, Upper Opequon Creek, and Tom's Creek watersheds, respectively (Table 4.11). The required reductions based on Upper Quail Run, which has the highest required reductions, are 4.88 times as great as those required Tom's Creek, which as the lowest required reductions and 1.96 times as great as those required by Upper Opequon Creek. Upper Opequon Creek requires 2.51 times the reductions required by Tom's Creek. The average required reductions from these three references is 50%; Upper Quail Run has the greatest deviation from this average. The Stroubles Creek reductions with SWAT are based on modeling of the watershed delineated with four subbasins and including the sediment detention basin described previously. The reference watersheds are also modeled with four subbasins.

**Table 4.11. SWAT Sediment Yields and Percent Reductions Required, DOQQ-Based Land Use.**

	Stroubles Creek	References		
		Upper Opequon Creek	Quail Run	Tom's Creek
Total Sediment Yield (Mg/yr)	15850	8647	1850	12980
Required Sediment Reduction (Mg/yr)		7203	14000	2870
Required Sediment Reduction		45%	88%	18%
Deviation of Required Reduction from Average Reduction		5%	38%	33%
Ratio to Lowest Required Reductions		2.51	4.88	1.00

## **Discussion of Reference Watershed Comparisons**

Regardless of model used or the source of land use information, substantial differences in required sediment reductions in the impaired Stroubles Creek watershed occur depending on the watershed chosen as a reference. In all cases examined, Upper Quail Run required the greatest percent reduction, followed by Upper Opequon Creek, and Tom's Creek. Clearly, the choice of reference watershed affects the resulting loading reductions and will thus have a substantial impact on the resulting TMDL. Some of the differences are noteworthy, with one reference watershed requiring as much as a 6-fold increase in reductions over a different reference watershed.

The low sediment load in Upper Quail Run, seen in all three modeling environments, can likely be attributed to the very high proportion of forest, which has low runoff volumes and low sediment detachment. The low proportion of agricultural land in this watershed is also a contributing factor to the low sediment load. Tom's Creek always requires the smallest percent reduction for Stroubles Creek. This cannot be explained by just one factor, but is probably affected by several issues. For example, the distribution of land uses in the Tom's Creek basin, when defined by DOQQs, is similar to that in Stroubles Creek. In addition, the ratio of sediment per area from agricultural land use sources to sediment per area from urban land use sources is similar between Tom's Creek and Stroubles Creek (for GWLF modeling using the NLCD land use).

An examination of Table 3.1 does not reveal any obvious first choice for a reference watershed using the method of watershed characteristic comparison that is most often used in the benthic TMDL process. Although Upper Quail Run has a relatively high amount of urban land use for a reference watershed, its percent of forested land is very high compared to Stroubles Creek. Upper Quail Run's results are always the most different, possibly indicating that the percent forest needs to be closer to the percent forest in the impaired watershed for better accuracy. Upper Opequon Creek has a comparable percentage of forested land, but a relatively higher percentage of land in agriculture. Tom's Creek has a relatively similar proportion of agriculture land. In addition, Tom's Creek is similar in size to Stroubles Creek, which is beneficial because it requires minimal area-adjustment, since area-adjustment may introduce anomalies in channel

dimensions. For example, the area-adjustment of Upper Quail Run results in a very long stream channel, which contributes to channel erosion, and Upper Quail Run does have a relatively high channel erosion in the GWLF modeling with DOQQ-based land use (Table 4.9). (The channel erosion in the GWLF modeling with NLCD-based land use is dominated by the small a-factor, which overrides the stream length and causes a small value for channel erosion.) Based on a comparison of the watershed characteristics evaluated in Table 3.1, Tom's Creek is probably the best reference watershed for Stroubles Creek. In addition to being similar in size, the similarity in agricultural land percentage is beneficial because agricultural land is a significant contributor to sediment. Upper Opequon Creek is a reasonable choice for a reference watershed since it has comparable proportion of forest land to Stroubles Creek, and a similar slope. Upper Quail Run is the least appropriate: it is primarily forested and is very small compared to Stroubles Creek, requiring significant area-adjustment. However, results from this research indicate that Tom's Creek is not as consistent across modeling environments as the other two reference watersheds considered. Upper Opequon Creek, on the other hand, produces similar results for required sediment reduction regardless of the water quality model used, and therefore may be preferred to ensure consistency. Another advantage to Upper Opequon Creek as a reference watershed based on the results of this research is that it always produces the median required sediment reductions (and is therefore the closest to the average required reduction show in Table 4.9, Table 4.10, and Table 4.11).

## *Chapter 5*

### SUMMARY AND CONCLUSIONS

Three major objectives were addressed in this research. The effect of the source of land use information used to develop land use-based parameters on the required stressor reductions in a benthically-impaired watershed was considered. What difference does the land use source have on the final required stressor load reductions from an impaired watershed? Two water quality used to simulate stressor loadings in watersheds were analyzed for their effects on required loading reductions. What difference does the model selected have on the final required stressor load reductions from an impaired watershed? The Reference Watershed Approach, used in benthic TMDLs to determine a target stressor load, was considered. What differences would the selection of different reference watersheds have on the final required stressor load reductions from an impaired watershed? These questions were addressed for the benthically impaired Stroubles Creek watershed, located in Montgomery County, Virginia. Stressor analysis of this watershed revealed that sediment was the primary stressor on the benthic macroinvertebrate assemblage.

Two sources of land use information were considered: land use interpreted from aerial photographs (DOQQs) and land use from the NLCD. DOQQ-based land use is more recent (circa 1998) than NLCD-based land use (circa 1992). Two computer models were selected for estimating required sediment load reductions. The first, the Generalized Watershed Loading Functions (GWLF) model, was selected because it has been used frequently in stressor simulation for other benthically-impaired watersheds in Virginia, and because it was used for the Stroubles Creek Benthic TMDL (Mostaghimi et al., 2003). The second model selected, the Soil and Water Assessment Tool (SWAT), was chosen because it is more complex than GWLF but it is well documented and has been used for TMDL development in other states. Reference watersheds were selected from among the benthically-unimpaired watersheds in Virginia. The three watersheds selected for this research, Upper Opequon Creek, Upper Quail Run, and Tom's Creek, all have similar characteristics to the impaired watershed. There is no commonly

accepted scientific procedure for the selection of reference watersheds; selection is based on best professional judgment of available data and, in some cases, public perception.

It was discovered that the choice of land use information caused different sediment reductions to be required in the impaired Stroubles Creek watershed. When Tom's Creek is the reference watershed, the reductions required by modeling with DOQQ-based land use information are 3.48 times greater than the reductions required by modeling with NLCD-based land use information. When different models are used, differences were again seen in the required percent reductions for Stroubles Creek. Tom's Creek watershed has the greatest discrepancy between models. In this watershed, the sediment reductions for the impaired watershed required by modeling with GWLF are 2.75 times greater than those required by modeling with SWAT. Choice of reference watershed also causes differences in required percent reductions. The reference watersheds were compared in the three studied modeling environments: GWLF using NLCD-based land use, GWLF using DOQQ-based land use, and SWAT using DOQQ-based land use. The largest differences in required percent reductions are using the GWLF model with land use based on the NLCD: the required reductions based on Upper Quail Run are 6.05 times as great as those required using Tom's Creek, which has the lowest required reductions. When the SWAT model is used to determine sediment loads using DOQQ-based land use, the required reductions based on Upper Quail Run are 4.88 times as great as those required Tom's Creek, which has the lowest required reductions. Clearly, different sources of land use information, different computer models, and different reference watersheds can have a substantial effect on the stressor reduction requirements of a benthic TMDL. Since TMDLs become legal documents, these anomalies should be of concern to environmental regulators.

The differences in TMDL development under varying conditions occur for a number of reasons. When data is derived from different sources, such as different land use layers, the input parameters change considerably, resulting in different sediment loads and therefore different required reductions. Some land uses, such as agriculture, are more influential than others in determining sediment load, and differences in these land uses therefore result in substantial differences in model results. More specific division of general land uses into specific land use types (such as different types of pasture land) also affect the outcome of sediment modeling.

Between land use sources, differentiation into specific land use types is not consistent. The models themselves are also quite different, and the differences in the processes implemented in these models can result in inconsistent requirements for the impaired watershed. Finally, the natural variability in reference watershed characteristics leads to variability in the required percent reductions among the results from the different references. Of this natural variability, the land use differences between reference watersheds is one of the most important contributors to the differences in the required sediment reduction from Stroubles Creek.

### **Reference Watershed Approach Alternatives**

Due to the variability in the Reference Watershed Approach when different water quality models and reference watersheds are selected, a different approach for determining the target stressor load for benthically-impaired waters needs to be developed.

The use of regression equations has been examined as an alternative to the Reference Watershed Approach. In her thesis, Laurie Frondorf developed a series of regression equations relating stressors to RBPII scores and to individual benthic metrics used in developing the RBPII score. These equations, both linear and non-linear, express correlated relationships (Frondorf, 2001). Although these equations are currently limited in scope, further research and experimental application of these equations could promote their use as a replacement for the Reference Watershed Approach. A significant benefit to using these equations instead of the Reference Watershed Approach is that these equations incorporate numerous reference watersheds into the determination of the target load of the stressors, whereas the Reference Watershed Approach only considers one watershed.

An additional alternative to the Reference Watershed Approach is the development of criteria for pollutants that often stress the benthic assemblage. Sediment, nutrients, and organic loadings are commonly identified as the primary stressor in the Stressor Analysis during benthic TMDL development. Although development of criteria for these pollutants is complicated, and may require a suite of criteria for different ecoregions, establishing these criteria would eliminate the need for the Reference Watershed Approach when setting the target load for these stressors

in a waterbody. The benefit of using criteria is that they eliminate inconsistency in TMDL development by establishing the same target goal for all ecologically similar waters.

A third alternative to the Reference Watershed Approach is averaging of the required stressor reductions from several reference watersheds. This would help to eliminate some of the inconsistencies among reference watersheds and would tend toward a more generic reference. When done for the watersheds in this research, as shown in Table 5.1, there is at most a 1.3-fold difference in required reductions between watersheds.

**Table 5.1. Averaging of Required Sediment Reductions among Reference Watersheds.**

	GWLF with DOQQ-based Land Use	GWLF with NLCD-based Land Use	SWAT with DOQQ-based Land Use
<i>Upper Opequan Creek</i> - Required Sediment Reductions	54%	39%	45%
<i>Upper Quail Run</i> - Required Sediment Reductions	73%	87%	88%
<i>Tom's Creek</i> - Required Sediment Reductions	50%	14%	18%
<b>Average</b>	<b>59%</b>	<b>47%</b>	<b>50%</b>
<b>Ratio to of Reductions to Lowest Required Reductions</b>	<b>1.26</b>	<b>1.00</b>	<b>1.08</b>

## *Chapter 6*

### RECOMMENDATIONS FOR FURTHER STUDY

Exploration of the Reference Watershed Approach used in developing TMDLs for benthic impairments has led to several recommendations for further study. These recommendations relate to the benthic TMDL process, computer modeling, and Reference Watershed Approach alternatives.

The benthic TMDL process is unique to Virginia (USEPA, 2004b) and is a unique type of TMDL. Other TMDLs are developed for the stressor itself, but in the case of a benthic TMDL, determining the stressor is part of the process, and rather than stressor reduction being the final indicator of success, it is rather the return of the benthic macroinvertebrate assemblage to an unimpaired condition that is the ultimate goal of the TMDL. The biota of a stream serves as an important sentinel for overall stream health, and biological monitoring should continue to be an integral part of any water quality assessment scheme. However, the TMDL process should be restricted to pollutants and environmental stressors, which conform to the definition of the TMDL process. When biological monitoring reveals an impaired benthic assemblage, further monitoring should be required to adequately determine the stressor(s). Only after several years of further assessment should the TMDL process be initiated, and it should be specifically based on that stressor(s).

In addition to examining the Reference Watershed Approach, the Stressor Analysis must also be reexamined. The determination of the primary stressor(s) in an impaired watershed is made by comparing ambient water quality data from the impaired watershed to another watershed that is not impaired – a reference watershed. The question needs to be addressed as to whether or not the primary stressor(s) change when the reference watersheds in the Stressor Analysis change.

An additional recommendation for further study concerns the certainty of computer modeling. Input parameters are often estimates, but rarely is the certainty of a parameter or the result of a calculation incorporating that parameter considered. Model results are not hard and fast

answers: they are values with percent error. Even when a model can be calibrated and validated in a given watershed, the results of the modeling should be stated to the degree of certainty of the calibration and validation. In addition, the accuracy of the observed data to which calibration and validation is being made should be considered. Since TMDLs establish legal requirements, the uncertainty of the values in TMDLs should not be ignored.

Development and improvement of the calculations in hydrology and pollutant transport models is another area requiring further study. In the Reference Watershed Approach, sediment values are only compared to values resulting from other simulations – the absolute accuracy of the values themselves are not considered. It would be highly beneficial to know the accuracy of the values predicted by the models. This would require observed sediment data to compare to the predicted data.

Although uncertainty in the Reference Watershed Approach has been demonstrated by this study, further research of the Reference Watershed Approach is warranted. Not only should other benthically-impaired watersheds with sediment as the primary stressor be considered, but watersheds with other stressors, such as nutrients, as the primary stressor should also be examined. In addition, the guidelines used to select a reference watershed should be scrutinized to determine which watershed characteristics are the most important for reference watershed selection.

Regression equations have the potential to serve as successful alternatives to the Reference Watershed Approach. Currently, these equations are only valid for a limited number of stressors. Further development of equations would expand their usefulness. For example, the regression equations developed by Frondorf (2001) incorporate habitat parameters that are estimated by DEQ biologists. These parameters are measured subjectively and are unit-less. Currently, no research exists to show how changes in management practices result in changes in these habitat scores, and they cannot serve as TMDL target stressors. Equations would be more useful based on objectively measured stream characteristics (such as total suspended solids) and that are known to improve with certain management practices, assuming that regression equations with good correlation coefficients exist.

In addition, more accurate and reproducible measurements of habitat parameters are required . For example, habitat parameters such as sediment and embeddedness are known to impact the benthic assemblage, but their measurement is currently limited to a subjective scale. Correlating measurements such as total suspended solids, an objectively measurable value, with the habitat values would enhance our ability to measure progress in improving the habitats of the benthic assemblage.

Understanding the way in which stressors affect the benthic macroinvertebrate assemblage is critical for understanding how to improve the health of this assemblage. Further study of critical thresholds for the individual taxa within the benthic macroinvertebrate assemblage could help both to establish criteria for certain stressors and to determine the primary stressor(s) during Stressor Analysis.

As an alternative to the Reference Watershed Approach, Virginia could establish criteria for pollutants such as nutrients, sediment, and organic loading in order to escape the need for a reference watershed. Further research is required before these criteria can be developed appropriately. Additional knowledge of the relationship between benthic macroinvertebrates and stressors is required to establish the level at which the benthic macroinvertebrates become impaired. In addition, criteria for many of these stressors will have to be different in different ecoregions, and therefore an understanding of the natural differences between ecoregions is crucial.

Finally, the implementation of benthic TMDLs requires study. Currently, very little research exists to show the success of implementation of best management practices in restoring the health of the benthic macroinvertebrate assemblage. Since these organisms are the reason for requiring a TMDL, an understanding of how BMPs reduce stressors and consequently how stressor reduction restores the benthic macroinvertebrate assemblage is critical.

## APPENDICES

## **Appendix A: Quail Run Land Use**

For the Quail Run watershed, the DOQQ digitization and land use assignment had been completed prior to this research using categories that did not correspond to the categories in Table 3.2. The Quail Run category list included only one “pasture” category, and excluded “hay”. Proper distribution of the area designated in the Quail Run categories as “pasture” into the necessary categories of “rotational hay”, “improved pasture”, “unimproved pasture”, and “overgrazed pasture” was crucial because the parameters that determine erosion and sediment yield for these characteristics are markedly different and can result in quite different sediment loads. Therefore, the Quail Run categories were adjusted from the DOQQ land uses to the VT TMDL land uses using the following procedure. Estimations for the division of the “pasture” category were developed from a land use definition table determined for each of Virginia’s hydrologic unit (HUP) for DCR’s statewide non-point source pollution (NPS) assessment in 2002. (Yagow et al., 2002) In this file, the relevant land uses were “hay”, “pasture”, “cattle-grazed pasture”, “pasture that has had poultry litter applied”, and “pasture that has had manure applied”. Categorical matching of the NPS-assessment categories to the desired categories for this research is shown in Table A.1. The percentage of each of the four desired VT TMDL categories (“hay”, “improved pasture”, “unimproved pasture”, and “overgrazed pasture”) out of the total “pasture” (including “hay”, “pasture”, “poultry litter-applied pasture”, “manure-applied pasture”, and “cattle-grazed pasture” from the NPS Assessment categories) in the hydrologic unit were calculated. These percentages were then applied to the total “pasture” in the DOQQ-derived land use to develop approximations of the amount of land in “hay”, “improved pasture”, “unimproved pasture”, and “overgrazed pasture” in the Quail Run watershed.

**Table A.1. Pasture Assessment for Quail Run.**

<b>Statewide NPS Assessment Category</b>	<b>VT TMDL Category</b>
Hay	Hay
Pasture	Improved pasture
Poultry litter-applied pasture Manure-applied pasture	Unimproved pasture
Cattle-grazed pasture	Overgrazed pasture

## **Appendix B: GWLF Parameter Descriptions**

The text below was written by Dr. Gene Yagow (Yagow, 2004) to describe the parameters used in the GWLF transport file. Page numbers refer to the GWLF Manual (Haith et al., 1992). Comments regarding specific decisions made for this research are included in italics. In addition to these parameters, several others are defined following his text.

### ***Watershed-Related Parameter Descriptions***

No. of Rural Land Uses: The number of land uses simulated with both runoff and sediment components.

No. of Urban Land Uses: The number of land uses simulated with a build-up/wash off component.

Recession coefficient (day<sup>-1</sup>): The recession coefficient is a measure of the rate at which stream flow recedes following the cessation of a storm, and is approximated by averaging the ratios of stream flow on any given day to that on the following day during a wide range of weather conditions, all during the recession limb of each storm's hydrograph. Calculate using GWLF manual guidance (p.30), or use a default value = 0.0, then calibrate.

*A value of 0.06 was used for the recession coefficient for all runs in this research. Although this value could not be calibrated for Stroubles Creek, the impaired watershed, the value of 0.06 was chosen based on other watersheds in the region that could be calibrated. This value was used for all the reference watersheds to provide consistency across the runs.*

Seepage coefficient (day<sup>-1</sup>): The seepage coefficient represents the amount of flow lost as seepage to deep storage. Use a default value = 0.0, then calibrate (GWLF Manual p.30).

Initial unsaturated storage (cm): Initial depth of water stored in the unsaturated (surface) zone. Use the recommended default value of 10 cm (GWLF Manual, p.36).

Initial saturated storage (cm): Initial depth of water stored in the saturated zone. Use the recommended default value of 0 cm.

Initial snow (cm): Initial amount of snow on the ground at the beginning of the simulation. Use the recommended default value of 0 cm.

Sediment delivery ratio: The fraction of erosion – detached sediment – that is transported or delivered to the edge of the stream. The GWLF Manual (p.31-32) presents a graphical procedure, but for our modeling, the following algorithms from AVGWLF were used to calculate SDR based on the square kilometers of land (Land\_sqkm) in each watershed:

$$\text{Land\_sqkm} < 50: \quad \text{SDR} = 0.000005 * \text{Land\_sqkm}^2 - 0.0014 * \text{Land\_sqkm} + 0.198 \quad \text{Eq. B.1.}$$

$$\text{Land\_sqkm} \geq 50: \quad \text{SDR} = 0.4518 * (\text{Land\_sqkm})^{-0.298} \quad \text{Eq. B.2.}$$

Unsaturated Soil Moisture Capacity (SMC): The amount of moisture in the root zone. SMC was estimated as the depth of the rooting zone times the soil volumetric available water capacity (AWC). An average rooting depth of 100 cm was used as recommended in the GWLF manual (p.30). AWC was calculated as an area-weighted average available water

capacity SSURGO attribute in cm/cm, from all soils within each watershed. SMC was calculated as  $100 * AWC$ .

**Climatic Records:** Model simulations are run from April through December in the first year to initialize storages denoted by and were not included in the model output load summaries. Therefore, the number of years that need to be input to GWLF is the full number of calendar years of data + 1 for the initialization period.

- A. **No. of Years:** The number of years of weather data in the *weather.dat* file to be used in any given simulation run.
- B. **Beg. Year:** The 4-digit calendar year corresponding to the beginning month of weather data.
- C. **End Year:** The 4-digit calendar year corresponding to the last month of weather data.

**Antecedent Rainfall for each of 5 previous days (cm):** The amount of rainfall on each of the five days preceding the first day in the weather file. Use a default value = 0 for each day.

### ***Month-Related Parameter Descriptions***

**Month:** Months are ordered, starting with April and ending with March – in keeping with the design of the model and its assumption that stored sediment is flushed from the system at the end of each Apr-Mar cycle.

**ET CV:** The composite evapotranspiration cover coefficient for each watershed. A CV is assigned to each land use for dormant (Ket\_Dorm) and growing (Ket\_Grow) months, based on GWLF guidance (p.23,28-29). A composite area-weighted Ket\_Dorm and Ket\_Grow is calculated in the spreadsheets, based on the distribution of land uses within each watershed. A routine from AVGWLF was modified to vary the ET\_CV from month to month, based on the composite Ket\_Dorm and Ket\_Grow values for each watershed.

**Hours per Day:** Mean number of daylight hours. The centroid latitude was calculated for each watershed, and monthly values interpolated from Table B-9 in the GWLF manual (p.29).

**Growing Season:** This flag is set to “0” for dormant months and “1” for months during the growing season. The growing season was defined as the period between the 50% Probabilities of occurrence of the Last Freeze Date in Spring and the First Freeze Date in Fall (Climatology of the U.S., No. 20, April 1978, NOAA). These dates were obtained for 87 National Weather Stations across the state, and contour plots generated in ArcView to define monthly boundaries for beginning and ending months. Beginning and ending months were then assigned to each watershed.

**Erosion Coefficient:** This is a regional coefficient used in Richardson’s equation for calculating daily rainfall erosivity. Values for this two-part coefficient were assigned to watersheds based on the Rainfall Erosivity Zones defined in the GWLF manual (p.31,36). Separate values were assigned to the months October-March (the “Rain\_Cool” parameter), and for April-September (the “Rain\_Warm” parameter). Assignment to individual watersheds was enhanced by relating the Erosivity Zones to the Virginia Climatic Zones in RUSLE, which provided a clearer basis for delineating the zones. Zone 21 values were used for the mountainous zone in Virginia (Clim\_zone 110).

## ***Land use-Related Parameter Descriptions***

**Land Use:** A descriptor for the various land uses simulated in the model.

**Area ha:** The area of each land use in a watershed in hectares. The area of each land use in a watershed was determined from GIS cross-tabulation of the watershed/sub-watershed boundary and either DOQQ or MRLC land cover. The split between hi-till and lo-till cropland came from a 2002 DCR land use inventory (Yagow et al., 2002), and division between pervious and impervious urban land uses was based on standard definitions in TR-55 (USDA, 1986).

**Curve Number:** The SCS curve number (CN) is used in calculating runoff associated with a daily rainfall event. The SCS curve number (CN) for any land use is a function of the hydrologic soil group (HSG) characteristic of the associated soils in each watershed. The GWLF manual provides general guidance (p.23-27). The CN values need to be calculated as an area-weighted average of CNs related to the watershed-specific proportionate extent of soils in each of the four HSG groups – A, B, C, and D. Values associated with each land use/HSG combination are included in Table C.1

**KLSCP:** This parameter is the product of the K, LS, C, and P factors from the universal soil loss equation (USLE). General GWLF guidance is provided (p.30-35). This product was calculated after evaluating the following individual USLE factors:

K-factor: obtained as an attribute of SSURGO soils

LS-factor: calculated according to the metric version of USLE procedures (Wischmeier and Smith, 1978) as:

$$LS = 5.8 \cdot (L/22.13)^m \cdot (0.065 + 0.043 \cdot S + 0.0065 \cdot S^2) \quad \text{Eq. B.3.}$$

where  $m = 0.2$ , for  $S \leq 1.0$ ,  
 $m = 0.3$ ,  $1.0 < S \leq 3.5$ ,  
 $m = 0.4$ ,  $3.5 < S \leq 4.5$ ,  
 $m = 0.5$ , for  $S > 4.5$ ,  
 $S =$  slope, (%),

Slope was evaluated from 30-m DEMs as the average slope within each HRU.

$L =$  slope length, (m).

Slope length (L) was calculated by watershed based on the expected inverse relationship with average slope shown in the equation below:

$$L = 121.92 - 3.556 \cdot (\% \text{ slope})$$

- a. C-factor: evaluated as a function of both land use and physiographic region. The initial C-factor values by land use and the 10 regions used in the 2002 Statewide NPS Assessment and their respective sources, are included in Table C.1. (Yagow et al., 2002)
- b. P-factor: currently assigned a default value = 1. This factor could also be used to account for BMP implementation by land use.

### ***Channel Erosion Parameters (Evans, 2003)***

% Developed land: percentage of the watershed with urban-related land uses – defined as all land in MDR, HDR, and COM land uses, as well as the impervious portions of LDR.

Animal density: calculated as the number of beef and dairy 1000-lb equivalent animal units (AU) divided by the watershed area in acres.

Stream length: calculated as the total stream length of natural stream channel, in meters. Excludes the non-erosive hardened and piped sections of the stream.

Stream length with livestock access: calculated as the total stream length in the watershed where livestock have unrestricted access to streams, resulting in stream bank trampling, in meters.

Mean channel depth (m): calculated from relationships developed for the Chesapeake Bay Watershed Model by physiographic region, of the general form  $y = a * A^b$ , where  $y$  = mean channel depth in ft,  $A$  = drainage area in square miles, and “a” and “b” are regional coefficients.

### ***Additional GWLF Parameters***

The following descriptions were written to explain parameters not addressed described by Yagow (2004).

**ET Adjustment Factor:** An additive factor for adjusting all ET cover coefficients; used for calibration; default is zero.

**ET Flag:** Value of 0 means that evapotranspiration is calculated from saturated vapor pressure using the Hamon equation; value of 1 means that evapotranspiration is calculated using the Blaney-Criddle formula.

**a Factor:** “The value of the empirically-derived ‘a’ constant is related to a wide variety of watershed characteristics such as the amount of infiltration, runoff, inherent soil erodibility, amount of rainfall, and other watershed-related factors (Prosser et al., 2001; Rutherford, 2000).” (Evans et al., 2003) This parameter is calculated as:

$$a = (0.000452 * PD) + (0.000033 * AD) + (0.000005 * CN) + (0.000522 * K) - 0.000514$$

where : a = the empirical constant for calculating LER as described above,  
PD = percent developed land in watershed,  
AD = animal density measured in Animal Units/acre, **Eq. B.4**  
CN = area-weighted curve number,  
K = area-weighted soil erodibility factor.

A minimum value of  $1 \times 10^{-7}$  is required. (Evans et al., 2003)

**Sediment Build-up Rate:** in units of kg/ha-day, the mass of suspended solids that is expected to accumulate on an impervious surface. This parameter is in the nutrient file. *Based on descriptions in the GWLF User’s Manual (Table B-17, p. 41), values used in this research are: LDR= 2.5, MDR= 6.2, HDR= 3.9, COM= 2.8 (all in kg/ ha-day).*

**Appendix C: Example Parameter Development Lookup Table for GWLF**

**Table C.1. Curve Number, USLE Cropping Factor, and Sediment Accumulation Rate Lookup Tables for GWLF parameters.**

TMDL LU	Land Use	Description	Curve Number for HSG:				CN_Source	CF_1	CF_Source	Ket_D	Ket_Gr
			A	B	C	D					
3	pasture1	pasture, good or improved	39.0	61.0	74.0	80.0		0.003		1.00	1.00
4	pasture2	pasture, fair or unimproved	49.0	69.0	79.0	84.0		0.013	AVGWLF low intensity urban, p.51	1.00	1.00
5	pasture3	pasture, poor or overgrazed	68.0	79.0	86.0	89.0		0.071		1.00	1.00
6	open urban grass	close-seeded...,contour, good	55.0	69.0	78.0	83.0	TR-55, p.2-6	0.01300		1.00	1.00
7	hay	close-seeded...,contour, good	55.0	69.0	78.0	83.0	TR-55, p.2-6	0.01300		0.60	1.00
10	pur_L_resid	low intensity residential, 88% pervious	49.0	69.0	79.0	84.0	GWLF,p27,openspace-fair	0.003		1.00	1.00
11	pur_M_resid	med intensity residential, 70% pervious	49.0	69.0	79.0	84.0	GWLF,p27,openspace-fair	0.003		1.00	1.00
12	pur_H_resid	high intensity residential, 35% pervious	49.0	69.0	79.0	84.0	GWLF,p27,openspace-fair	0.003	Hession,p.12	1.00	1.00
13	pur_H_com	high intensity commercial, 21% pervious	49.0	69.0	79.0	84.0	GWLF,p27,openspace-fair	0.003	1/2 that of pervious urban	1.00	1.00
14	imp_L_resid	low intensity residential, 12% impervious	83.0	89.0	92.0	93.0	GWLF,p27,paved w/ open ditches		PermPast, no canopy, 80% G cover	0.00	0.00
15	imp_M_resid	med intensity residential, 30% impervious	98.0	98.0	98.0	98.0	GWLF,p27,paved with curbs		PermPast, no canopy, 60% G cover	0.00	0.00
16	imp_H_resid	high intensity residential, 65% impervious	98.0	98.0	98.0	98.0	GWLF,p27,paved with curbs		Hession,p.12	0.00	0.00
17	imp_H_com	high intensity commercial, 79% impervious	98.0	98.0	98.0	98.0	GWLF,p27,paved with curbs		Hession,p.12	0.00	0.00
8	forest	woods, fair	36.0	60.0	73.0	79.0	TR-55, p.2-7	0.00050	Modeled as dissolved nutrients only!	0.80	1.00
9	transitional	fallow, bare soil	77.0	86.0	91.0	94.0	TR-55, p.2-6	0.175	Hession,p.12	0.30	0.30
2	LOW_TILL	N. Mtn&Valley (Region 1)	67.3	77.3	84.5	87.7	**	0.155	Hession, p.25	0.55	1.00
1	HIGH_TILL	N. Mtn&Valley (Region 1)	69.2	79.2	86.4	89.8	**	0.352	"	0.40	1.00
2	LOW_TILL	S. Mtn&Valley (Region 2)	69.3	79.1	86.3	89.4	**	0.180	"	0.55	1.00
1	HIGH_TILL	S. Mtn&Valley (Region 2)	70.9	80.6	87.8	91.1	**	0.325	"	0.40	1.00
2	LOW_TILL	N. Piedmont (Region 3)	65.9	76.3	83.5	86.6	**	0.114	"	0.55	1.00
1	HIGH_TILL	N. Piedmont (Region 3)	68.1	78.6	85.7	89.4	**	0.317	"	0.40	1.00
2	LOW_TILL	S. Piedmont (Region 4)	65.9	76.3	83.5	86.6	**	0.170	"	0.55	1.00
1	HIGH_TILL	S. Piedmont (Region 4)	68.1	78.6	85.7	89.4	**	0.356	"	0.40	1.00
2	LOW_TILL	N. Coastal Plain (Region 5)	67.2	77.3	84.4	87.5	**	0.217	"	0.55	1.00
1	HIGH_TILL	N. Coastal Plain (Region 5)	69.2	79.2	86.3	89.8	**	0.380	"	0.40	1.00
2	LOW_TILL	S. Coastal Plain (Region 6)	60.4	74.6	82.9	86.8	**	0.238	"	0.55	1.00
1	HIGH_TILL	S. Coastal Plain (Region 6)	61.2	75.3	83.7	87.7	**	0.466	"	0.40	1.00
2	LOW_TILL	Bayside	60.4	74.6	82.9	86.8	**	0.238	"	0.55	1.00
1	HIGH_TILL	Bayside	61.2	75.3	83.7	87.7	**	0.466	"	0.40	1.00
2	LOW_TILL	Eastern Shore	60.4	74.6	82.9	86.8	**	0.238	"	0.55	1.00
1	HIGH_TILL	Eastern Shore	61.2	75.3	83.7	87.7	**	0.466	"	0.40	1.00
2	LOW_TILL	Frederick County	67.3	77.3	84.5	87.7	**	0.155	"	0.55	1.00
1	HIGH_TILL	Frederick County	69.2	79.2	86.4	89.8	**	0.352	"	0.40	1.00
2	LOW_TILL	Northern Virginia	65.9	76.3	83.5	86.6	**	0.114	"	0.55	1.00
1	HIGH_TILL	Northern Virginia	68.1	78.6	85.7	89.4	**	0.317	"	0.40	1.00

In the "Source" Columns, TR-55 refers to USDA, 1986; GWLF refers to Haith et al., 1992; AVGWLF refers to Evans et al., 2001; Hession refers to Hession et al., 1997.

## **Appendix D: GWLF Input Files**

### **Transport.dat**

In order to facilitate comparison of parameters between watersheds, the input files have been dissected and put into tables. Lines one and two of the GWLF transport files are shown in Table D.1 and Table D.4. In GWLF, “rural” land uses are those that are pervious, and “urban” land uses are impervious. These were previously defined in Table 3.3. Five days of antecedent rainfall are the next parameters in the transport file, listed on lines 3-7; for all watersheds, these are zero, since the model is run for many years, rendering the initial five days of antecedent rainfall inconsequential. The other parameters in the transport files are shown in Table D.2, Table D.3, Table D.5, Table D.6, and Table D.7. Parameters organized by month are the month label, evapotranspiration cover coefficient, daylight hours, growing season flag, and erosion coefficient; these are listed next in the transport file. Next parameters organized by land use are listed, which include the land use type, area, curve number, USLE parameters “KLSCP,” and a land use abbreviation. In these tables, “d” represents DOQQ-based land use; “n” represents NLCD-based land use; “A” stands for “adjusted,” meaning that this file represents reference watershed parameters that have been area-adjusted to the impaired watershed. In addition to these abbreviations, the Stroubles Creek subbasins that have been aggregated with their upstream watersheds to allow for correct modeling are represented with an “x”; that is, the file named “1x” is based on subbasin 1 combined with all the subbasins that contribute to subbasin 1. See Figure 3.2 for subbasin locations. The transport files themselves, which are titled “transportXX.dat” (the XX is the file number), are included after the tables. The lookup tables for parameter development from the “LANDUSE” and “WATERSHED” spreadsheets are also included following the transport files.

### **Nutrient.dat**

Only one parameter in the nutrient file is relevant to sediment modeling: the sediment build-up or accumulation rate on impervious surfaces. These values are bolded in the nutrient.dat file. The rest of the values used in the nutrient files are dummy values since nutrients were not being modeled and these parameters do not affect sediment loss.

**Table D.1. GWLF Parameters, NLCD- and DOQQ-based Land Use, lines 1-2; Stroubles Creek and Reference Watersheds.**

File Name	Transport File Number	Number of Rural Land Uses	Number of Urban Land Uses	ET adjustment factor for calibration	Recession Coefficient (day-1)	Seepage Coefficient (day-1)	Initial Unsaturated Storage (cm)	Initial Saturated Storage (cm)	Initial Snow (cm)
STEd	14	13	4	0	0.06	0	10	0	0
OPEdA	15	13	4	0	0.06	0	10	0	0
QALdA	16	13	4	0	0.06	0	10	0	0
TOMdA	17	13	4	0	0.06	0	10	0	0
STEn	5	13	4	0	0.06	0	10	0	0
HYSnA	7	13	4	0	0.06	0	10	0	0
OPEnA	8	13	4	0	0.06	0	10	0	0
QALnA	9	13	4	0	0.06	0	10	0	0
TOMnA	10	13	4	0	0.06	0	10	0	0

File Name	Transport File Number	Sediment Delivery Ratio	Unsaturated Available Water Capacity	Number of Years	Beginning Year	Ending Year	ET Formula Flag	a Factor	Total Stream Length (m)	Mean Channel Depth (m)
STEd	14	0.1665	12.61	11	1984	1995	0	1.68E-04	22974.0	1.5
OPEdA	15	0.1665	14.00	11	1984	1995	0	5.43E-05	18405.3	1.5
QALdA	16	0.1665	13.94	11	1984	1995	0	4.01E-05	44043.2	1.5
TOMdA	17	0.1665	12.81	11	1984	1995	0	4.54E-05	21088.6	1.5
STEn	5	0.1665	15.15	11	1984	1995	0	9.59E-05	22974.0	1.5
HYSnA	7	0.1665	14.72	11	1984	1995	0	1.00E-07	17729.2	1.5
OPEnA	8	0.1665	14.04	11	1984	1995	0	2.31E-05	18365.9	1.5
QALnA	9	0.1665	11.51	11	1984	1995	0	1.00E-07	44043.2	1.5
TOMnA	10	0.1665	13.27	11	1984	1995	0	6.90E-06	21117.8	1.5

\*STEd is the entire Stroubles Creek watershed. d = DOQQ land use; n = NLCD land use. A = area adjusted to match impaired watershed.

Table D.2. GWLF parameters, DOQQ-based, lines 8-end, Stroubles Creek and Reference Watersheds.

transport14 STED					transport15 OPEdA					transport16 QALdA					transport17 TOMdA				
Month	ET CC	Day hrs	Grow Flag	Eros Coeff	Month	ET CC	Day hrs	Grow Flag	Eros Coeff	Month	ET CC	Day hrs	Grow Flag	Eros Coeff	Month	ET CC	Day hrs	Grow Flag	Eros Coeff
APR	0.821	12.96	0	0.3	APR	0.940	13.00	0	0.3	APR	0.959	13.00	0	0.3	APR	0.942	12.96	0	0.3
MAY	0.825	13.92	1	0.3	MAY	0.944	14.06	1	0.3	MAY	0.965	14.02	1	0.3	MAY	0.947	13.92	1	0.3
JUN	0.826	14.42	1	0.3	JUN	0.946	14.61	1	0.3	JUN	0.967	14.54	1	0.3	JUN	0.949	14.42	1	0.3
JUL	0.826	14.22	1	0.3	JUL	0.946	14.36	1	0.3	JUL	0.967	14.32	1	0.3	JUL	0.949	14.22	1	0.3
AUG	0.826	13.36	1	0.3	AUG	0.946	13.51	1	0.3	AUG	0.967	13.44	1	0.3	AUG	0.949	13.36	1	0.3
SEP	0.822	12.20	1	0.3	SEP	0.941	12.20	1	0.3	SEP	0.960	12.20	1	0.3	SEP	0.943	12.20	1	0.3
OCT	0.806	11.04	1	0.1	OCT	0.920	11.00	1	0.1	OCT	0.932	11.00	1	0.1	OCT	0.919	11.04	1	0.1
NOV	0.778	10.04	0	0.1	NOV	0.885	9.89	0	0.1	NOV	0.882	9.96	0	0.1	NOV	0.877	10.04	0	0.1
DEC	0.754	9.48	0	0.1	DEC	0.854	9.29	0	0.1	DEC	0.840	9.36	0	0.1	DEC	0.841	9.48	0	0.1
JAN	0.746	9.78	0	0.1	JAN	0.844	9.59	0	0.1	JAN	0.826	9.66	0	0.1	JAN	0.829	9.78	0	0.1
FEB	0.786	10.64	0	0.1	FEB	0.895	10.55	0	0.1	FEB	0.896	10.58	0	0.1	FEB	0.889	10.64	0	0.1
MAR	0.813	11.80	0	0.1	MAR	0.930	11.80	0	0.1	MAR	0.944	11.80	0	0.1	MAR	0.930	11.80	0	0.1

Land Use	Area (ha)	CN	KLSCP	LU flag	Land Use	Area (ha)	CN	KLSCP	LU flag	Land Use	Area (ha)	CN	KLSCP	LU flag	Land Use	Area (ha)	CN	KLSCP	LU flag
HIGH_T	9.43	87.49	0.862	hit	HIGH_T	75.84	84.10	0.434	hit	HIGH_T	0.00	85.53	0.000	hit	HIGH_T	1.04	87.56	1.125	hit
LOW_TI	117.95	85.92	0.477	lot	LOW_TI	58.12	84.10	0.191	lot	LOW_TI	0.00	83.66	0.000	lot	LOW_TI	12.96	85.97	0.623	lot
pastur	469.80	73.41	0.011	pag	pastur	1022.07	73.40	0.006	pag	pastur	10.31	72.48	0.008	pag	pastur	392.30	73.41	0.013	pag
pastur	14.23	78.55	0.069	pa2	pastur	159.85	78.51	0.025	pa2	pastur	14.89	77.83	0.033	pa2	pastur	83.02	78.52	0.068	pa2
pastur	19.37	85.67	0.199	pa3	pastur	5.14	85.66	0.109	pa3	pastur	11.45	85.18	0.178	pa3	pastur	15.22	85.67	0.299	pa3
open u	312.86	77.61	0.038	ugr	open u	58.45	77.76	0.024	ugr	open u	59.47	76.95	0.048	ugr	open u	17.63	77.77	0.056	ugr
hay	4.67	77.61	0.042	hay	hay	100.49	77.76	0.027	hay	hay	20.62	76.95	0.033	hay	hay	3.10	77.77	0.018	hay
forest	684.35	72.41	0.004	for	forest	698.63	72.34	0.002	for	forest	1726.79	71.48	0.004	for	forest	1438.96	72.35	0.004	for
transi	18.18	90.79	0.679	trn	transi	17.65	90.87	0.554	trn	transi	0.00	90.42	0.000	trn	transi	36.27	90.87	1.450	trn
pur_L	49.11	78.55	0.014	puL	pur_L	37.00	78.51	0.007	puL	pur_L	543.76	77.83	0.017	puL	pur_L	302.32	78.52	0.016	puL
pur_M	246.24	78.55	0.009	puM	pur_M	93.62	78.51	0.004	puM	pur_M	0.00	77.83	0.000	puM	pur_M	57.29	78.52	0.014	puM
pur_H	50.32	78.55	0.009	puH	pur_H	3.00	78.51	0.002	puH	pur_H	3.42	77.83	0.006	puH	pur_H	0.00	78.52	0.000	puH
pur_H	56.50	78.55	0.007	puC	pur_H	19.03	78.51	0.006	puC	pur_H	0.00	77.83	0.000	puC	pur_H	9.52	78.52	0.013	puC
imp_L	6.70	91.85	0	iuL	imp_L	5.05	91.77	0	iuL	imp_L	74.15	91.65	0	iuL	imp_L	41.23	91.77	0	iuL
imp_M	105.53	98.00	0	iuM	imp_M	40.12	98.00	0	iuM	imp_M	0.00	98.00	0	iuM	imp_M	24.55	98.00	0	iuM
imp_H	93.45	98.00	0	iuH	imp_H	5.57	98.00	0	iuH	imp_H	6.34	98.00	0	iuH	imp_H	0.00	98.00	0	iuH
imp_H	212.56	98.00	0	iuC	imp_H	71.59	98.00	0	iuC	imp_H	0.00	98.00	0	iuC	imp_H	35.80	98.00	0	iuC

Table D.3. GWLF parameters, NLCD-based, lines 8-end, Stroubles Creek and Reference Watersheds.

transport5 STE					transport7 HYS					transport8 OPE					transport9 QAL					transport10 TOM				
Month	ET CC	Day hrs	Grow Flag	Eros Coeff	Month	ET CC	Day hrs	Grow Flag	Eros Coeff	Month	ET CC	Day hrs	Grow Flag	Eros Coeff	Month	ET CC	Day hrs	Grow Flag	Eros Coeff	Month	ET CC	Day hrs	Grow Flag	
APR	0.912	12.96	0	0.3	APR	0.991	13.00	0	0.3	APR	0.973	13.00	0	0.3	APR	0.973	13.00	0	0.3	APR	0.980	12.96	0	
MAY	0.917	13.92	1	0.3	MAY	0.997	14.00	1	0.3	MAY	0.977	14.06	1	0.3	MAY	0.980	14.02	1	0.3	MAY	0.988	13.92	1	
JUN	0.919	14.42	1	0.3	JUN	0.999	14.50	1	0.3	JUN	0.979	14.61	1	0.3	JUN	0.983	14.54	1	0.3	JUN	0.990	14.42	1	
JUL	0.919	14.22	1	0.3	JUL	0.999	14.30	1	0.3	JUL	0.979	14.36	1	0.3	JUL	0.983	14.32	1	0.3	JUL	0.990	14.22	1	
AUG	0.919	13.36	1	0.3	AUG	0.999	13.40	1	0.3	AUG	0.979	13.51	1	0.3	AUG	0.983	13.44	1	0.3	AUG	0.990	13.36	1	
SEP	0.913	12.20	1	0.3	SEP	0.992	12.20	1	0.3	SEP	0.974	12.20	1	0.3	SEP	0.975	12.20	1	0.3	SEP	0.982	12.20	1	
OCT	0.891	11.04	1	0.1	OCT	0.965	11.00	1	0.1	OCT	0.954	11.00	1	0.1	OCT	0.941	11.00	1	0.1	OCT	0.949	11.04	1	
NOV	0.852	10.04	0	0.1	NOV	0.918	10.00	0	0.1	NOV	0.918	9.89	0	0.1	NOV	0.883	9.96	0	0.1	NOV	0.892	10.04	0	
DEC	0.819	9.48	0	0.1	DEC	0.877	9.40	0	0.1	DEC	0.888	9.29	0	0.1	DEC	0.833	9.36	0	0.1	DEC	0.843	9.48	0	
JAN	0.808	9.78	0	0.1	JAN	0.864	9.70	0	0.1	JAN	0.878	9.59	0	0.1	JAN	0.816	9.66	0	0.1	JAN	0.827	9.78	0	
FEB	0.864	10.64	0	0.1	FEB	0.931	10.60	0	0.1	FEB	0.928	10.55	0	0.1	FEB	0.899	10.58	0	0.1	FEB	0.908	10.64	0	
MAR	0.901	11.80	0	0.1	MAR	0.977	11.80	0	0.1	MAR	0.963	11.80	0	0.1	MAR	0.956	11.80	0	0.1	MAR	0.964	11.80	0	

Land Use	Area (ha)	CN	KLSCP	LU flag	Land Use	Area (ha)	CN	KLSCP	LU flag	Land Use	Area (ha)	CN	KLSCP	LU flag	Land Use	Area (ha)	CN	KLSCP	LU flag	Land Use	Area (ha)	CN	KLSCP
HIGH_T	7.89	87.49	1.118	hit	HIGH_T	7.18	85.38	1.330	hit	HIGH_T	66.05	84.11	0.653	hit	HIGH_T	0.75	85.34	1.215	hit	HIGH_T	5.36	86.81	2.049
LOW_TI	98.76	85.92	0.619	lot	LOW_TI	30.94	83.79	0.737	lot	LOW_TI	50.62	84.11	0.287	lot	LOW_TI	0.75	83.46	0.535	lot	LOW_TI	67.04	85.24	1.135
pastur	172.76	73.41	0.011	pag	pastur	293.28	69.47	0.015	pag	pastur	572.70	73.41	0.006	pag	pastur	49.21	72.12	0.009	pag	pastur	168.90	72.17	0.017
pastur	405.60	78.55	0.048	pa2	pastur	707.78	75.50	0.065	pa2	pastur	750.96	78.52	0.025	pa2	pastur	24.19	77.58	0.039	pa2	pastur	396.54	77.60	0.075
pastur	0.05	85.67	0.263	pa3	pastur	0.08	83.55	0.352	pa3	pastur	0.02	85.67	0.139	pa3	pastur	34.36	84.98	0.215	pa3	pastur	0.05	85.02	0.410
open u	61.02	77.61	0.021	ugr	open u	0.00	75.03	0.000	ugr	open u	5.75	77.77	0.028	ugr	open u	0.00	76.75	0.000	ugr	open u	0.00	76.75	0.023
hay	96.68	77.61	0.048	hay	hay	155.45	75.03	0.065	hay	hay	43.56	77.77	0.025	hay	hay	26.46	76.75	0.039	hay	hay	94.52	76.75	0.075
forest	934.47	72.41	0.001	for	forest	1271.44	68.42	0.001	for	forest	844.52	72.35	0.001	for	forest	2005.01	71.12	0.000	for	forest	1659.76	71.17	0.002
transl	33.30	90.79	0.605	trn	transl	1.70	89.35	1.170	trn	transl	30.78	90.87	0.420	trn	transl	3.75	90.31	1.745	trn	transl	12.59	90.31	1.039
pur_L	451.99	78.55	0.006	puL	pur_L	2.92	75.50	0.010	puL	pur_L	68.44	78.52	0.008	puL	pur_L	287.69	77.58	0.015	puL	pur_L	48.94	77.60	0.010
pur_M	0.00	78.55	0.006	puM	pur_M	0.00	75.50	0.010	puM	pur_M	0.00	78.52	0.008	puM	pur_M	0.00	77.58	0.015	puM	pur_M	0.00	77.60	0.010
pur_H	1.26	78.55	0.007	puH	pur_H	0.00	75.50	0.010	puH	pur_H	2.30	78.52	0.008	puH	pur_H	0.00	77.58	0.015	puH	pur_H	0.00	77.60	0.010
pur_H	30.16	78.55	0.006	puC	pur_H	0.05	75.50	0.010	puC	pur_H	4.64	78.52	0.008	puC	pur_H	0.00	77.58	0.015	puC	pur_H	2.32	77.60	0.010
imp_L	61.64	91.85	0	iuL	imp_L	0.40	90.87	0	iuL	imp_L	9.33	91.77	0	iuL	imp_L	39.23	91.55	0	iuL	imp_L	6.67	91.57	0
imp_M	0.00	98.00	0	iuM	imp_M	0.00	98.00	0	iuM	imp_M	0.00	98.00	0	iuM	imp_M	0.00	98.00	0	iuM	imp_M	0.00	98.00	0
imp_H	2.34	98.00	0	iuH	imp_H	0.00	98.00	0	iuH	imp_H	4.26	98.00	0	iuH	imp_H	0.00	98.00	0	iuH	imp_H	0.00	98.00	0
imp_H	113.48	98.00	0	iuC	imp_H	0.19	98.00	0	iuC	imp_H	17.47	98.00	0	iuC	imp_H	0.00	98.00	0	iuC	imp_H	8.72	98.00	0

**Table D.4. GWLF Parameters, lines 1-2, for Stroubles Creek Subbasins; DOQQ-based Land Use.**

Watershed Name	Transport File Number	Number of Rural Land Uses	Number of Urban Land Uses	ET adjustment factor for calibration	Recession Coefficient (day-1)	Seepage Coefficient (day-1)	Initial Unsaturated Storage (cm)	Initial Saturated Storage (cm)	Initial Snow (cm)
STE1	141	13	4	0	0.06	0	10	0	0
STE2	142	13	4	0	0.06	0	10	0	0
STE3	143	13	4	0	0.06	0	10	0	0
STE4	144	13	4	0	0.06	0	10	0	0
STE5	145	13	4	0	0.06	0	10	0	0
STE6	146	13	4	0	0.06	0	10	0	0
STE7	147	13	4	0	0.06	0	10	0	0
STE8	148	13	4	0	0.06	0	10	0	0
1x	149	13	4	0	0.06	0	10	0	0
2x	1410	13	4	0	0.06	0	10	0	0
4x	1411	13	4	0	0.06	0	10	0	0
8x	1412	13	4	0	0.06	0	10	0	0

Watershed Name	Transport File Number	Sediment Delivery Ratio	Unsaturated Available Water Capacity	Number of Years	Beginning Year	Ending Year	ET Formula Flag	a Factor	Total Stream Length (m)	Mean Channel Depth (m)
STE1	141	0.1895	0.1177	11	1984	1995	0	1.00E-07	5,734.3	1.5
STE2	142	0.1958	0.1347	11	1984	1995	0	2.88E-05	869.5	1.5
STE3	143	0.1954	0.1672	11	1984	1995	0	6.70E-05	1,861.6	1.5
STE4	144	0.1937	0.1751	11	1984	1995	0	1.75E-04	3,557.8	1.5
STE5	145	0.1942	0.1665	11	1984	1995	0	2.15E-04	2,121.7	1.5
STE6	146	0.1920	0.1589	11	1984	1995	0	3.40E-04	807.4	1.5
STE7	147	0.1942	0.1641	11	1984	1995	0	3.87E-04	1,729.6	1.5
STE8	148	0.1951	0.1648	11	1984	1995	0	1.77E-04	1,902.6	1.5
1x	149	0.1665	0.1516	11	1984	1995	0	1.99E-04	18,584.6	1.5
2x	1410	0.1738	0.1629	11	1984	1995	0	2.59E-04	12,850.3	1.5
4x	1411	0.1780	0.1654	11	1984	1995	0	2.79E-04	10,119.1	1.5
8x	1412	0.1855	0.1618	11	1984	1995	0	3.31E-04	6,561.3	1.5

Table D.5. GWLF parameters, DOQQ-based, lines 8-end; Stroubles Creek Subbasins.

*transport141 STE1*

Month	ET CC	Day hrs	Grow Flag	Eros Coeff
APR	0.978	12.96	0	0.3
MAY	0.985	13.92	1	0.3
JUN	0.988	14.42	1	0.3
JUL	0.988	14.22	1	0.3
AUG	0.988	13.36	1	0.3
SEP	0.979	12.20	1	0.3
OCT	0.945	11.04	1	0.1
NOV	0.885	10.04	0	0.1
DEC	0.834	9.48	0	0.1
JAN	0.817	9.78	0	0.1
FEB	0.902	10.64	0	0.1
MAR	0.961	11.80	0	0.1

*transport142 STE2*

Month	ET CC	Day hrs	Grow Flag	Eros Coeff
APR	0.958	12.96	0	0.3
MAY	0.963	13.92	1	0.3
JUN	0.965	14.42	1	0.3
JUL	0.965	14.22	1	0.3
AUG	0.965	13.36	1	0.3
SEP	0.960	12.20	1	0.3
OCT	0.938	11.04	1	0.1
NOV	0.900	10.04	0	0.1
DEC	0.867	9.48	0	0.1
JAN	0.856	9.78	0	0.1
FEB	0.910	10.64	0	0.1
MAR	0.948	11.80	0	0.1

*transport143 STE3*

Month	ET CC	Day hrs	Grow Flag	Eros Coeff
APR	0.976	12.96	0	0.3
MAY	0.984	13.92	1	0.3
JUN	0.987	14.42	1	0.3
JUL	0.987	14.22	1	0.3
AUG	0.987	13.36	1	0.3
SEP	0.978	12.20	1	0.3
OCT	0.943	11.04	1	0.1
NOV	0.881	10.04	0	0.1
DEC	0.829	9.48	0	0.1
JAN	0.811	9.78	0	0.1
FEB	0.899	10.64	0	0.1
MAR	0.959	11.80	0	0.1

*transport144 STE4*

Month	ET CC	Day hrs	Grow Flag	Eros Coeff
APR	0.838	12.96	0	0.3
MAY	0.840	13.92	1	0.3
JUN	0.841	14.42	1	0.3
JUL	0.841	14.22	1	0.3
AUG	0.841	13.36	1	0.3
SEP	0.839	12.20	1	0.3
OCT	0.830	11.04	1	0.1
NOV	0.814	10.04	0	0.1
DEC	0.800	9.48	0	0.1
JAN	0.796	9.78	0	0.1
FEB	0.819	10.64	0	0.1
MAR	0.834	11.80	0	0.1

Land Use	Area (ha)	CN	KLSCP	LU flag
HIGH_T	0.88	87.64	0.820	hit
LOW_TI	11.01	86.07	0.454	lot
pastur	68.78	73.68	0.014	pag
pastur	2.49	78.76	0.136	pa2
pastur	0.23	85.82	0.184	pa3
open u	1.21	77.80	0.108	ugr
hay	0.00	77.80	0.000	hay
forest	504.83	72.68	0.004	for
transi	0.89	90.89	1.105	trn
pur_L	12.12	78.76	0.017	puL
pur_M	11.53	78.76	0.007	puM
pur_H	0.00	78.76	0.000	puH
pur_H	0.00	78.76	0.000	puC
imp_L	1.65	91.92	0	iuL
imp_M	4.94	98.00	0	iuM
imp_H	0.00	98.00	0	iuH
imp_H	0.00	98.00	0	iuC

Land Use	Area (ha)	CN	KLSCP	LU flag
HIGH_T	0.31	87.92	0.719	hit
LOW_TI	3.85	86.34	0.398	lot
pastur	54.77	74.19	0.013	pag
pastur	1.37	79.16	0.102	pa2
pastur	0.46	86.09	0.550	pa3
open u	0.61	78.17	0.122	ugr
hay	0.00	78.17	0.000	hay
forest	76.80	73.19	0.003	for
transi	3.22	91.11	0.610	trn
pur_L	8.91	79.16	0.015	puL
pur_M	4.95	79.16	0.012	puM
pur_H	0.00	79.16	0.000	puH
pur_H	0.00	79.16	0.000	puC
imp_L	1.22	92.02	0	iuL
imp_M	2.12	98.00	0	iuM
imp_H	0.00	98.00	0	iuH
imp_H	0.00	98.00	0	iuC

Land Use	Area (ha)	CN	KLSCP	LU flag
HIGH_T	4.00	87.95	0.989	hit
LOW_TI	50.05	86.38	0.548	lot
pastur	87.31	74.25	0.012	pag
pastur	0.00	79.23	0.000	pa2
pastur	0.00	86.12	0.000	pa3
open u	1.27	78.25	0.029	ugr
hay	0.00	78.25	0.000	hay
forest	37.87	73.25	0.001	for
transi	0.54	91.16	0.179	trn
pur_L	0.41	79.23	0.003	puL
pur_M	0.48	79.23	0.010	puM
pur_H	0.00	79.23	0.000	puH
pur_H	0.47	79.23	0.007	puC
imp_L	0.06	92.03	0	iuL
imp_M	0.20	98.00	0	iuM
imp_H	0.00	98.00	0	iuH
imp_H	1.76	98.00	0	iuC

Land Use	Area (ha)	CN	KLSCP	LU flag
HIGH_T	1.97	88.03	0.655	hit
LOW_TI	24.64	86.44	0.363	lot
pastur	125.33	74.37	0.008	pag
pastur	0.53	79.33	0.013	pa2
pastur	8.66	86.17	0.203	pa3
open u	55.05	78.38	0.035	ugr
hay	0.00	78.38	0.000	hay
forest	8.69	73.37	0.001	for
transi	2.08	91.24	0.264	trn
pur_L	1.08	79.33	0.006	puL
pur_M	14.63	79.33	0.007	puM
pur_H	15.12	79.33	0.009	puH
pur_H	3.51	79.33	0.006	puC
imp_L	0.15	92.03	0	iuL
imp_M	6.27	98.00	0	iuM
imp_H	28.09	98.00	0	iuH
imp_H	13.20	98.00	0	iuC

**Table D.6. GWLF parameters, DOQQ-based, lines 8-end; Stroubles Creek Subbasins.**

transport145 STE5					transport146 STE6					transport147 STE7					transport148 STE8				
Month	ET CC	Day hrs	Grow Flag	Eros Coeff	Month	ET CC	Day hrs	Grow Flag	Eros Coeff	Month	ET CC	Day hrs	Grow Flag	Eros Coeff	Month	ET CC	Day hrs	Grow Flag	Eros Coeff
APR	0.770	12.96	0	0.3	APR	0.671	12.96	0	0.3	APR	0.571	12.96	0	0.3	APR	0.798	12.96	0	0.3
MAY	0.772	13.92	1	0.3	MAY	0.672	13.92	1	0.3	MAY	0.571	13.92	1	0.3	MAY	0.799	13.92	1	0.3
JUN	0.773	14.42	1	0.3	JUN	0.672	14.42	1	0.3	JUN	0.571	14.42	1	0.3	JUN	0.800	14.42	1	0.3
JUL	0.773	14.22	1	0.3	JUL	0.672	14.22	1	0.3	JUL	0.571	14.22	1	0.3	JUL	0.800	14.22	1	0.3
AUG	0.773	13.36	1	0.3	AUG	0.672	13.36	1	0.3	AUG	0.571	13.36	1	0.3	AUG	0.800	13.36	1	0.3
SEP	0.771	12.20	1	0.3	SEP	0.671	12.20	1	0.3	SEP	0.571	12.20	1	0.3	SEP	0.798	12.20	1	0.3
OCT	0.761	11.04	1	0.1	OCT	0.669	11.04	1	0.1	OCT	0.570	11.04	1	0.1	OCT	0.791	11.04	1	0.1
NOV	0.744	10.04	0	0.1	NOV	0.665	10.04	0	0.1	NOV	0.569	10.04	0	0.1	NOV	0.777	10.04	0	0.1
DEC	0.730	9.48	0	0.1	DEC	0.661	9.48	0	0.1	DEC	0.568	9.48	0	0.1	DEC	0.766	9.48	0	0.1
JAN	0.725	9.78	0	0.1	JAN	0.660	9.78	0	0.1	JAN	0.568	9.78	0	0.1	JAN	0.762	9.78	0	0.1
FEB	0.749	10.64	0	0.1	FEB	0.666	10.64	0	0.1	FEB	0.569	10.64	0	0.1	FEB	0.781	10.64	0	0.1
MAR	0.765	11.80	0	0.1	MAR	0.670	11.80	0	0.1	MAR	0.571	11.80	0	0.1	MAR	0.794	11.80	0	0.1

Land Use	Area (ha)	CN	KLSCP	LU flag	Land Use	Area (ha)	CN	KLSCP	LU flag	Land Use	Area (ha)	CN	KLSCP	LU flag	Land Use	Area (ha)	CN	KLSCP	LU flag
HIGH_T	1.16	87.47	1.120	hit	HIGH_T	0.00	87.74	0.000	hit	HIGH_T	0.00	87.16	1.362	hit	HIGH_T	1.11	87.58	0.691	hit
LOW_TI	14.51	85.91	0.620	lot	LOW_TI	0.00	86.17	0.000	lot	LOW_TI	0.03	85.60	0.755	lot	LOW_TI	13.87	86.01	0.383	lot
pastur	45.65	73.38	0.007	pag	pastur	46.11	73.86	0.017	pag	pastur	0.00	72.81	0.000	pag	pastur	41.85	73.53	0.006	pag
pastur	5.38	78.53	0.035	pa2	pastur	0.17	78.89	0.178	pa2	pastur	0.00	78.09	0.000	pa2	pastur	4.28	78.62	0.041	pa2
pastur	8.74	85.66	0.175	pa3	pastur	0.00	85.92	0.000	pa3	pastur	0.00	85.36	0.000	pa3	pastur	1.28	85.74	0.102	pa3
open u	64.53	77.59	0.032	ugr	open u	63.85	77.90	0.045	ugr	open u	41.83	77.18	0.043	ugr	open u	84.50	77.72	0.034	ugr
hay	4.67	77.59	0.040	hay	hay	0.00	77.90	0.000	hay	hay	0.00	77.18	0.000	hay	hay	0.00	77.72	0.000	hay
forest	20.35	72.38	0.001	for	forest	25.10	72.86	0.003	for	forest	5.13	71.81	0.002	for	forest	5.58	72.50	0.001	for
transi	7.09	90.78	0.557	trn	transi	3.14	90.94	1.009	trn	transi	1.23	90.54	0.651	trn	transi	0.00	90.84	0.000	trn
pur_L	2.50	78.53	0.004	puL	pur_L	10.79	78.89	0.014	puL	pur_L	12.48	78.09	0.011	puL	pur_L	0.83	78.62	0.004	puL
pur_M	28.18	78.53	0.006	puM	pur_M	118.02	78.89	0.010	puM	pur_M	65.58	78.09	0.009	puM	pur_M	2.87	78.62	0.003	puM
pur_H	4.42	78.53	0.008	puH	pur_H	11.45	78.89	0.009	puH	pur_H	18.27	78.09	0.009	puH	pur_H	1.06	78.62	0.010	puH
pur_H	9.75	78.53	0.007	puC	pur_H	18.19	78.89	0.006	puC	pur_H	14.33	78.09	0.007	puC	pur_H	10.26	78.62	0.006	puC
imp_L	0.34	91.85	0	iuL	imp_L	1.47	91.97	0	iuL	imp_L	1.70	91.73	0	iuL	imp_L	0.11	91.86	0	iuL
imp_M	12.08	98.00	0	iuM	imp_M	50.58	98.00	0	iuM	imp_M	28.11	98.00	0	iuM	imp_M	1.23	98.00	0	iuM
imp_H	8.21	98.00	0	iuH	imp_H	21.26	98.00	0	iuH	imp_H	33.92	98.00	0	iuH	imp_H	1.97	98.00	0	iuH
imp_H	36.68	98.00	0	iuC	imp_H	68.42	98.00	0	iuC	imp_H	53.92	98.00	0	iuC	imp_H	38.59	98.00	0	iuC

**Table D.7. GWLF parameters, DOQQ-based, lines 8-end; Stroubles Creek Subbasins.**

*transport149 STE 1x*

Month	ET CC	Day hrs	Grow Flag	Eros Coeff
APR	0.821	12.96	0	0.3
MAY	0.825	13.92	1	0.3
JUN	0.826	14.42	1	0.3
JUL	0.826	14.22	1	0.3
AUG	0.826	13.36	1	0.3
SEP	0.822	12.20	1	0.3
OCT	0.806	11.04	1	0.1
NOV	0.778	10.04	0	0.1
DEC	0.754	9.48	0	0.1
JAN	0.746	9.78	0	0.1
FEB	0.786	10.64	0	0.1
MAR	0.813	11.80	0	0.1

*transport1410 STE 2x*

Month	ET CC	Day hrs	Grow Flag	Eros Coeff
APR	0.768	12.96	0	0.3
MAY	0.770	13.92	1	0.3
JUN	0.771	14.42	1	0.3
JUL	0.771	14.22	1	0.3
AUG	0.771	13.36	1	0.3
SEP	0.769	12.20	1	0.3
OCT	0.759	11.04	1	0.1
NOV	0.742	10.04	0	0.1
DEC	0.727	9.48	0	0.1
JAN	0.722	9.78	0	0.1
FEB	0.746	10.64	0	0.1
MAR	0.763	11.80	0	0.1

*transport1411 STE 4x*

Month	ET CC	Day hrs	Grow Flag	Eros Coeff
APR	0.722	12.96	0	0.3
MAY	0.724	13.92	1	0.3
JUN	0.724	14.42	1	0.3
JUL	0.724	14.22	1	0.3
AUG	0.724	13.36	1	0.3
SEP	0.723	12.20	1	0.3
OCT	0.717	11.04	1	0.1
NOV	0.708	10.04	0	0.1
DEC	0.700	9.48	0	0.1
JAN	0.697	9.78	0	0.1
FEB	0.710	10.64	0	0.1
MAR	0.720	11.80	0	0.1

*transport1412 STE 8x*

Month	ET CC	Day hrs	Grow Flag	Eros Coeff
APR	0.670	12.96	0	0.3
MAY	0.671	13.92	1	0.3
JUN	0.671	14.42	1	0.3
JUL	0.671	14.22	1	0.3
AUG	0.671	13.36	1	0.3
SEP	0.670	12.20	1	0.3
OCT	0.667	11.04	1	0.1
NOV	0.662	10.04	0	0.1
DEC	0.658	9.48	0	0.1
JAN	0.656	9.78	0	0.1
FEB	0.663	10.64	0	0.1
MAR	0.669	11.80	0	0.1

Land Use	Area (ha)	CN	KLSCP	LU flag
HIGH_T	9.43	87.58	0.872	hit
LOW_TI	117.95	86.01	0.483	lot
pastur	469.80	73.53	0.011	pag
pastur	14.23	78.62	0.069	pa2
pastur	19.37	85.74	0.193	pa3
open u	312.86	77.72	0.038	ugr
hay	4.67	77.72	0.040	hay
forest	684.35	72.50	0.004	for
transi	18.18	90.84	0.652	trn
pur_L	49.11	78.62	0.014	puL
pur_M	246.24	78.62	0.009	puM
pur_H	50.32	78.62	0.009	puH
pur_H	56.50	78.62	0.007	puC
imp_L	6.70	91.86	0	iuL
imp_M	105.53	98.00	0	iuM
imp_H	93.45	98.00	0	iuH
imp_H	212.56	98.00	0	iuC

Land Use	Area (ha)	CN	KLSCP	LU flag
HIGH_T	8.55	87.58	0.875	hit
LOW_TI	106.94	86.01	0.484	lot
pastur	401.02	73.53	0.010	pag
pastur	11.74	78.62	0.049	pa2
pastur	19.14	85.74	0.193	pa3
open u	311.64	77.72	0.038	ugr
hay	4.67	77.72	0.040	hay
forest	179.52	72.50	0.002	for
transi	17.29	90.84	0.615	trn
pur_L	36.99	78.62	0.013	puL
pur_M	234.71	78.62	0.009	puM
pur_H	50.32	78.62	0.009	puH
pur_H	56.50	78.62	0.007	puC
imp_L	5.05	91.86	0	iuL
imp_M	100.59	98.00	0	iuM
imp_H	93.45	98.00	0	iuH
imp_H	212.56	98.00	0	iuC

Land Use	Area (ha)	CN	KLSCP	LU flag
HIGH_T	4.24	87.58	0.782	hit
LOW_TI	53.04	86.01	0.433	lot
pastur	258.95	73.53	0.009	pag
pastur	10.37	78.62	0.038	pa2
pastur	18.68	85.74	0.184	pa3
open u	309.76	77.72	0.037	ugr
hay	4.67	77.72	0.040	hay
forest	64.85	72.50	0.002	for
transi	13.54	90.84	0.613	trn
pur_L	27.68	78.62	0.011	puL
pur_M	229.28	78.62	0.009	puM
pur_H	50.32	78.62	0.009	puH
pur_H	56.04	78.62	0.007	puC
imp_L	3.77	91.86	0	iuL
imp_M	98.26	98.00	0	iuM
imp_H	93.45	98.00	0	iuH
imp_H	210.80	98.00	0	iuC

Land Use	Area (ha)	CN	KLSCP	LU flag
HIGH_T	1.11	87.58	0.691	hit
LOW_TI	13.90	86.01	0.383	lot
pastur	87.96	73.53	0.012	pag
pastur	4.45	78.62	0.046	pa2
pastur	1.28	85.74	0.102	pa3
open u	190.18	77.72	0.040	ugr
hay	0.00	77.72	0.000	hay
forest	35.82	72.50	0.003	for
transi	4.36	90.84	0.901	trn
pur_L	24.10	78.62	0.012	puL
pur_M	186.47	78.62	0.009	puM
pur_H	30.78	78.62	0.009	puH
pur_H	42.78	78.62	0.006	puC
imp_L	3.29	91.86	0	iuL
imp_M	79.91	98.00	0	iuM
imp_H	57.16	98.00	0	iuH
imp_H	160.92	98.00	0	iuC

Sample GWLF Transport File

Transport5.dat

Below is the transport file required by GWLF, shown in the required formatting. These values were for the Stroubles Creek watershed using NLCD-based land cover parameters, and are reflected in the appropriate columns of Table D.1 and Table D.2.

13,4,0  
0.06,0,10,0,0,0.1665,15.15,11,1984,1994,0,0.0000959,22974,1.5  
0  
0  
0  
0  
0  
"APR",0.912,12.96,0,0.3  
"MAY",0.917,13.92,1,0.3  
"JUN",0.919,14.42,1,0.3  
"JUL",0.919,14.22,1,0.3  
"AUG",0.919,13.36,1,0.3  
"SEP",0.913,12.2,1,0.3  
"OCT",0.891,11.04,1,0.1  
"NOV",0.852,10.04,0,0.1  
"DEC",0.819,9.48,0,0.1  
"JAN",0.808,9.78,0,0.1  
"FEB",0.864,10.64,0,0.1  
"MAR",0.901,11.8,0,0.1  
"HIGH\_TILL",7.893,87.49,1.11772,"hit"  
"LOW\_TILL",98.757,85.92,0.61904,"lot"  
"pasture1",172.757,73.41,0.01111,"pag"  
"pasture2",405.602,78.55,0.04814,"pa2"  
"pasture3",0.053,85.67,0.26294,"pa3"  
"open urban grass",61.02,77.61,0.02055,"ugr"  
"hay",96.678,77.61,0.04814,"hay"  
"forest",934.47,72.41,0.00099,"for"  
"transitional",33.3,90.79,0.60486,"trn"  
"pur\_L\_resid",451.994,78.55,0.00643,"puL"  
"pur\_M\_resid",0,78.55,0.00646,"puM"  
"pur\_H\_resid",1.26,78.55,0.00650,"puH"  
"pur\_H\_com",30.164,78.55,0.00620,"puC"  
"imp\_L\_resid",61.636,91.85,0.00000,"iuL"  
"imp\_M\_resid",0,98.00,0.00000,"iuM"  
"imp\_H\_resid",2.34,98.00,0.00000,"iuH"  
"imp\_H\_com",113.476,98.00,0.00000,"iuC"

Sample GWLF Nutrient File

Nutrient600.dat

Below is the nutrient file required by GWLF, shown in the required formatting. These values were dummy values except for the sediment build-up rates on impervious surfaces, which are in bold. These values were used for all simulated watersheds in this research.

1400,2532,0.71,0.021  
6,1,8,8,11  
2.2,0.21  
3.94,0.68  
2.9,0.2  
4,0.51  
5.1,0.82  
2.9,0.2  
2.9,0.2  
0.125,0.01  
0.74,0.05  
2.05,0.25  
2.05,0.25  
2.05,0.25  
2.05,0.25  
**2.5**,0.018,0.0018  
**6.2**,0.015,0.0018  
**3.9**,0.023,0.0029  
**2.8**,0.036,0.0040  
14.806,1.72,14.806,1.72  
26.083,5.549,26.083,5.549  
4.379,0.326,4.379,0.326  
6.04,0.831,6.04,0.831  
7.701,1.337,7.701,1.337

14.123,1.308,14.123,1.308

0,0

0,0

0,0

0,0

0,0

0,0

0,0

0,0

0,0

0,0

0,0

0,0

1

512,58,0,6

512,58,0,6

512,58,0,6

512,58,0,6

512,58,0,6

512,58,0,6

512,58,0,6

512,58,0,6

512,58,0,6

512,58,0,6

512,58,0,6

512,58,0,6

512,58,0,6

4.72,1.5,1.6,0.4

## Appendix E: SWAT Land Use Parameters

**Table E.1. Urban Land Use Parameters in the SWAT Urban.dat File.**

IUNUM	URBNAME	URBFLNM	FIMP	FCIMP	CURBDEN	URBCOEF	DIRTMX	THALF	TNCONC	TPCONC	TNO3CONC	OV_N	CN2A	CN2B	CN2C	CN2D
1	URHD	Residential-High Density	0.600	0.440	0.240	0.180	225.000	0.750	550.000	232.000	7.200	0.100	31.00	59.00	72.00	79.00
2	URMD	Residential-Medium Density	0.380	0.300	0.240	0.180	225.000	0.750	550.000	232.000	7.200	0.100	31.00	59.00	72.00	79.00
3	URML	Residential-Med/Low Density	0.200	0.170	0.240	0.180	225.000	0.750	460.000	196.000	6.000	0.100	31.00	59.00	72.00	79.00
4	URLD	Residential-Low Density	0.120	0.100	0.240	0.180	225.000	0.750	460.000	196.000	6.000	0.100	31.00	59.00	72.00	79.00
5	UCOM	Commercial	0.670	0.620	0.280	0.180	200.000	1.600	420.000	240.000	5.500	0.100	31.00	59.00	72.00	79.00
6	UIDU	Industrial	0.840	0.790	0.140	0.180	400.000	2.350	430.000	104.000	5.600	0.100	31.00	59.00	72.00	79.00
7	UTRN	Transportation	0.980	0.950	0.120	0.180	340.000	3.900	480.000	212.000	6.300	0.100	31.00	59.00	72.00	79.00
8	UINS	Institutional	0.510	0.470	0.120	0.180	340.000	3.900	480.000	212.000	6.300	0.100	31.00	59.00	72.00	79.00

**Table E.2. Urban.dat Variable Definitions.**

Variable name	Definition
IUNUM.	Number of urban land type This value should be equivalent to the line number.
URBNAME	4-character code for urban land type. The 4-letter codes in the plant growth and urban databases are used by the GIS interfaces to link land use/land cover maps to SWAT plant types. This code is printed to the output files. When adding a new urban category, the four letter code for the new urban land type must be unique.
URBFLNM	Full description for urban land type—may take up to 54 characters. (not used by SWAT)
FIMP	Fraction total impervious area in urban land type. This includes directly and indirectly connected impervious areas. Urban areas differ from rural areas in the fraction of total area that is impervious. Construction of buildings, parking lots and paved roads increases the impervious cover in a watershed and reduces infiltration. With development, the spatial flow pattern of water is altered and the hydraulic efficiency of flow is increased through artificial channels, curbing, and storm drainage and collection systems.
FCIMP	Fraction directly connected impervious area in urban land type. Impervious areas can be differentiated into two groups: the area that is hydraulically connected to the drainage system and the area that is not directly connected. As an example, assume there is a house surrounded by a yard where runoff from the roof flows into the yard and is able to infiltrate into the soil. The rooftop is impervious but it is not hydraulically connected to the drainage system. In contrast, a parking lot whose runoff enters a storm water drain is hydraulically connected. When modeling urban areas the connectedness of the drainage system must be quantified. The best methods for determining the fraction total and directly connected impervious areas is to conduct a field survey or analyze aerial photographs.
CURBDEN	Curb length density in urban land type (km/ha). Curb length may be measured directly by scaling the total length of streets off of maps and multiplying by two. To calculate the density the curb length is divided by the area represented by the map.
URBCOEF	Wash-off coefficient for removal of constituents from impervious area (mm-1). Wash off is the process of erosion or solution of constituents from an impervious surface during a runoff event. The original default value for urbcoef was calculated as 0.18 mm-1 by assuming that 13 mm of total runoff in one hour would wash off 90% of the initial surface load (Huber and Heaney, 1982). Using sediment transport theory, Sonnen (1980) estimated values for the wash-off coefficient ranging from 0.002-0.26 mm-1. Huber and Dickinson (1988) noted that values between 0.039 and 0.390 mm-1 for the wash-off coefficient give sediment concentrations in the range of most observed values. This variable is used to calibrate the model to observed data.
DIRTMX	Maximum amount of solids allowed to build up on impervious areas (kg/curb km).
THALF	Number of days for amount of solids on impervious areas to build up from 0 kg/curb km to half the maximum allowed, i.e. 1/2 DIRTMX (days).
TNCONC	Concentration of total nitrogen in suspended solid load from impervious areas (mg N/kg sed).
TPCONC	Concentration of total phosphorus in suspended solid load from impervious areas (mg P/kg sed).
TNO3CONC	Concentration of nitrate in suspended solid load from impervious areas (mg NO3-N/kg sed).

**Table E.3. Plant Land Use Parameters in the SWAT Crop.dat File.**

ICNUM	CPNM	IDC	CROPNAME	BIO_E	HVSTI	BLAI	FRGRW1	LAIMX1	FRGRW2	LAIMX2	DLAI	CHTMX	RDMX	T_OPT	T_BASE	WSYF	USLE_C	GSI	VPDFR
1	AGRL	4	Agricultural Land-Generic	33.50	0.45	3.00	0.15	0.05	0.50	0.95	0.64	1.00	2.00	30.00	11.00	0.250	0.200	0.005	4.000
2	AGRR	4	Agricultural Land-Row Crops	39.00	0.50	3.00	0.15	0.05	0.50	0.95	0.70	2.50	2.00	25.00	8.00	0.300	0.200	0.007	4.000
6	FRST	7	Forest-Mixed	15.00	0.76	5.00	0.05	0.05	0.40	0.95	0.99	6.00	3.50	30.00	10.00	0.010	0.001	0.002	4.000
4	ORCD	7	Orchard	15.00	0.10	4.00	0.10	0.15	0.50	0.75	0.99	3.50	2.00	20.00	7.00	0.050	0.001	0.007	4.000
15	RNGE	6	Range-Grasses	34.00	0.90	2.50	0.05	0.10	0.25	0.70	0.35	1.00	2.00	25.00	12.00	0.900	0.003	0.005	4.000
18	WATR	6	Water	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000	0.000
9	WETL	6	Wetlands-Mixed	47.00	0.90	6.00	0.10	0.20	0.20	0.95	0.70	2.50	2.20	25.00	12.00	0.900	0.003	0.005	4.000
14	WPAS	6	Winter Pasture	30.00	0.90	4.00	0.15	0.01	0.50	0.95	0.80	1.50	2.00	15.00	0.00	0.900	0.003	0.005	4.000

**Table E.4. Crop.dat Variable Definitions.**

Variable name	Definition
ICNUM	Land cover/plant code. The different plants listed in crop.dat must have consecutive values for ICNUM. ICNUM is the numeric code used in the management file to identify the land cover to be modeled.
CPNM	A four character code to represent the land cover/plant name. The 4-letter codes in the plant growth and urban databases are used by the GIS interfaces to link land use/land cover maps to SWAT plant types. This code is printed to the output files. When adding a new plant species or land cover category, the four letter code for the new plant must be unique.
IDC	Land cover/plant classification.
DESCRIPTION	Full land cover/plant name. This description is not used by the model and is present to assist the user in differentiating between plant species.
BIO_E	Radiation-use efficiency or biomass-energy ratio ((kg/ha)/(MJ/m <sup>2</sup> )).
HVSTI	Harvest index for optimal growing conditions.
BLAI	Maximum potential leaf area index.
FRGRW1	Fraction of the plant growing season or fraction of total potential heat units corresponding to the 1st point on the optimal leaf area development curve.
LAIMX1	Fraction of the maximum leaf area index corresponding to the 1st point on the optimal leaf area development curve.
FRGRW2	Fraction of the plant growing season or fraction of total potential heat units corresponding to the 2nd point on the optimal leaf area development curve.
LAIMX2	Fraction of the maximum leaf area index corresponding to the 2nd point on the optimal leaf area development curve.
DLAI	Fraction of growing season when leaf area declines.
CHTMX	Maximum canopy height (m).
RDMX	Maximum root depth (m).
T_OPT	Optimal temperature for plant growth (°C).
T_BASE	Minimum (base) temperature for plant growth (°C).
WSYF	Lower limit of harvest index ((kg/ha)/(kg/ha)).
USLE_C	Minimum value of USLE C factor for water erosion applicable to the land cover/plant.
GSI	Maximum stomatal conductance at high solar radiation and low vapor pressure deficit (m s <sup>-1</sup> ).
VPDFR	Vapor pressure deficit (kPa) corresponding to the second point on the stomatal conductance curve.
FRGMAX	Fraction of maximum stomatal conductance corresponding to the second point on the stomatal conductance curve.
WAVP	Rate of decline in radiation use efficiency per unit increase in vapor pressure deficit.
CO2HI	Elevated CO <sub>2</sub> atmospheric concentration (µL CO <sub>2</sub> /L air) corresponding the 2nd point on the radiation use efficiency curve.
BIOEHI	Biomass-energy ratio corresponding to the 2nd point on the radiation use efficiency curve.
RSDCO_PL	Plant residue decomposition coefficient.

(See Neitsch et al., 2002a for more information.)

**Appendix F: Reservoir Parameters Determined by SWAT Modeling**

Values for the reservoir on Stroubles Creek simulated by SWAT were obtained from Woodside (1988) and Hoehn et al. (1975). These values are shown in Figure F.1. Parameter definitions are in Table F.1.

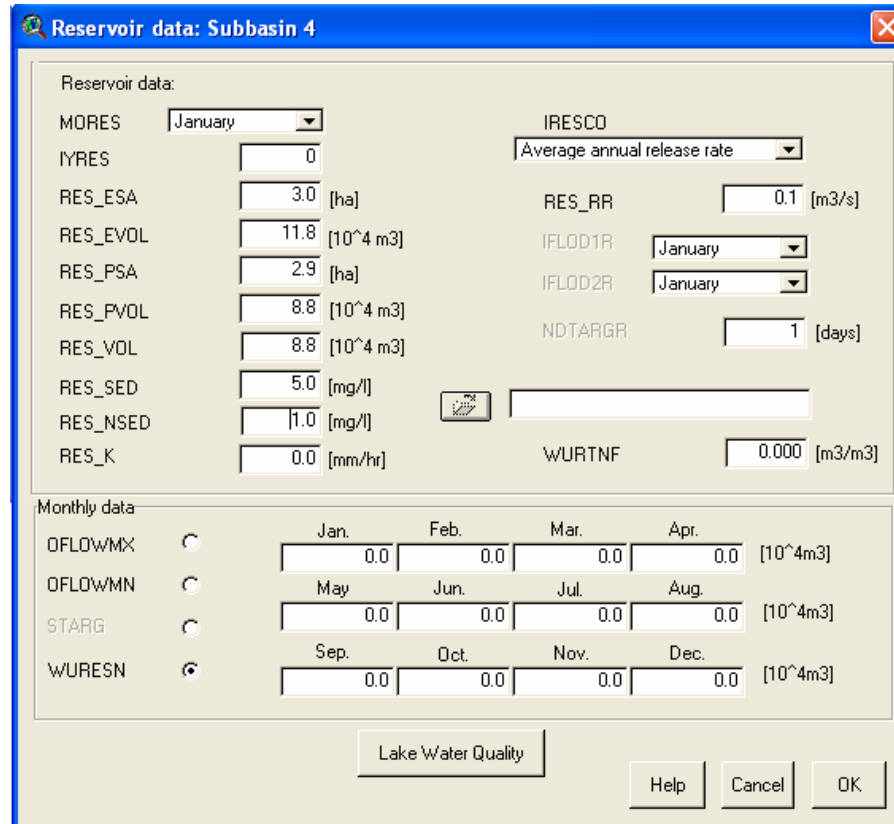


Figure F.1. Screen Capture of AVSWAT Window Displaying Parameter Values for Reservoir in Stroubles Creek.

**Table F.1. Variable Definitions for the “.res” File Used by SWAT in Reservoir Simulation.**

<b>Variable name</b>	<b>Definition</b>
TITLE	The first line of the file is reserved for user comments. The comments may take up to 80 spaces. The title line is not processed by the model and may be left blank.
RES_SUB	Number of the subbasin with which the reservoir is associated. Weather for subbasin is used for the reservoir. If no subbasin number is assigned to RES_SUB, the model uses weather data from subbasin 1 to model climatic processes on the reservoir.
MORES	Month the reservoir became operational (0-12). If 0 is input for MORES and IYRES, the model assumes the reservoir is in operation at the beginning of the simulation.
IYRES	Year of the simulation the reservoir became operational (e.g. 1980). If 0 is input for MORES and IYRES, the model assumes the reservoir is in operation at the beginning of the simulation.
RES_ESA	Reservoir surface area when the reservoir is filled to the emergency spillway (ha)
RES_EVOL	Volume of water needed to fill the reservoir to the emergency spillway (10 <sup>4</sup> m <sup>3</sup> ).
RES_PSA	Reservoir surface area when the reservoir is filled to the principal spillway (ha).
RES_PVOL	Volume of water needed to fill the reservoir to the principal spillway (10 <sup>4</sup> m <sup>3</sup> ).
RES_VOL	Initial reservoir volume. If the reservoir is in existence at the beginning of the simulation period, the initial reservoir volume is the volume on the first day of simulation. If the reservoir begins operation in the midst of a SWAT simulation, the initial reservoir volume is the volume of the reservoir the day the reservoir becomes operational (10 <sup>4</sup> m <sup>3</sup> ).
RES_SED	Initial sediment concentration in the reservoir (mg/L).
RES_NSED	Equilibrium sediment concentration in the reservoir (mg/L).
RES_K	Hydraulic conductivity of the reservoir bottom (mm/hr).
IRESKO	Outflow simulation code: 0 = compute outflow for uncontrolled reservoir with average annual release rate
OFLOWMX(mon)	Maximum daily outflow for the month (m <sup>3</sup> /s). Set all months to zero if you do not want to trigger this requirement.
OFLOWMN(mon)	Minimum daily outflow for the month (m <sup>3</sup> /s). Set all months to zero if you do not want to trigger this requirement.
RES_RR	Average daily principal spillway release rate (m <sup>3</sup> /s). Required if IRESKO = 0.

### **Appendix G: Area Adjustments of Reference Watersheds for SWAT Modeling**

All the reference watershed areas were adjusted to 24.763 km<sup>2</sup>, the area of the impaired Stroubles Creek Watershed. Additional adjustments were made using the area ratios shown in Table G.1. These adjustments are shown in Table G.2.

**Table G.1. Ratios Used for Area Adjustment of Reference Watershed Parameters.**

	Ratio of Stroubles Creek Area to Reference Watershed Area
Upper Opequon	0.1667
Upper Quail Run	8.1057
Tom's	1.1965

**Table G.2. Area-adjusted Channel Length and Channel Width Parameters for SWAT Modeling of Reference Watersheds.**

	channel length		channel width	
Upper Opequon Subbasin #	CH_L1 old	CH_L1 new	CH_W1 old	CH_W1 new
1	25.901	4.319	17.503	2.919
2	12.790	2.133	9.567	1.595
3	14.234	2.373	9.900	1.651
4	9.906	1.652	6.095	1.016

Upper Quail Run Subbasin #	CH_L1 old	CH_L1 new	CH_W1 old	CH_W1 new
1	2.551	20.678	1.105	8.957
2	1.333	10.805	1.097	8.892
3	1.762	14.282	0.968	7.846
4	2.344	19.000	1.214	9.840

Tom's Creek Subbasin #	CH_L1 old	CH_L1 new	CH_W1 old	CH_W1 new
1	3.585	4.289	2.620	3.135
2	3.894	4.659	3.133	3.748
3	3.778	4.520	3.441	4.117
4	4.428	5.298	4.446	5.319

## Appendix H: SWAT Sample Input Files

### Sample SWAT Basin File

Below is the basin data required by SWAT. This file contains general watershed attributes.

#### Basins.bsn

```
Basin data      .bsn file Fri Mar 26 16:58:21 2004 AVSWAT2000 - SWAT interface MDL
24.763 | DA_KM : Area of the watershed [km2]
0.000 | DT : . Time step for infiltration and channel routing [hr]
1.000 | SFTMP : Snowfall temperature [°C]
0.500 | SMTMP : Snow melt base temperature [°C]
4.500 | SMFMX : Melt factor for snow on June 21 [mm H2O/°C-day]
4.500 | SMFMN : Melt factor for snow on December 21 [mm H2O/°C-day]
1.000 | TIMP : Snow pack temperature lag factor
1.000 | SNOCVMX : Minimum snow water content that corresponds to 100% snow cover [mm]
0.500 | SNO5COV : Fraction of snow volume represented by SNOCVMX that corresponds to 50%
snow cover
1.000 | RCN : Concentration of nitrogen in rainfall [mg N/l]
4.000 | SURLAG : Surface runoff lag time [days]
1.000 | APM : Peak rate adjustment factor for sediment routing in the subbasin (tributary channels)
1.000 | PRF : Peak rate adjustment factor for sediment routing in the main channel
0.001 | SPCON : Linear parameter for calculating the maximum amount of sediment that can be
reentrained during channel sediment routing
1.500 | SPEXP : Exponent parameter for calculating sediment reentrained in channel sediment routing
0.000 | PARM1 : Not active
0.000 | PARM2 : Not Active
0.000 | PARM3 : Not Active
0.000 | PARM4 : Not Active
0.000 | PARM5 : Not Active
1.000 | EVRCH : Reach evaporation adjustment factor
3.000 | EVLAI : Leaf area index at which no evaporation occurs from water surface [m2/m2]
0.000 | FFCB : Initial soil water storage expressed as a fraction of field capacity water content
0.003 | CMN : Rate factor for humus mineralization of active organic nitrogen
20.000 | UBN : Nitrogen uptake distribution parameter
20.000 | UBP : Phosphorus uptake distribution parameter
0.200 | NPERCO : Nitrogen percolation coefficient
10.000 | PPERCO : Phosphorus percolation coefficient
175.000 | PHOSKD : Phosphorus soil partitioning coefficient
0.400 | PSP : Phosphorus sorption coefficient
0.050 | RSDCO : Residue decomposition coefficient
0.500 | PERCOP : Pesticide percolation coefficient
0 | IRTPEST : Number of pesticide to be routed through the watershed channel network
0.000 | WDPQ : Die-off factor for persistent bacteria in soil solution. [1/day]
0.000 | WGPQ : Growth factor for persistent bacteria in soil solution [1/day]
0.000 | WDLPQ : Die-off factor for less persistent bacteria in soil solution [1/day]
0.000 | WGLPQ : Growth factor for less persistent bacteria in soil solution. [1/day]
0.000 | WDPS : Die-off factor for persistent bacteria adsorbed to soil particles. [1/day]
0.000 | WGPS : Growth factor for persistent bacteria adsorbed to soil particles. [1/day]
0.000 | WDLPS : Die-off factor for less persistent bacteria adsorbed to soil particles. [1/day]
0.000 | WGLPS : Growth factor for less persistent bacteria adsorbed to soil particles. [1/day]
175.000 | BACTKDQ : Bacteria partition coefficient
```

1.070 | THBACT : Temperature adjustment factor for bacteria die-off/growth  
0.000 | MSK\_CO1 : Calibration coefficient used to control impact of the storage time constant (Km) for normal flow  
3.500 | MSK\_CO2 : Calibration coefficient used to control impact of the storage time constant (Km) for low flow  
0.200 | MSK\_X : Weighting factor controlling relative importance of inflow rate and outflow rate in determining water storage in reach segment

*Sample SWAT Subbasin File*

Below is the subbasin data required by SWAT. There must be a subbasin file for each subbasin delineated in a watershed. This file contains parameters related to specific characteristics of an individual subbasin. At the bottom of the file are the references to other files containing data regarding the HRUs in the subbasin.

000010000.sub

```
.sub file Subbasin:1 Fri Mar 26 16:55:33 2004 AVSWAT2000 - SWAT interface MDL
    26 | HRUTOT : Total number of HRUs modeled in subbasin
    37.218782 | LATITUDE : Latitude of subbasin [degrees]
    623.00 | ELEV : Elevation of subbasin [m]
| ELEV_B: Elevation at center of elevation bands [m]
0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
| ELEV_B_FR: Fraction of subbasin area within elevation band
0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
| SNOEB: Initial snow water content in elevation band [mm]
0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
    0.000 | PLAPS : Precipitation lapse rate [mm/km]
    0.000 | TLAPS : Temperature lapse rate [°C/km]
    0.000 | SNO_SUB : Initial snow water content [mm]
    11.955 | CH_L1 : Longest tributary channel length [km]
    0.010 | CH_S1 : Average slope of tributary channel [m/m]
    8.848 | CH_W1 : Average width of tributary channel [mm/km]
    0.500 | CH_K1 : Effective hydraulic conductivity in tributary channel [mm/hr]
    0.014 | CH_N11 : Manning's "n" value for the tributary channels
    0.000 | CO2 : Carbon dioxide concentration [ppmv]
| RFINC: Climate change monthly rainfall adjustment (January - June)
0.000 0.000 0.000 0.000 0.000 0.000
| RFINC: Climate change monthly rainfall adjustment (July - December)
0.000 0.000 0.000 0.000 0.000 0.000
| TMPINC: Climate change monthly temperature adjustment (January - June)
0.000 0.000 0.000 0.000 0.000 0.000
| TMPINC: Climate change monthly temperature adjustment (July - December)
0.000 0.000 0.000 0.000 0.000 0.000
| RADINC: Climate change monthly radiation adjustment (January - June)
0.000 0.000 0.000 0.000 0.000 0.000
| RADINC: Climate change monthly radiation adjustment (July - December)
0.000 0.000 0.000 0.000 0.000 0.000
| HUMINC: Climate change monthly humidity adjustment (January - June)
0.000 0.000 0.000 0.000 0.000 0.000
| HUMINC: Climate change monthly humidity adjustment (July - December)
0.000 0.000 0.000 0.000 0.000 0.000
| HRU data files
000010001.hru000010001.mgt000010001.sol000010001.chm000010001.gw
000010002.hru000010002.mgt000010002.sol000010002.chm000010002.gw
000010003.hru000010003.mgt000010003.sol000010003.chm000010003.gw
000010004.hru000010004.mgt000010004.sol000010004.chm000010004.gw
```

000010005.hru000010005.mgt000010005.sol000010005.chm000010005.gw  
000010006.hru000010006.mgt000010006.sol000010006.chm000010006.gw  
000010007.hru000010007.mgt000010007.sol000010007.chm000010007.gw  
000010008.hru000010008.mgt000010008.sol000010008.chm000010008.gw  
000010009.hru000010009.mgt000010009.sol000010009.chm000010009.gw  
000010010.hru000010010.mgt000010010.sol000010010.chm000010010.gw  
000010011.hru000010011.mgt000010011.sol000010011.chm000010011.gw  
000010012.hru000010012.mgt000010012.sol000010012.chm000010012.gw  
000010013.hru000010013.mgt000010013.sol000010013.chm000010013.gw  
000010014.hru000010014.mgt000010014.sol000010014.chm000010014.gw  
000010015.hru000010015.mgt000010015.sol000010015.chm000010015.gw  
000010016.hru000010016.mgt000010016.sol000010016.chm000010016.gw  
000010017.hru000010017.mgt000010017.sol000010017.chm000010017.gw  
000010018.hru000010018.mgt000010018.sol000010018.chm000010018.gw  
000010019.hru000010019.mgt000010019.sol000010019.chm000010019.gw  
000010020.hru000010020.mgt000010020.sol000010020.chm000010020.gw  
000010021.hru000010021.mgt000010021.sol000010021.chm000010021.gw  
000010022.hru000010022.mgt000010022.sol000010022.chm000010022.gw  
000010023.hru000010023.mgt000010023.sol000010023.chm000010023.gw  
000010024.hru000010024.mgt000010024.sol000010024.chm000010024.gw  
000010025.hru000010025.mgt000010025.sol000010025.chm000010025.gw  
000010026.hru000010026.mgt000010026.sol000010026.chm000010026.gw

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## VITA

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