Engineering 90 Project Report

Development of a Computer-Based Nonpoint Source Pollutant Loading Model for Small Suburban Watersheds:

Swarthmore Subwatershed-scale Suburban Nonpoint Source Pollutant Loading Model

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ABSTRACT

A novel nonpoint-point source lumped-parameter pollutant loading model appropriate for use in prediction of average yearly loads on small suburban watersheds is presented. Three numerical physical process models describing transport processes observed in such watersheds are developed. These models are combined and implemented in a computer program written using object-oriented techniques in the Microsoft® Visual Basic for Applications programming language with a Microsoft® Excel Graphical User Interface. This functionality of this model is demonstrated through a case study application to the Little Crum Creek Watershed, located in the suburban area near Philadelphia, Pennsylvania. The process modules are integrated into a resource allocation optimization model, *StormWISE (Storm Water Investment Strategy Evaluator),* developed by Dr. Arthur McGarity of Swarthmore College, to allow an user to calculate both loads and optimal investment levels for remediation of water quality problems in a suburban stream related to storm water runoff.

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TABLE OF CONTENTS

I. INTRODUCTION

Significant amounts of sediment, nutrients, heavy metals, and other pollutants find their way into surface water bodies from sources which cannot be specifically located. The primary hydrologic pathway through which these nonpoint sources contribute pollutant loads is storm water runoff, but their dispersed nature lead to difficulty in quantifying and characterizing the exact loads they contribute.

In recent years, characterization and management of nonpoint source pollution has been a priority, which has led to the development of numerous models of contributing processes. Most of these have been developed as spatially dependent models requiring information characterizing the land surface contributing to the polluted water body of interest. The vast majority of these models are empirical in nature, which can make their application to specific drainage areas difficult and imprecise. The development of the existing models and creation of new ones is a priority in the United States, as the goals of the second phase of the Clean Water Act are addressed.

Impending local legislation development in Pennsylvania has provided impetus for studying the loads and Best Management Practices (BMPs) available for use to decrease surface water pollution in suburban Philadelphia. The watershed approach, considering loads from all land areas contributing to a specific water body, has shown much promise as a basis for legislation implementation in this area, particularly on a small scale. Most pollutant load prediction models have been developed with large-scale watersheds in mind, which have been shown to produce load predictions inadequate for small watersheds (McGarity and Willis 2008).

This inadequacy has provided impetus for the development of a new model which will be useful for small watersheds, and which will consider processes observed in this context. The methods implemented combine portions of processes described by some of the larger-scale models, but in a way that addresses the unique character of suburban land uses.

II. BACKGROUND AND IMPETUS FOR MODEL DEVELOPMENT

The Little Crum Creek is a small tributary to the lower Crum Creek in a suburban area west of Philadelphia, which has been on the United States Environmental Protection Agency's federal 303D list of impaired waterways. The watershed encompasses about three square miles of land in suburban Philadelphia, including areas in five municipalities, and experiences considerable problems associated with storm water runoff. One of the most visible effects of the sediment transport processes occurring from runoff is the accumulation of vast quantities of sediment in the floodplain above a small lake in Ridley Park Township. This is a man-made lake created by a dam on the creek, which allows the problems with storm water to be particularly apparent to residents in the community. Every few years, the township must hire contractors to dredge the sediment beds to avoid stagnation of the creek water and improve aesthetic quality of the area.

For several years, the municipalities of the Little Crum Creek Watershed partnership have been working together to find ways to decrease the pollutant loads in the watershed. In addition, the partnership has been working with Dr. Arthur McGarity and the Swarthmore College community to develop appropriate pathways by which to address these problems. This project is the culmination of more than a year of work with the Little Crum Creek Watershed, the Chester-Ridley-Crum Watersheds Association, and Dr. McGarity, and addresses the most pressing concern for the project to move forward at the time: the need for an appropriate model to predict pollutant loads from the watershed.

In 1972, the United States Congress passed what became known as the Clean Water Act. This document and subsequent addendums, written in response to such disasters as the 1969 burning of the Cuyahoga River, the outlines the processes by which surface water quality goals would be attained in the coming years. The USEPA was charged with regulating and controlling measures undertaken to improve the quality of surface water to the point that all navigable waters, and their tributaries, would be "fishable and swimmable" for the recreational use of citizens and preservation and restoration of aquatic habitats.

The first phase of the Clean Water Act involved identifying and regulating point sources of refuse dumping (those which can be linked directly to one source, such as an industrial plant or wastewater treatment facility). For the most part, this has been successful; the quality of water in streams and lakes around the country have been significantly improved due to this effort. However, it was discovered early on that considerable amounts of pollutants could not be accounted for by point sources; rather, runoff from land surfaces was contributing at least as much as industrial wastes, particularly during storm events. This shifted the focus of the second phase of the Clean Water Act toward ways of addressing these "non-point sources", which include contributions due to runoff of all land surfaces which drain into a body of water.

The best way of addressing this non-point source issue is a greatly contested issue in the field of water pollution control. Some advocate for geographic area control, while others suggest political boundary regulations. One of the most prominent methods is the study of runoff contributions on the watershed scale. This is a logical basis, as it accounts for all land draining into a body of water ("drainage area"), though it can be impractical for regulation from a political standpoint, as municipal boundaries do not often lie along watershed boundaries. Nonetheless, watershed-based studies of pollutant are common, especially in the case that regulation is planned for a larger political boundary (for example, a watershed could be county-scale while regulation is state-wide).

One of the proposed methods for remediation of surface water quality in streams and lakes is by limiting a water body's Total Maximum Daily Load (TMDL). This concept has been implemented in several watersheds around the country, and generally consists of a set cap on the total amount of a certain pollutant which can be introduced to a water body over the course of a specified period of time. This is conceptualized as a daily load, but is often implemented as an average yearly load, since concentrations can vary significantly on a daily basis.

Primary pollutants considered by TMDL regulations include sediment (in the form referred to as "Total Suspended Solids"), nitrogen and phosphorous. Sediment adds to the turbidity of water when it is entrained, which can disorient aquatic life, and absorbs sunlight, increasing water temperature. Nitrogen and Phosphorus are harmful in their biologically active forms, as they provide nutrients which stimulate the growth of bacterial and algal colonies. Exponential growth of such colonies often leads to extreme oxygen depletion in freshwater streams, which can lead to the death of other oxygen-dependent aquatic life. Nutrient loads are often associated with fertilizer application in agricultural and suburban areas, since nitrogen and phosphorus are necessary for plant growth and are primary components of commercial fertilizers. Since only a small percentage of fertilizer nutrients are actually absorbed into the soil, farmers and homeowners often over-fertilize and the excess finds its way into nearby surface water.

In order to be able to set TMDL limits, current levels of pollutant loads must be calculated so that realistic regulations can be set. Since field measurements of such loads is heavily taxing to both time and resources, a host of computer-based pollutant loading models have been developed in recent years to aid in prediction of existing total mass and concentration loads, most often based on a yearly time scale. These generally require inputs of watershed parameters such as area data for different land use types, measurements of average hill slope, precipitation and temperature data, soil types, and in some cases, digital elevation models of the landscape.

These pollutant loading models vary in specificity and the amount of data required for input; as with all models, those which are more descriptive of a particular watershed tend to give more accurate predictions (though this is not necessarily true). However, they also tend to require more intensive data preprocessing, so in each case the time and expertise cost must be juxtaposed with the benefits gained from a more accurate prediction. Distributed parameter models consider the geography of each land use parcel and its proximity to a water body in calculating loads, while lumped parameter models divide the watershed into a limited number of smaller drainage areas, and does not consider the specific location of each parcel of land in the watershed. Both types of models have their advantages, and tradeoffs have been widely discussed in the literature (Limbrunner 2008).

Lumped parameter models tend to be more realistic for the screening-level analysis necessary for optimizations such as that undertaken in applying the StormWISE model. There is a considerable tradeoff in the amount of time required to run a model and the specificity of the load predictions. Land uses vary widely across suburban watersheds, as residences neighbor shopping centers, which neighbor playing fields and forested park land. Distributed models would be nearly impossible to implement in a meaningful way for small watersheds, since the quality of available land use data would limit the input to approximately 10- to 30 meter grids. Thus, inaccuracy could be a considerable problem, negating the additional information gained about the proximity of land uses to the stream.

On the other hand, lumped parameter models allow characterization of land by general drainage area; this takes considerably less computational work, and for the purposes of StormWISE allows more than enough accuracy if a small watershed is of interest.

Multiple lumped-parameter models were applied to the Little Crum Creek watershed as part of the Little Crum Creek Action Plan Phase One (McGarity 2009) through 2008, ranging in complexity from simple export coefficient models to full-scale runoff models (McGarity and Willis 2008). The focus of applying these models was the calculation of a realistic yearly sediment load for input into the screening-level resource allocation model StormWISE (McGarity 2006), since this is the most serious problem in the Little Crum Creek. The application of these models to such a small land area resulted in an extremely wide range of predicted sediment loads, varying within an order of magnitude. When compared to event mean concentrations obtained from samples collected during storm events, it was concluded that these models, which were developed for either rural or urban areas, inaccurately describe the processes occurring in a small suburban watershed. The model presented here is designed to take into consideration the unique combination of rural and urban land uses present in many suburban areas, as well as the hydrodynamics of surface water in such a small watershed.

The model presented here is a lumped parameter model, which takes into consider the total area of each of several land use types in two drainage areas. Elements of several models are integrated (particularly RUNQUAL, TMDL2K, and AVGWLF) to produce sediment, nitrogen, and phosphorous load predictions on a monthly and yearly basis. It is then applied to the Little Crum Creek watershed as a case study for comparison to observed loads.

The model is programmed in Visual Basic for Applications® to allow for an object-oriented approach to be taken with code modules. These allow additional flexibility if the model is to be changed, as well as providing structure for integration of model portions. In particular, this allowed two developers to work on code simultaneously and integrate their work seamlessly. The program is run using macros behind the Microsoft Excel® program, allowing the use of a graphical user interface familiar to most users. Minimal preprocessing of data is required; these aspects will allow ease of use for non-professional watershed managers across the country that might otherwise be unable to apply a meaningful model to predict loads on their watershed.

As in many pollutant load prediction models, this model is based on parameters which are input as sets for each land area. The watershed in question is assumed to be broken into a given number of smaller sub-drainage areas (referred to as 'drainages'). Within each drainage, the total land area is divided into each of a set number of land use categories. Most calculations are performed by land use category in each drainage, which allows for flexibility in presenting results and performing post-model calculations, or exportation of loads to future calculation modules.

III. THEORY

A. *Runoff: Soil Conservation Service Curve Number Method*

The Soil Conservation Service (SCS) Curve Number Method is one of the most prominent models used for predicting runoff volume, which is in turn used to calculate numerous surface water hydrodynamic effects. The method described by the Soil Conservation Service assumes that the volume of runoff produced during a storm is a function of the amount of rainfall absorbed, which depends on the antecedent moisture content of the soil as well as several soil properties related to its imperviousness (Walter and Shaw, 2005). The runoff is calculated using the method described by Haith in RUNQUAL (1993), and is reported in terms of depth as

$$Q_t = \frac{\left(R_t + M_t - 0.2W_t\right)^2}{R_t + M_t - 0.8W_t}$$

for $Q_t > R_t + M_t - 0.2W_t$, where Q_t is the runoff on day t (cm), R_t is the rainfall on day t (cm), M_t is the depth of snowmelt water on day t (cm), and W_t is a detention parameter for day t (cm), given by the relation

$$W_t = \frac{2540}{CN_t} - 25.4$$

and CN_t is the curve number for day t; curve numbers are based on the five-day antecedent precipitation, calculated as

$$A_t = \sum_{j=t-5}^{t-1}\left(R_j + M_j\right)$$

where curve numbers take on values described by a piecewise linear function when there us no snowmelt; the portions of the function are identified as CN_1, CN_2, CN_3, which are functions of dry, wet, and average antecedent moisture limits (0, AM_1, and AM_2, respectively), all in cm. If snowmelt does occur, the wettest antecedent moisture conditions are assumed. The curve number for day t is calculated as

$$CN_t = \begin{cases} CN_1 + \dfrac{CN_2 - CN_1}{AM_1} A_t & A_t = AM_1, M_t = 0 \\ CN_2 + \dfrac{CN_3 - CN_2}{AM_2 - AM_1}(A_t - AM_1) & AM_1 < A_t < AM_2, M_t = 0 \\ CN_3 & A_t = AM_2 \quad or \quad M_t > 0 \end{cases}$$

The antecedent moisture content limits, AM_1 and AM_2, vary between dormant and growing season (defined by average monthly ambient temperatures above and below 10 degrees Celsius, respectively). During the dormant period, these take on values of -1.3 and 3.6 cm, respectively, and during growing season, -2.8 and 5.3 cm, respectively.

Calculations for CN_1 and CN_3 are based on empirical relationships to values of CN_2 derived by Hawkins (1978). These are of the form

$$CN_1 = \frac{CN_2}{2.334 - 0.01337 CN_2}$$
$$CN_3 = \frac{CN_2}{0.4036 + 0.0059 CN_2}$$

In climates where temperature fluctuations are common, runoff from melting snow can contribute to total volumes considerably. Predictions of these contributions (snow water, SN_t) are based on a daily mass balance of this volume on a ground surface at the beginning of day t,

$$SN_{t+1} = SN_t + \Delta SN_t - M_t$$

where ΔSN_t is the new snow water volume accumulated on that day, and M_t the snow melt on day t, which is calculated as

$$M_t = \begin{cases} Min(0.45 T_t, SN_t) & T_t > 0 \\ 0 & T_t \le 0 \end{cases}$$

where T_t is the ambient air temperature on day t in degrees Celsius. Snow and rain volumes are calculated from observed precipitation on that day, P_t (cm). In the case that the temperature is below freezing (zero degrees Celsius), all precipitation is calculated as a volume of snow water, ΔSN_p, while otherwise it is calculated as rainfall R_t.

An average curve number based on values tabulated by the Soil Conservation Service for the pervious and impervious portions of each land use is adjusted using the method described by Haith (1993) on a daily basis, and the daily rainfall and snowmelt are calculated from daily measured precipitation and temperature data for the watershed in question. These are used to calculate a daily runoff depth (cm), which is used for several pollutant load process calculations.

It should be noted that many urban and suburban streams do not have any significant base flow. This is due to the impervious nature of much of the ground cover in these areas, as well as their small size, in the case of suburban streams. Impervious surfaces disallow the infiltration of ground water into the stream, particularly in cases where the channel has actually been lined with an impervious material, as occurs where stream channels have been replaced with storm sewers. Therefore, this model assumes that any groundwater contribution to stream flow is negligible.

B. *Pollutants: Build-Up/Wash-Off Model*

In periods with little or no rainfall, sediment and debris tend to accumulate on impervious surfaces; this is commonly observed in parking lots and on paved walkways. If the dry spell lasts for a long time, there is a quantifiable upper limit on how much will accumulate, due to gravity and the natural processes which deposit the debris; eventually, the buildup and decay rates will be equivalent. When a rain storm or excessive snowmelt occurs, most of the accumulated sediment is caught up by quickly-moving water on the surface, and carried along with the runoff into a surface water body (Limbrunner 2008). This process contributes significantly to the suspended solids concentration of runoff in areas with considerable impervious areas, and is thus an important one to include in loading calculations for suburban watersheds.

The build-up/wash-off process is relatively simple to model using saturation functions, with accumulation calculated on a daily basis from the differential equation

$$\frac{\partial L}{\partial t} = m - \beta L$$

where $L(t)$ is the accumulation load on day t during dry periods (kg/ha), m is a characteristic mass accumulation rate (kg/ha-day), and β is a characteristic depletion rate (1/day). Solving the differential equation yields the relation

$$L(t) = L_o e^{-\beta t} + \frac{m}{\beta}\left(1 - e^{-\beta L}\right)$$

where L_o is the initial accumulation at time $t=0$ (kg/ha). This saturation-type function takes on a maximum value asymptote at

$$L_{\max} = \frac{m}{\beta}$$

Several studies have shown that this asymptote is approached after twelve days, regardless of rate (Sartor and Boyd, 1972; Haith 1993); Haith suggests a conservative approximation of attaining 90% of L_{max} in twenty days, which leads to an approximation (for $L_o=0$)

$$0.9L_{\max} = 0.9\frac{m}{\beta} = \frac{m}{\beta}\left(1 - e^{-20\beta}\right)$$

$$\beta = 0.12$$

This value for β is used in the daily calculations for build-up/wash-off of sediment on the impervious portions of each of the land uses in this model. An approximation of the accumulated load over a time interval of one day is used for the model; this takes the form

$$L_{t+1} = L_t e^{-0.12} + \frac{m}{0.12}\left(1 - e^{-0.12}\right)$$

where L_t is the accumulation at the beginning of day t in kilograms. This equation is modified to include the effects of wash off due to runoff by including the pollutant load from runoff, X_t as

$$L_{t+1} = L_t e^{-0.12} + \frac{m}{0.12}\left(1 - e^{-0.12}\right) - X_t$$

The runoff term X_t is a measure based on area washed off, an export coefficient measured in kg/ha for day t, calculated as a function of accumulated load

$$X_t = w_t\left[L_t e^{-0.12} + \frac{m}{0.12}\left(1 - e^{-0.12}\right)\right]$$

The scaling factor w_t presented by Haith (1993) is a first-order wash off function derived from observed data, based on the assumption that 0.5in (1.27 cm) of rainfall will wash off 90% of pollutants,

$$w_t = 1 - e^{-1.81 Q_t}$$

The total runoff and pollutant loads are thus calculated by land use based on the area of each land use type present, as well as the impervious percentage of each land use in the region of interest. The impervious percentage can be calculated for the watershed of interest from satellite-generated GIS datasets, or from average values found in literature (McGarity 2009). The loads from the pervious and impervious portions of each land use are calculated separately due to the disparate build-up and wash-off processes occurring on each surface type. The total daily runoff depth for each drainage Q_t is thus calculated as an area-weighted average of the impervious and pervious portions as

$$Q_t = \frac{\sum_{j=1}^{m}\left[I_j A_j Q_{I,j,t} + \left(1 - I_j\right) A_j Q_{P,j,t}\right]}{\sum_{j=1}^{m} A_j}$$

where m is the total number of land uses in the drainage; A_j is the area of land use j in the drainage; $Q_{I,j,t}$ and $Q_{P,j,t}$ are the runoff depth calculated for impervious and pervious portions on land use j on day t, respectively; and I_j is the fraction of land use j covered by impervious surfaces. Haith (1993) suggests the daily washed off load (kg) of each pollutant for each drainage be calculated as a sum

$$BW_t = \sum_{j=1}^{m}\left[I_j A_j X_{I,j,t} + \left(1 - I_j\right) A_j X_{P,j,t}\right]$$

where $X_{I,j,t}$ and $X_{P,j,t}$ are the runoff pollutant load from impervious and pervious surfaces calculated as described above for land use j on day t, respectively.

C. *Pollutants: Land Surface Sediment Load Model*

Most models developed for use in urban areas disregard any sediment load from pervious surfaces, because cities tend to have minimal areas of land covered in vegetation and exposed soil. However, in suburban watersheds, this cannot be assumed because a considerable portion of the land surface is pervious, in the form of lawns, parks, occasional forests, playing fields, and the like. The mechanics of sediment loss due to rainfall impact must be accounted for, and methods used for agricultural soil deposition provide a convenient and practical solution for calculating the sediment load from these areas.

The Universal Soil Loss Equation (USLE) was developed by the United States Department of Agriculture as an empirical model for predicting soil loss from agricultural land (Wischmeier and Smith 1978); it is currently the most commonly used method of its type, though it has gone through several adjustments since it was first developed. The most current version of the Revised Universal Soil Loss Equation is widely available as both an online calculation tool and as USDA Handbook 703 (Renard et al 1996).

The RUSLE bases calculation of annual soil loss *(A)* on a number of factors and properties of the soil type, rainfall, and cover which directly affect the erosion rate, which are generalized to rainfall erosivity (*R*), soil erosivity *(K)*, land surface topography *(L* and *S)*, land cover and vegetation type *(C)*, and any existing management practices *(P)* as

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

The rainfall erosivity factor, *R*, accounts for the energy transferred from falling rain to any soil with which it comes in contact, and is related to both the intensity of rainfall and the total amount of precipitation. A generalized average rainfall erosivity factor has been calculated for each area of the United States, and can be found in RUSLE literature (Renard and Freimund 1994); such a value is useful for long time periods and large areas. Though the RUSLE was not developed for calculation of sediment loads on a daily basis (Wischmeier 1976), Limbrunner (2008) suggests that a daily load calculated by the RUSLE will still provide a useful parameter for comparison to observed loads. Van Dijk et al (2005) provide relationships for development of a rainfall erosivity factor based on real precipitation data, which Limbrunner (2008) suggests extending to a daily calculation. Since precipitation data for individual storm events is usually unavailable, all rainfall occurring in one day is considered to be one storm lasting twenty-four hours.

The rainfall erosivity factor is expressed by Limbrunner (2008) as a product of the total energy of rainfall impact during a storm *(E)* and the maximum 30-minute rainfall intensity (I_{30}) during that storm, which is a form recognized widely. Van Dijk et al (2005) assume an exponential depth-intensity distribution for storm events, which Limbrunner lends the total storm kinetic energy with the form

$$E_t = P_t e_{\max}\left(1 - \frac{a}{b\breve{R}_t + 1}\right)$$

where E_t is in $Jm^{-2}mm^{-1}$, P_t is the total daily precipitation (mm), e_{max} is the maximum kinetic energy content of the precipitation ($Jm^{-2}mm^{-1}$), *a* and *b* are parameters, average values for which are derived by Van Dijk et al (2002), and $\breve{R}_t$ is a depth-averaged rainfall intensity (mm/h). Parameter values suggested by Limbrunner for the constants include e_{max}= 28.3 $Jm^{-2}mm^{-1}$, a = 0.52 h/mm, and b = 0.042 h/mm, while $\breve{R}_t$ is approximated as the average hourly precipitation, $\breve{R}_t \approx \frac{P_t}{24}$. In order to utilize commonly available daily precipitation data (in cm/day), we can substitute these approximations and parameter values to yield the form

$$E_t = P_t e_{\max}\left(1 - \frac{a}{b\left(\frac{P_t}{24}\right) + 1}\right) = 10P_t(0.283)\left(1 - \frac{0.52}{0.042\left(\frac{10P_t}{24}\right) + 1}\right) = 2.83P_t\left(1 - \frac{0.52}{0.0175P_t + 1}\right)$$

where E_t is in MJ, P_t is in cm, and e_{max} is converted to units MJ/ha/cm.

In addition, the study by Van Dijk et al (2005) suggests the maximum mean 30-minute rainfall intensity, I_{30}, for a storm (day *t*) can be calculated as

$$I_{30,t} = \frac{P_t}{0.5} e^{\left(-invE_1 \frac{0.5\breve{R}_t}{P_t}\right)}$$

where $invE_1(u)$ is the inverse exponential integral function

$$invE_1(u) = \int_u^\infty \frac{e^{-u}}{u} \partial u$$

whose values vary over known ranges. Making use of the same approximation for $\breve{R}_t$ as above and appropriate values for $invE_1(u)$ found in Van Dijk et al (2005), this is simplified by Limbrunner (2008) to

$$I_{30,t} = \frac{P_t}{0.5} e^{\left(-invE_1 \frac{0.5P_t}{24P_t}\right)} = \frac{P_t}{0.5} e^{\left(-invE_1 \frac{0.5}{24}\right)} = 0.1434P_t$$

where $I_{30,t}$ is in mm/h and P_t is the total daily rainfall. Thus, the daily rainfall erosivity factor for the entire watershed, as calculated in this model, has the form

$$R_t = E_t I_{30,t} = \left(2.83P_t\left(1 - \frac{0.52}{0.0175P_t + 1}\right)\right)(10 \cdot 0.1434P_t)$$

$$R_t = 4.058P_t^2\left(1 - \frac{0.52}{0.0175P_t + 1}\right)$$

The soil erodibility factor, *K*, is a parameter dependent on soil type; it is a measure of the susceptibility of a particular soil to erosion due to rainfall impact. It is expressed in terms of the amount of soil per area removed by a certain volume of rainfall with a given energy, and is commonly reported in units of Mg-ha-h/ha-MJ-mm. Average values for *K* are tabulated for US soils by the Natural Resources Conservation Service. These values are easily obtainable in GIS and tabular format for any region from the NRCS Soil Data Mart.

The average values for the erodibility factor obtained for an area should be adjusted in areas which experience seasonal temperature fluctuation. Soils tend to be more cohesive when frozen, since moisture in the soil tends to crystallize and trap sediment particles in place. The seasonality adjustment used here is one adapted from Limbrunner (2008) and similar to that presented by Renard et al (1996). A daily erodibility factor (K_t) is thus calculated from the average for a given land use as a periodic function of time,

$$K_t = a_K K\left(1 + b_K \cos\left(\frac{2\pi(j_t - \phi_K)}{365}\right)\right)$$

where K_t is the erodibility factor on Julian day j_t, a_K is an unitless erosivity scale factor, b_K is an erosivity seasonality factor, and ϕ_K is an erosivity phase factor for erodibility; these are all adjustable parameters based on location as well as soil classification.

An area-averaged erodibility factor for each land use in each drainage zone, calculated by GIS methods, is used as an input for this model. In addition, the seasonal adjustment factors a_K, b_K , and ϕ_K are available as input parameters, though reasonable values are included in the model.

Though runoff volume does not vary with the slope of the land surface, the soil loss per unit area does increase with slope, as the ease with which runoff detaches and transports is greatly enhanced; this is fully described by Wischmeier and Smith (1978). This augmentation is accounted for in the calculation of a fraction relating the average slope of a hypothetical continuous tract of a certain land use *j* in the watershed to a standard 22m long tract with continuous 9 percent slope. Since this is a lumped parameter model, this is taken to be the average slope and length for land of use *j*. This fraction is referred to as the length-slope factor, *LS*, and is represented by a power law relation derived by Wischmeier and Smith

$$LS = \left(\frac{\lambda}{22}\right)^m \left(65.41\sin^2(\theta) + 4.56\sin(\theta) + 0.065\right)$$

where λ is the slope length in meters, θ is the average slope in degrees, and m takes on fractional values based on the average slope (1978). The slope length can be a difficult parameter to derive; for this reason, Moore and Wilson (1992) derived an approximation for LS based on the local slope and contributing area. Fortunately, the length-slope factor can be calculated from GIS topographical datasets by following a simple procedure, such as that found in the appendices. This input must be calculated for each land use category in each drainage of the watershed; as it is a ratio, the length slope factor is unitless.

The cover and management factor, C, describes soil exposure to direct rain impact. This has the most effect in agricultural areas, where the crop rotation and harvesting procedures impact the ease with which soil particles are detached and washed away by runoff. This is less impact in suburban areas, where most pervious land is well-maintained and exposed soil is rare. Nonetheless, this is included as an input parameter in the model for cases where this is deemed an important factor for surface erosion. This cover factor is effectively a fraction, and thus unitless.

The support practice factor, P, is included to account for any best management practices already in place. Again, this is most important in agricultural areas, where a soil conservation best management practice can have quantifiable effects when applied to land areas. Tabulated values of P are available for agricultural land uses, if necessary. Derivation of a value for the support practice other than unity in suburban areas will require consultation of an expert. In general, an assumption of unity is sufficient as most suburban watershed have minimal best management practices already in place. The support practice factor is a fraction and thus a unitless quantity.

D. *Pollutants: Stream Bank Erosion Model*

The natural processes of sediment and nutrient transport are augmented considerably when large volumes of water and high velocity flows occur in a stream. This is often the case during rainstorms in suburban areas. Decreased land surface permeability, as caused by increased urbanization, allows a large percentage of rainfall to find its way to the stream quickly. This runoff carries with it sediment and nutrients from impervious surfaces, which loosen sediments along the stream bank as it flows by; high-velocity flows have considerable kinetic energy to loosen the bank; high-volume flows flood the channel, destabilizing the bank over time by destroying plants which hold it back.

Numerous models have been developed for bank erosion, though many tend to take on the form of a power function based on the volumetric flow in the stream. The most common calculation of bank erosion is as a lateral erosion rate, which is the lateral distance into the stream bank removed by stream flow every year. Evans et al (2003) suggest a calculation based on the empirical sediment transport function

$$C = aQ^b$$

where Q is the discharge for some period (m^3), C is the sediment yield (kg), and a and b are empirical constants; this is translated to a lateral erosion rate (*LER)* based on constants obtained by Rutherford (2000) in the form

$$LER = dQ^{0.6}$$

Rutherford (2000) observed a relationship between the meander migration rate M (m/yr) and discharge rate (volumetric flow, m^3/s) of the form

$$M = 0.0435Q^{0.6008}$$

Evans et al (2003) suggest calculation of sediment load from bank erosion on a monthly basis, using the value for *d* found by Dietrich et al (1999) to be approximately 0.008 when estimating annual lateral erosion rates and loads for streams in Australia. In order to do so, Evans et al (2003) develop a method of adjusting the value on a monthly basis, which Limbrunner (2008) suggests can be ignored if calculations are performed on a daily basis, rather than monthly. Thus, the sediment transport function takes on the form

$$C = \frac{a}{365} Q^b$$

where *b* is the exponent value derived by Rutherford (2000) and *a* is the adjusted parameter accounting for the volume of bank sediment eroded, which has the form

$$a = d(lh)\rho$$

where *d* is 0.008 (from correlations observed by Rutherford), *l* is the total length of the stream (m), *h* is the average steam depth (m), and ρ is the average bulk density of stream bank sediment (kg/m^3). Substituting this into the above equation yields

$$C = \frac{0.008}{365}(lh\rho)Q^{0.6008}$$

Bank erosion is generally understood to occur only when the flow is higher than a certain threshold value, as has been observed in the Little Crum Creek. This threshold is reported by Limbrunner (2008) as a volumetric flow rate, Q_c. Since many suburban watersheds have negligible base flow, runoff is the primary flow used for calculation of daily average stream flow *Q* in the model presented here. The daily runoff volume $q_{i,j}$ calculated by the SCS Curve Number method can be used as a storm volume over a daily time step to find the daily volumetric flow. This yields a daily runoff volumetric flow rate

$$Q_t = \frac{1}{86400} \sum_{i=1}^{n} \sum_{j=1}^{m} q_{i,j}$$

where Q_t is the average volumetric flow rate for day t in m^3/s, n is the total number of delineated drainages in the watershed, and m is the total number of land uses in each drainage. To account for any discrepancy between observed and predicted flow rates, a calibration factor, k, has been added. Thus, the daily load of sediment generated by bank erosion can represented as

$$C_t = \begin{cases} k\left(\frac{0.008}{365}(lh\rho)Q_t^{0.6008}\right), & Q_t > Q_c \\ 0, & else \end{cases}$$

In the Little Crum Creek, this effect has been observed over time at many sites in the watershed. Flow data and stream samples from nine months of observed storm events suggest that considerable stream bank erosion occurs when the stream velocity exceeds 2.5 ft/s. A corresponding volumetric flow rate has been extracted from these data, and the difference between it and the flow rate predicted by the model for the storm events is accounted for in the calibration factor, k. Thus, the calibration factor is calculated as

$$k = \frac{1}{w}\sum_{i=1}^{w}\frac{Q_{actual}}{Q_{predicted}}$$

for w observed storm events in which the stream velocity exceeded 2.5ft/s, where Q_{actual} is the observed volumetric flow rate calculated from rainfall data, and $Q_{predicted}$ is the volumetric flow rate calculated as Q_t for the day's rainfall.

E. *Nutrient Load Calculations: Nitrogen and Phosphorous*

Nitrogen and Phosphorous are the primary chemically reactive pollutants of concern in suburban streams and watersheds, because of the implications of their presence in high concentrations. In general, nitrogen and phosphorus can be assumed to be present in soil in concentrations characteristic for each land use type. For some land use types, these can be directly predicted based on fertilizer use, while for others the concentration must be estimated based on values presented in the literature.

The contribution to nutrient loads from build-up/wash-off processes is directly calculated based on the runoff and corresponding sediment load generated from each land use; the pollutant generation rate for pervious and impervious portions of each land use are taken as input parameters. The contributions from the land surface sediment and bank erosion loads are calculated based on the same average concentration of nutrient in the sediment. It is assumed that an array of land uses will intersect the stream channel, so an aggregate average concentration of each pollutant (kg/m^3) in the soil eroded by either land surface or bank erosion is used to calculate the total nutrient load from these processes.

F. *Pollutant Load Calculations: Total Sediment and Nutrient Loads*

All of the processes described have been observed in small suburban watersheds, though the load calculations have not been previously combined in this form. This loading model was developed primarily for use with a screening-level resource allocation optimization model; thus, the simple aggregation of the loads predicted by build-up/wash-off, land surface sediment load, and stream bank erosion is sufficiently sensitive for its intended purpose. Thus, though daily, monthly, and yearly load calculations from each of the model portions are available, the primary data of interest are the yearly load predictions for all three processes combined.

The aggregate load is calculated on a daily basis by combining all three calculated loads; since the build up- wash off and land surface erosion loads are calculated for each land use area in each drainage, these are first combined to allow the calculations of event mean concentrations and export coefficients for each land use over the watershed. The total load for each land use *j* in each drainage *i* is thus calculated

$$T_{i,j,t} = BW_{i,j,t} + RUSLE_{i,j,t}$$

which is then aggregated for each drainage

$$T_{i,t} = \sum_{j=1}^{m} \left[BW_{i,j,t} + RUSLE_{i,j,t} \right]$$

For the entire watershed, this is aggregated for all *n* drainages in the watershed. The stream bank erosion contribution is not dependent on land use or drainage area; rather it is calculated for the entire watershed based on stream length and other parameters. It is thus included in the watershed daily calculation

$$T_t = \sum_{i=1}^{n} T_{i,t} + C_t = \sum_{i=1}^{n} \sum_{j=1}^{m} \left[BW_{i,j,t} + RUSLE_{i,j,t} \right] + C_t$$

This format of data aggregation facilitates a daily, monthly, and yearly average event mean concentration to be calculated for days with precipitation, as the daily load is available. These describe the behavior of the watershed response to precipitation; comparison of event mean concentrations from similar storms can be used to determine characteristic loads for the watershed. The most useful of these is the yearly average event mean concentration

$$EMC_{yr} = \sum_{t=1}^{365} T_t \Bigg/ \sum_{t=1}^{365} Q_t$$

Calculation of export coefficients for monthly and yearly time steps for each land used are also facilitated by this format; these describe an average load per area for the given time period based on land use type (or drainage, et cetera). The average yearly export coefficient for land use *j* based on *l* years of data is calculated

$$EC_{avg,yr,j} = \frac{1}{l} \sum_{k=1}^{l} \sum_{i=1}^{n} \sum_{t=1}^{365} T_{k,i,j,t}$$

It should be noted that these export coefficients do not include stream bank erosion, which would increase the effective load per area of watershed considerably. However, the effects of stream bank erosion can be considered separately when analyzing the total watershed load.

IV. MODEL IMPLEMENTATION

A. *User Input Data Required*

In order to be able to properly utilize the functionality of this pollutant loading model, several datasets must be collected for the watershed of interest, and some preprocessing of this data in Geographic Information Systems (GIS) format must be performed. First, a digital elevation model of the entire area must be made available for use, and the watershed boundaries must be delineated through a GIS tool such as TauDEM (Tarboton 2004) or the ArcHYDRO toolset (Maidment 2002). This boundary must be used to delineated appropriate drainage areas (Headwaters and Lowlands categories recommended), which must be overlaid on an appropriate land use dataset, such as the Multi-resolution Land Use Consortium 2001 satellite-derived dataset. From this, land use areas in each drainage should be calculated. GIS data layers are also available from the NRCS Soil Data Mart, as mentioned above. Soil datasets will allow for calculation of average values for the soil erodibility factor K and length-slope factor LS for use in RUSLE calculations.

In addition to GIS data, daily precipitation and average temperature data must be available for at least one year. Parameters for the bulk density of stream bank sediment, nutrient concentration in bank sediment, and location-specific parameters for bank erosion and RUSLE calculations will also require preprocessing of data; however, most of these tasks should be relatively simple to perform, making this model functional for a large variety of users. If possible, the calculation of a calibration factor for stream bank erosion should be derived from observed storm events in the watershed. Procedures for deriving this calibration factor are described in the case study portion of this report.

B. *Model Calculations and Code Structure*

Most calculations in this model are performed on a daily basis for each land use in each drainage area. Each of the source models described calculate a contribution individually, and the total is recorded for each day. A flow chart of some key parts of the model can be found in Figure 1 below.

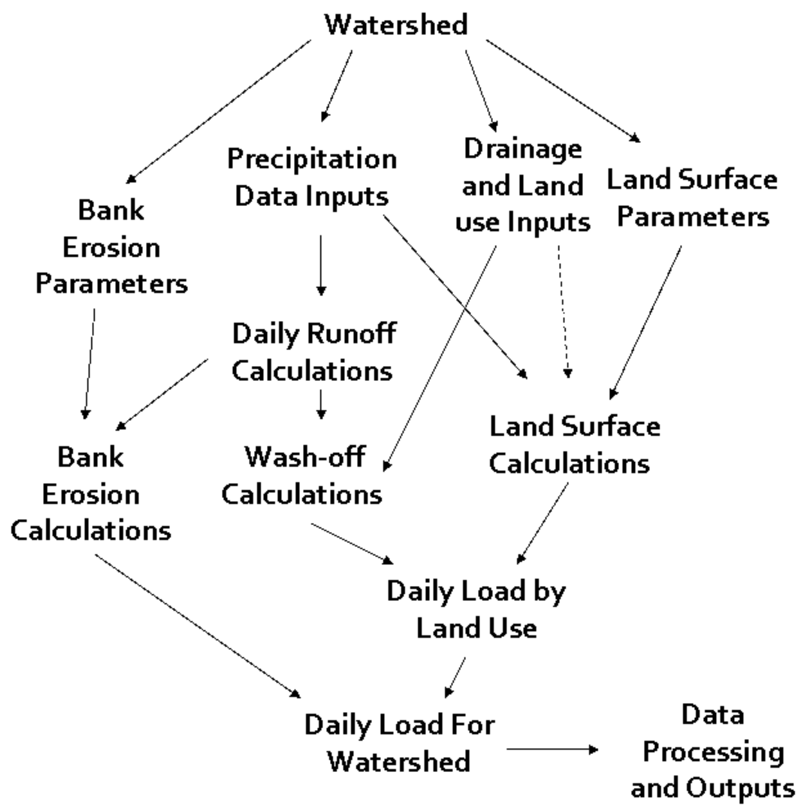


Figure 1. Flowchart of model operation from creation of Watershed Class Object to output. Dashed lines indicate partial inclusion of data or process in the following step.

The model is written utilizing an object-oriented approach so as to allow for simple modification of code to allow for use in numerous applications and to aid the ease of making adjustments to the functions. The watershed is represented by a *WatershedClass* module, which organizes and holds all information and loads calculated by the process modules. Further descriptions of the functionality of each class module can be found tabulated in Appendix B.

The SCS curve number method is utilized on a daily basis to calculate a curve number for predicting how the land surface will react to any rainfall or snow melt which might occur on that day. One curve number is calculated for the entire watershed by the *SCSMethodClass*; since the curve number is based exclusively on the precipitation and snow melt, it is a reasonable assumption that the depth of rain or snow fall and snow melt will be constant across a small watershed. The daily curve number calculation requires daily precipitation data, collected by the *RunQualDataClass,* as input as well as a user-defined average curve number, which can be found tabulated by the Soil Conservation Service for any given area in the United States. This method is used to calculate a daily depth of runoff, which is reported in centimeters for each land use type, depending on percent of that land use which is impervious. This is recorded for each land use in each drainage area in *DayDatClasses*, an array of which is available to other class modules for calculation of build-up/wash-off and bank erosion loads.

The build-up/wash-off model utilizes the runoff depth calculation performed according to the SCS curve number methodology in combination with the pervious percentage of the land cover from each land use type to calculate the maximum mass of sediment which is aggregated on each land use type. For each day with rainfall, then, the saturation function described above is used to determine how much of the sediment is washed off into the surface water runoff. This is also calculated on a daily basis, though separately for the pervious and impervious areas of each land use type in each drainage area of the watershed. The resulting loads for impervious and pervious portions of each land use are then aggregated and recorded for each day.

The Revised Universal Soil Loss Equation is implemented on a daily basis, as well. Most of the factors are constant with time for each land use, including the length-slope, cover, and management practice factors. Suggested values for the cover factor *(C)* the land use types used in the Little Crum Creek study are sourced from Limbrunner (2008). Daily values are calculated for the rainfall erosivity factor, as both the total storm kinetic energy *(E)* and maximum 30-minute rainfall intensity (I_{30}) are dependent on daily precipitation. In addition, daily values are calculated for the soil erodibility factor *(K)* due to its variation with season. A daily load from each land use area in each drainage is then calculated, and all values are summed to form a daily sediment load due to land surface soil loss. A nutrient load component is calculated based on the sediment load and a characteristic concentration of nutrients in the soil.

Average values for the soil erodibility factor *(K)* and the length-slope factor *(LS)* must be calculated from GIS-based Digital Elevation Models of the watershed. Several tools for calculating and tabulating these values by land use and drainage area can be found online or by following the instructions in Appendix A.

Tabulated values of the erodibility factor, *K*, are average values, which the model uses to calculate a daily value. This calculation is performed based on the equation described above. GIS-derived values of the length-slope factor are also average; however, these are generally not time-dependent, as they describe characteristics of the topography of the area of each land use type which relate to how easily soil particles will be eroded and transported by rainfall impact and runoff. These are characteristics relative to a standard 22m-long, 9 percent slope, as described above; topography most often does not change significantly over the time of analysis and DEM slope datasets are updated infrequently in any case.

Cover and management factor values are input parameters for each land use type, regardless of placement in the watershed, though these could vary between drainages if the user deems this appropriate. Suggested values derived from Limbrunner (2008) are tabulated below; these are appropriate for use with the land use categories listed, but tabulated values are available from alternate literature.

Table 1. Suggested RUSLE Land Cover Factors

Land Use	RUSLE Cover Factor (C)
Forest/Wetlands	0.001
Developed Wooded/Fields	0.01
Developed Low Intensity	0.05
Developed Medium Intensity	0.05
Developed High Intensity	0.1

A support practice factor *P* is included for each land use in each drainage, as well. For most applications, the provided value of unity will be sufficient, as no significant best management practices will be in use for an initial run of the model. If it is to be used for post-BMP analysis, changing this value will allow an updated prediction. A suggested value for this factor would be the fraction of surface sediment removed by BMPs. In any case, appropriate values should be obtained from consultation with an expert.

Running the *RUSLE_Data_From_Watershed* macro sets up the *RUSLE_Inputs* sheet for parameters to be entered. A *RUSLEClass* object is created for the watershed, which organizes all factors and calculations for the land surface erosion. The input parameters and areas are organized in an *Array2DRUSLEClasse*, which holds data for each land use (divided into pervious and impervious portions) by drainage area in a *RUSLELandUseFactorsClass*.

Calling the function *CalcRUSLE* in the *RUSLEClass* collects the necessary data from the *RUSLE_Inputs* sheet, as well as calculating daily values for the rainfall erosivity factor in a *RUSLERClass*, which contains a *DayDatClass* with each daily value. Daily soil loss is computed for the impervious and pervious portions of each land use based on the input factors, the erosivity factor calculated for the day, and an adjusted erodibility factor for the day. The daily calculated soil loss is recorded in a *DayDatClass* for each land use in each drainage. Each *DayDatClass* is then used to create monthly soil loss and yearly soil loss values in a *MonthDatClass* and*YearDatClass*. These are then aggregated across drainages for each land use , to aid the calculation of export coefficients, in a set of *Day-, Month-, and YearDatArrayClasses*. These are readily available datasets which can be obtained through simply *getProperty* statements; only those necessary for StormWISE calculations are currently being utilized.

Nutrient loads from land surface erosion is based on the load of sediment calculated for each day. A particulate concentration of each nutrient in soil mass is taken as an input for bank erosion load calculations; due to the small size of the watersheds, the soil is assumed to have fairly consistent concentrations of nutrients in soil regardless of land use type, though calculations are performed on a land use basis so that a contribution from each land use can be calculated and be used for export coefficient calculations. Thus, the total nutrient loads are calculated based on the total daily sediment eroded from each land use, which is then recorded in a *DayDatClass*.

The stream bank erosion calculations utilized in this model are a logical extension of the lateral erosion rate defined by Rutherford (2000), as described above. In order to calculate a load of sediment eroded, an average bulk density of the soil along the stream channel must be available for input, as the lateral erosion rate is translated to a volume of soil eroded daily. In addition, to calculate the volume of soil eroded, the total length of stream segments must be calculated for input. This can be derived with the TauDEM toolkit working in GIS, as well (Tarboton 2004). The average channel depth is required, and must be approximated from observations throughout the watershed.

In order to calculate nutrient loads from bank erosion, characteristic concentrations of pollutants in stream bank sediment are necessary. These calculated values are functions of soil type in the watershed. Due to the small scale of the watersheds, one value for each of these parameters should be sufficient to calculate an approximate loading.

Prior to calculating a bank erosion load, the model determines a value for *a,* a parameter describing the relationship between the volumetric flow and the bank erosion rate, as described in the previous section. If this value is known for the watershed in question, it can be entered as a parameter, and the average depth, total length, and average soil density inputs are not necessary. Otherwise, these three parameters must be entered in order to include bank erosion calculations.

A threshold volumetric flow rate at which bank erosion and stream bed mobilization begin in the creek to be modeled must be obtained and entered as a parameter in the *Bank_Erosion_Factors* sheet. This is obtainable if stream sampling has been occurred, as the threshold is made evident by a rapid increase in sediment concentration in stream samples. This should be observed for several storm events to obtain a reliable value. This value may vary depending on location in the watershed, but should not exceed an order of magnitude between locations; an average value may be used. For another method of calculating this, refer to Evans et al. (2003).

A calibration factor *k* must be calculated from recorded storms, as described in the theory section. This relates the actual observed average volumetric flow for storms triggering bank erosion and the predicted flow for these days. The predicted flow for these storm events can be obtained by entering the total rainfall depth for each storm day in the *Weather* sheet, with their antecedent five days of weather data, and running the model to obtain the volumetric flow predicted by the SCS method calculations. Alternately, this can be calculated manually from SCS methods described in *Technical Release 55* (Soil Conservation Service 1986).

The *BankErosionDataClass* is used to obtain inputs for, organize, and calculate data related to stream channel erosion. Runoff is obtained from the *SCSMethodClass* for the watershed, and used to calculate the daily average volumetric stream flow in cubic meters per second; this is scaled by the calibration factor *k*. The flow coefficient *a* is calculated from provided parameters inputs. For each day, the calibrated volumetric flow calculated is compared to the threshold flow, and a bank erosion load is calculated based on the daily calibrated flow rate. This load (kilograms) is transferred to a *DayDatClass,* and monthly and yearly loads are recorded in one *MonthDatClass* and *YearDatClass*. Since this calculation is not based on land use and is one aggregate load for the entire watershed, no aggregation between drainages or impervious and impervious regions are necessary. The daily sediment load is used to calculate daily, monthly, and yearly nutrient loads, as well. For each nutrient, the concentration of the pollutant in soil is multiplied by the calculated eroded sediment load to obtain the daily load of that nutrient, which is recorded in a *DayDatClass* and aggregated into a *MonthDatClass* and *YearDatClass*. All of these pollutant loads are organized into *Day-, Month-,* and *YearDatArrayClasses* to allow for access from other modules.

The underlying structure of each of these load process modules is such that the daily, monthly, or yearly load from each can be added together to obtain a total loading for the watershed. Daily loads of each pollutant are placed in *DayDatClasses*, which have been adapted to allow the addition of day-by-day data. Thus, a total daily load can be easily calculated by combining loads from all three modules into another *DayDatClass*.

However, the inputs from StormWISE require only aggregate yearly average data, which is added together by land use in each drainage, and then used to calculate an export coefficient for each land use.

C. *Summary of Model Implementation Instructions*

1. Closely observe and monitor several storm events to obtain threshold volumetric flow rate for bank erosion, as well as average stream depth.
2. Delineate watershed boundaries, streams, and drainages using DEMs and TauDEM or similar tool.
3. Overlay land use datasets with the watershed and drainage boundaries to obtain the area of each land use type in each drainage. Calculate length-slope and average soil erodibility factors for each land use in each drainage.
4. Obtain daily weather data and enter parameter data in *Weather*, *Watershed,* and *BankErosionFactors* sheets.
5. Run *RUSLE_Data_from_Watershed* Macro.
6. Enter remaining inputs in *RUSLE_Inputs* sheet.
7. Run *StormWISE_Setup* Macro.
8. Outputs appear in *Pollutant_Loads, Watershed_Benefits, Watershed_Main*, and *Results* sheets.
9. If desired, enter pollutant removal requirements in the *Watershed_Main* sheet and run the *Solve_LP* macro to run the StormWISE optimization model.

D. *Model Outputs*

As described above, the daily loads of sediment and nutrients from impervious and pervious portions of each land use in each drainage of the watershed are available for output from the model. This data is also available in monthly and yearly form, as well as average values for each time frame. Daily stream bank erosion calculations are available for the entire watershed, as well as monthly and yearly sums and averages.

As most TMDL legislation will likely be based on yearly aggregate data for the entire watershed, this data is available for all years modeled in the *Aggregate_Results_Manual* sheet. An average yearly load is also available there, as well as in the *Pollutant_Loads* sheet, as calculated from export coefficients calculated for each land use. Contributions from each model for sediment and nutrients are reported in monthly and yearly form in the *BuildUpWashOff_Outputs, BankErosion_Outputs,* and *RUSLE_Outputs* sheets; these are additionally aggregated, with daily data, in the *All_Process_Models* sheet. To demonstrate the capabilities of the calculations made, daily data for the impervious and pervious portions of each land use, as well as the aggregate for each land use, is reported for the land surface loading model in the *RUSLE_Outputs* sheet. In addition, if the *StormWISE_Setup* macro is run, export coefficients are calculated for each land use and reported in the *Pollutant_Loads* sheet.

As sediment load tends to determine all other pollutant loads, several graphs showing this effect with time have been created as outputs. These should update automatically upon running the model. A graph of the RUSLE daily sediment load for the first year of prediction is available in the *RUSLE_Daily_Sediment_fig* sheet. This shows the calculated load for each land use type for each day in the first year, but can easily be changed to reflect the output from any of the individual years of data. Each land use is represented by a line to ease interpretation, though the data is discrete in nature. A similar graph of predictions from all years is available in the *RUSLE_Daily_Sediment_All_fig* sheet. Overlaid graphs of monthly aggregate soil load for each year are available in the *Monthly_Aggregate_Soil_Loss_fig* sheet. This can be used to observe the effect of season on the sediment load.

V. CASE STUDY: LITTLE CRUM CREEK WATERSHED

A. *Data Used for Model Input*

i. *Weather data*

Ten years of daily precipitation and temperature data collected from the Philadelphia airport weather station were used for inputs in the *Weather* sheet. These were collected from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration. Daily precipitation data were input in measures of centimeters, and temperature data were entered in degrees Celsius. The data obtained from NCDC are from Station 724080-13739 (Philadelphia Airport).

ii. *Drainage Areas*

The watershed was delineated using TauDEM (Terrain Analysis Using Digital Elevation Models) for ArcGIS version 9.3. The digital elevation model used was sourced from the Pennsylvania Spatial Data Access (PASDA) repository. The area of Swarthmore College within the watershed boundary known to be drained by storm sewers to the ("Big") Crum Creek was removed manually from the watershed boundaries. The contributing areas for first- and second-order portions of the stream were grouped into a drainage labeled "Headwaters", while the areas contributing to third- through fifth-order streams were aggregated into the "Lowlands" drainage.

iii. *Land Use Areas*

Land use data were sourced from the Multi-Resolution Land Use Consortium dataset (MRLC)(2001 version). The following scheme, developed by McGarity (2009) was used for aggregation of the land use classes provided by the MRLC:

Table 2. Land Use Classifications Used in SSSN	
SSSN Land Use	MRLC 2001 Land Uses
Forest/ Wetland	Deciduous, Evergreen, and Mixed Forests; Woody and Emergent Herbaceous Wetlands
Developed Wooded/Fields	Developed Open; Pasture; Crops; Barren
Developed Low Intensity	Developed Low Intensity
Developed Medium Intensity	Developed Medium Intensity
Developed High Intensity	Developed High Intensity

iv. *Build-Up/ Wash-Off Inputs*

Impervious fractions for each land use type were generated from an intersection of land use and impervious GIS datasets. The data used was that developed by McGarity (2009) for the Little Crum Creek (LCC) watershed from PASDA (2000). Build-up rates for impervious and pervious portions of each land use were also those developed by McGarity (2009) for the Little Crum Creek. One value for the average SCS Curve Number for impervious surface was used for all land uses, as used by McGarity (2009). As all impervious surfaces in this suburban watershed tend to act similarly with respect to runoff, this is an appropriate assumption. The curve number used was 98, which reflects the near-complete impermeability of the characteristic impermeable areas (pavement, roofs, et cetera).

v. *Revised Universal Soil Loss Equation Inputs*

Several factors for the Revised Universal Soil Loss Equation (surface erosion) model were calculated for input prior to model implementation, while others were calculated within the model itself. The rainfall erosivity factor, *R*, was calculated within the model based on provided precipitation data, as described above. A yearly average value of *R* was found for the region to be approximately 175 (Gaffney and Lake 2005). Unfortunately, this value is not meaningful when calculations are made on a daily basis, as the effect of soil erosion by rainfall impact is far more apparent on the daily scale. In addition, the small scale of this watershed further suggests the appropriateness of daily calculations, as the amount of sediment eroded cannot be aggregated to large tracts of land. The average value for this region is useful only on a large scale where error introduced by lump-sum calculations would be small in comparison to the total load; in a small watershed like that of the Little Crum Creek, smaller total loads require more precise predictions.

Average soil erodibility factors were calculated using GIS datasets obtained from the United States Department of Agriculture (USDA) National Resources Conservation Service (NRCS) Soil Data Mart for Delaware County, Pennsylvania. The soil erodibility is based on soil type, and values for each soil type are provided by the NRCS for each soil type in the region. Tabulating the area of each soil type in each land use using GIS tools allows for an area-weighted value of average soil erodibility to be calculated for each drainage area. For the Little Crum Creek, a average for all soil types across the drainages was found to be approximately 0.45, though individual values for each land use were calculated based on prior watershed delineations. Instructions for calculating these values can be found in Appendix A. The average soil erodibility factor for each land use was then adjusted for the effect of seasonality as described above within the model before daily calculations of *RUSLE* soil contributions were made.

Average values of the length-slope factor, *LS*, for each land use were calculated prior to model implementation using GIS datasets. The numerical model for calculation of this factor described above can be calculated easily within the GIS framework, as slope and flow accumulation raster datasets can be manipulated easily in this context, while translation to appropriate input values for calculation within the model would be time-consuming an less accurate. Thus, some preprocessing is required for this parameter, but simple instructions can be found in Appendix A or online. This factor must be averaged based on land use type for each drainage, which can be tabulated within GIS by overlapping the land use, drainage, and length-slope data layers.

The cover and management factor, *C*, also depends on land use type, but not on drainage classification. There is some evidence that the drainage classification system used for this model ("Headwaters" and "Lowlands") would benefit from such a division, as cover and management would have more effect in upstream areas. However, as a proper method for developing such incongruent values has not been properly established, that was not included in this analysis.

The Little Crum Creek encompasses several small-scale best management practice installations, including an approximately one-acre constructed wetland and another one-acre restored wetland. However, for the purposes of this study, such measures have been disregarded as their effect on the stream has been minimal (though they retain considerable educational value). Thus, for all land use types within the watershed, the support practice factor (*P*) was allowed to be unity, suggesting little has been to degrade or improve the watershed. As a base case, this is a sound assumption; for future analyses, this can be changed to reflect any best management practices that have been implemented in the watershed.

vi. *Bank Erosion Parameters*

Several parameters were necessary for stream bank erosion modeling, some of which were obtainable from physical stream measurements, and others of which were derived from observational and recorded data from the watershed. The total stream length was calculated from the TauDEM watershed and stream delineation performed as an initial stage of the project; all streams of Strahler orders 1-5 were included in this approximate length. The average stream channel depth is approximated at 0.25m, though some places are considerably deeper and some considerably shallower. This parameter is used to calculate the stream bank erosion, which generally only occurs in periods of high flow, often nearly bank-full events. Thus, an average value is appropriate because the stream depth tends to increase with distance downstream, but any sediment eroded upstream and suspended in the stream flow will act to increase the eroding effect of the high volumetric flow rate.

The calibration factor, *k*, taken as an input parameter for stream bank erosion was calculated based on threshold volumetric flows for six recorded storm events in the Little Crum Creek where high sediment concentrations in collected samples suggested bank erosion had occurred. The volumetric flow recorded at the time when an approximated threshold stream velocity of 2.5 ft/s was just reached was collected for each storm. The total rainfall for each day on which one of these events occurred, along with the rainfall and temperature of the preceding five days, was obtained from the NCDC website and entered into an adjusted version of the model[1]. The runoff volume predicted by the SCS Curve Method module was then used to calculate the average stream volumetric flow for the day using the formulas derived above.

[1] *Qdata.xls Microsoft Excel File; "weather" and "test"sheets*

The average predicted volumetric flow for the day was generally smaller than the actual threshold volumetric flow, because the total depth of runoff was averaged over the entire day. However, what might be expected to be an immense disparity was actually observed to correlate rather closely. The average ratio of actual to predicted volumetric flow was found to be 1:1.29, and the values were relatively consistent between storms. This can be accounted for by the fact that the actual volumetric flow in-stream varies considerably during a storm event, as does the stream velocity; both follow a skewed bell curve shape recognizable from basic hydrology concepts. If a rain event is severe enough to warrant stream velocity above this threshold, the volumetric flow associated will fall somewhere along the increasing slope of the curve. This phenomenon is displayed in the figure below.

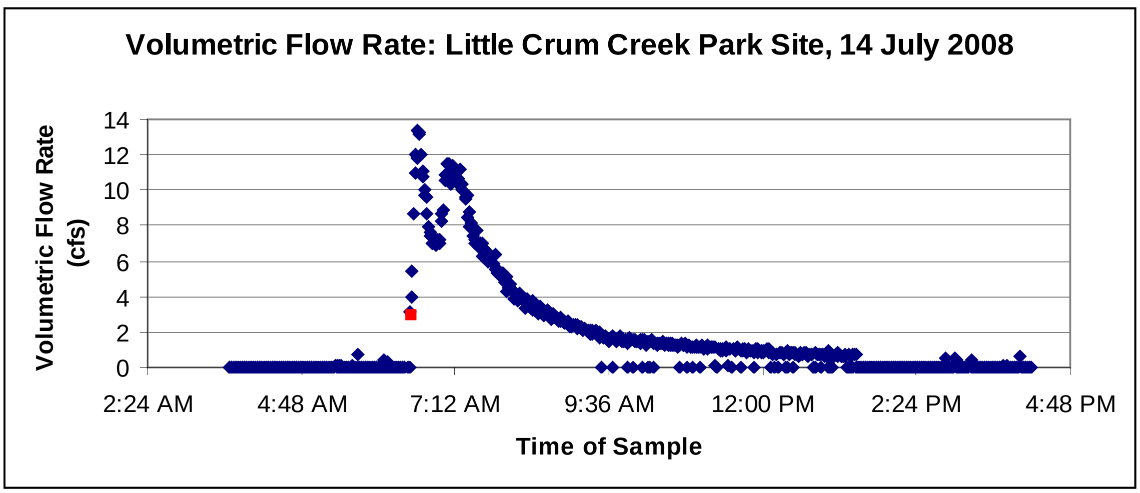


Figure 2. Volumetric flow rate for one storm used in calibration for the Little Crum Creek. The threshold stream velocity (and thus volumetric flow) is marked in red. All flow rates above this contribute to stream bank erosion, while those below do not.

Thus, some portion of the total stream flow will occur below the threshold while the remaining will occur above it; the ratio of these flows is variable with duration and intensity of the storm. An accepted method of accounting for this difference has not been developed, so it must be assumed that an average value will provide the best available approximation. Data from storms for one or more full years would greatly aide the calculation of a more descriptive value, but since data for only part of a year was available, this was used to the best possible extent.

An average bulk density of soil lying along the stream bank was approximated for the Little Crum Creek to be 1400 kg/m^3. This value is based on the general characterization of soil in the watershed as sandy/silty loam. The watershed has areas of both coastal plain and Piedmont geological regions, so there may be some difference between soil densities due to this; however, nearly the entire watershed is in the coastal plain, and thus one value is sufficient for a base case run. In addition, particulate nitrogen and phosphorus concentrations in the soil are assumed to be consistent throughout the watershed; these take on values suggested by Limbrunner (2008) at 9.99 g/m^3 soil and 99.9 g/m^3 soil, respectively.

B. *Intermediate Results*

In creation and application of this model, numerous intermediate calculations are produced. Many of these, as described in the *Model Outputs*, remain available for the modeler to utilize for any purpose necessary. The total daily predicted loads for each pollutant from each process model is available in the *All_Process_Models* sheet of the SSSN Excel file. In addition, the total monthly and yearly loads for each pollutant from each process model are available in the same sheet. The screen figures below show the setup of the available data in this sheet.

	Year	Day	RUSLE Daily Loads TSS (kg)	TP (kg)	TN (kg)	Build-up/ Wash-off Daily Loads TSS (kg)	TP (kg)	TN (kg)	Bank Erosion Daily Loads TSS (kg)	TP (kg)	TN (kg)
341	1	339	28.70627	0.00020484	0.002048397	173.9837	4.094788	0.465387184	0	0	0
342	1	340	7.260825	5.18112E-05	0.000518112	0	0	0	0	0	0
343	1	341	0	0	0	0	0	0	0	0	0
344	1	342	0	0	0	148.0866	3.485287	0.396115318	0	0	0
345	1	343	121.5054	0.000867028	0.008670279	0	0	0	0	0	0
346	1	344	0	0	0	0	0	0	0	0	0
347	1	345	0	0	0	0	0	0	0	0	0
348	1	346	0	0	0	0	0	0	0	0	0
349	1	347	0	0	0	0	0	0	0	0	0
350	1	348	0	0	0	0	0	0	0	0	0
351	1	349	0	0	0	6423.785	129.5777	15.62789532	2241.754	0.015997	0.159965
352	1	350	3753.493	0.026783857	0.267838568	641.9066	14.86411	1.716619178	1213.758	0.008661	0.08661
353	1	351	411.4502	0.002935991	0.029359907	0	0	0	0	0	0
354	1	352	0	0	0	0	0	0	0	0	0
355	1	353	0	0	0	0	0	0	0	0	0
356	1	354	0	0	0	0	0	0	0	0	0
357	1	355	0	0	0	0	0	0	0	0	0
358	1	356	0	0	0	0	0	0	0	0	0
359	1	357	0	0	0	4250.877	89.66906	10.64548809	1906.896	0.013607	0.136071
360	1	358	8.926126	6.36943E-05	0.000636943	0	0	0	0	0	0
361	1	359	0	0	0	0	0	0	0	0	0
362	1	360	0	0	0	0	0	0	0	0	0
363	1	361	0	0	0	213.0226	5.013588	0.569812098	0	0	0
364	1	362	37.12091	0.000264884	0.002648842	0	0	0	0	0	0
365	1	363	0	0	0	0	0	0	0	0	0
366	1	364	0	0	0	0	0	0	0	0	0
367	1	365	0	0	0	0	0	0	0	0	0
368	2	1	0	0	0	2823.383	66.28446	7.546677785	0	0	0

Figure 3. SSSN *All_Process_Models* Results Sheet displaying daily load data

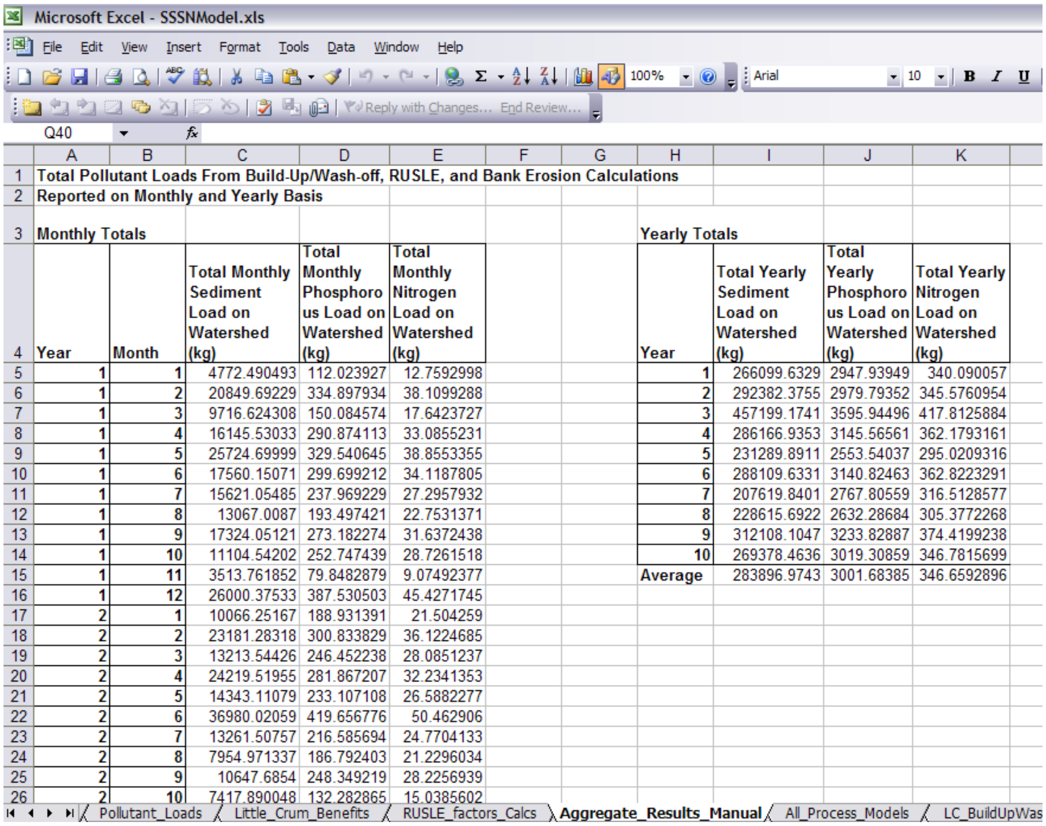
	Month	RUSLE Monthly Loads TSS (kg)	TP (kg)	TN (kg)	Build-up/ Wash-off Monthly Loads TSS (kg)	TP (kg)	TN (kg)	Bank Erosion Monthly Loads TSS (kg)	TP (kg)	TN (kg)
21	19	2431.297	0.017349042	0.17349	9270.203	216.3009	24.74197	3621.428	0.025841	0.258415
22	20	120.9083	0.000862767	0.008628	7936.577	186.7911	21.22947	0	0	0
23	21	630.0093	0.004495567	0.044956	10551.84	248.3424	28.22501	0	0	0
24	22	2276.256	0.016242712	0.162427	5618.292	132.1545	15.02569	1453.311	0.01037	0.103704
25	23	10182.15	0.072656929	0.726569	16292.3	348.1148	40.93328	6189.683	0.044168	0.441678
26	24	2623.212	0.018718488	0.187185	7507.286	169.1636	19.61583	1720.939	0.01228	0.122801
27	25	12561.89	0.089638033	0.89638	15527.23	328.0356	38.77751	4560.938	0.032546	0.325455
28	26	2041.639	0.01456855	0.145685	12170.37	277.8219	32.07668	0	0	0
29	27	48725.64	0.34769223	3.476922	20403.17	436.9482	51.25798	6572.458	0.046899	0.468992
30	28	55194.21	0.393850084	3.938501	15536.33	361.947	41.54494	9509.568	0.067858	0.678576
31	29	24883.68	0.177562865	1.775629	14341.07	318.4175	37.13421	7770.881	0.055451	0.554508
32	30	3392.427	0.024207387	0.242074	9408.262	221.3468	25.16322	1423.51	0.010158	0.101578
33	31	242.5328	0.001730645	0.017306	4144.759	97.54887	11.08678	0	0	0
34	32	242.7436	0.001732149	0.017321	9832.076	231.2523	26.29444	1631.485	0.011642	0.116418
35	33	2481.319	0.017705981	0.17706	8432.028	197.5447	22.52626	3707.965	0.026459	0.26459
36	34	5165.342	0.036858405	0.368584	11657.08	273.7198	31.15909	1778.335	0.01269	0.126897
37	35	20046.26	0.143044381	1.430444	20059.13	416.8954	49.54233	9495.769	0.067759	0.677591
38	36	62589.94	0.446623957	4.46624	19895.34	413.36	49.13844	11773.81	0.084015	0.840145
39	37	1270.326	0.009064682	0.090647	8949.477	203.2981	23.49814	0	0	0
40	38	18176.62	0.129703196	1.297032	15350.5	352.5305	40.62377	5962.018	0.042543	0.425433
41	39	19007.96	0.135635394	1.356354	18230.53	388.1502	45.86131	3707.141	0.026453	0.264531
42	40	23542.13	0.167989947	1.679899	10924.99	256.5198	29.22576	3346.288	0.023878	0.238782
43	41	28900.83	0.20622806	2.062281	19853.32	421.9421	49.65544	8732.074	0.06231	0.623096
44	42	2530.296	0.018055472	0.180555	9302.096	218.9127	24.8815	1221.813	0.008719	0.087185
45	43	8543.834	0.060966358	0.609664	16372.87	382.5303	43.79021	10048.28	0.071702	0.717017
46	44	248.718	0.001774781	0.017748	6264.862	147.2187	16.74981	1675.857	0.011958	0.119584
47	45	559.1194	0.003989716	0.039897	9340.788	219.8398	24.98558	0	0	0
48	46	2004.917	0.014306515	0.143065	8820.926	207.5084	23.59162	1216.932	0.008684	0.086837

Figure 4. SSSN *All_Process_Models* Results Sheet displaying monthly load data

Year	RUSLE Yearly Loads TSS (kg)	TP (kg)	TN (kg)	Build-up/ Wash-off Yearly Loads TSS (kg)	TP (kg)	TN (kg)	Bank Erosion Yearly Loads TSS (kg)	TP (kg)	TN (kg)
1	99897.049	0.712837	7.128368	129636.88	2938.202	339.1163	36565.7	0.260922	2.609224
2	114921.34	0.820046	8.200459	133517.52	2968.457	344.4424	43943.51	0.313568	3.135684
3	237567.62	1.695215	16.95215	161406.83	3574.838	415.7019	58224.72	0.415475	4.15475
4	111169.5	0.793274	7.932738	137714.25	3134.972	361.12	37283.18	0.266042	2.660421
5	84473.76	0.602781	6.027806	113286.52	2545.12	294.1789	33529.61	0.239258	2.392577
6	110192.83	0.786305	7.863045	139081.81	3130.19	361.7589	38834.99	0.277115	2.771154
7	66364.894	0.473561	4.735609	119058.94	2761.486	315.8809	22196.01	0.158384	1.583844
8	73139.583	0.521903	5.219032	118137.42	2624.403	304.5889	37338.69	0.266438	2.664382
9	119070.95	0.849656	8.496563	143197.18	3221.776	373.2147	49839.97	0.355644	3.556438
10	111093.06	0.792728	7.927283	131075.08	3009.44	345.7946	27210.33	0.194165	1.941652
Average	**112789.06**	**0.80**	**8.05**	**132611.24**	**2990.89**	**345.58**	**38496.67**	**0.27**	**2.75**

Figure 5. SSSN *All_Process_Models* Results Sheet displaying yearly load data

These values are also available separated by process model output, and aggregated in the *Aggregate_Results_Manual* sheet, displayed below. Daily loads by land use and drainage are also available for the land surface erosion model (RUSLE) in the *LC_RUSLE_Outputs* sheet, also displayed below.



Total Pollutant Loads From Build-Up/Wash-off, RUSLE, and Bank Erosion Calculations

Reported on Monthly and Yearly Basis

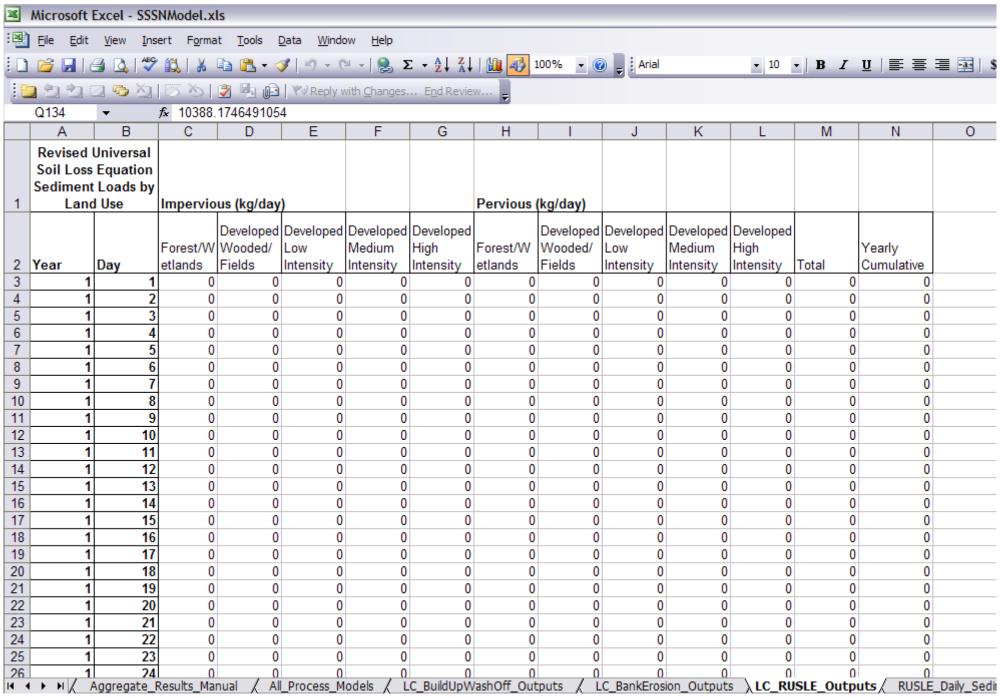
Monthly Totals

Year	Month	Total Monthly Sediment Load on Watershed (kg)	Total Monthly Phosphorous Load on Watershed (kg)	Total Monthly Nitrogen Load on Watershed (kg)
1	1	4772.490493	112.023927	12.7592998
1	2	20849.69229	334.897934	38.1099288
1	3	9716.624308	150.084574	17.6423727
1	4	16145.53033	290.874113	33.0855231
1	5	25724.69999	329.540645	38.8553355
1	6	17560.15071	299.699212	34.1187805
1	7	15621.05485	237.969229	27.2957932
1	8	13067.0087	193.497421	22.7531371
1	9	17324.05121	273.182274	31.6372438
1	10	11104.54202	252.747439	28.7261518
1	11	3513.761852	79.8482879	9.07492377
1	12	26000.37533	387.530503	45.4271745
2	1	10066.25167	188.931391	21.504259
2	2	23181.28318	300.833829	36.1224685
2	3	13213.54426	246.452238	28.0851237
2	4	24219.51955	281.867207	32.2341353
2	5	14343.11079	233.107108	26.5882277
2	6	36980.02059	419.656776	50.462906
2	7	13261.50757	216.585694	24.7704133
2	8	7954.971337	186.792403	21.2296034
2	9	10647.6854	248.349219	28.2256939
2	10	7417.890048	132.282865	15.0385602

Yearly Totals

Year	Total Yearly Sediment Load on Watershed (kg)	Total Yearly Phosphorous Load on Watershed (kg)	Total Yearly Nitrogen Load on Watershed (kg)
1	266099.6329	2947.93949	340.090057
2	292382.3755	2979.79352	345.5760954
3	457199.1741	3595.94496	417.8125884
4	286166.9353	3145.56561	362.1793161
5	231289.8911	2553.54037	295.0209316
6	288109.6331	3140.82463	362.8223291
7	207619.8401	2767.80559	316.5128577
8	228615.6922	2632.28684	305.3772268
9	312108.1047	3233.82887	374.4199238
10	269378.4636	3019.30859	346.7815699
Average	283896.9743	3001.68385	346.6592896

Figure 6. SSN *Aggregate_Results_Manual* Output Sheet displaying aggregate monthly loads for all pollutants from build-up/ wash-off, land surface, and stream bank erosion process models



Revised Universal Soil Loss Equation Sediment Loads by Land Use		Impervious (kg/day)					Pervious (kg/day)						
Year	Day	Forest/Wetlands	Developed Wooded/ Fields	Developed Low Intensity	Developed Medium Intensity	Developed High Intensity	Forest/Wetlands	Developed Wooded/ Fields	Developed Low Intensity	Developed Medium Intensity	Developed High Intensity	Total	Yearly Cumulative
1	1	0	0	0	0	0	0	0	0	0	0	0	0
1	2	0	0	0	0	0	0	0	0	0	0	0	0
1	3	0	0	0	0	0	0	0	0	0	0	0	0
1	4	0	0	0	0	0	0	0	0	0	0	0	0
1	5	0	0	0	0	0	0	0	0	0	0	0	0
1	6	0	0	0	0	0	0	0	0	0	0	0	0
1	7	0	0	0	0	0	0	0	0	0	0	0	0
1	8	0	0	0	0	0	0	0	0	0	0	0	0
1	9	0	0	0	0	0	0	0	0	0	0	0	0
1	10	0	0	0	0	0	0	0	0	0	0	0	0
1	11	0	0	0	0	0	0	0	0	0	0	0	0
1	12	0	0	0	0	0	0	0	0	0	0	0	0
1	13	0	0	0	0	0	0	0	0	0	0	0	0
1	14	0	0	0	0	0	0	0	0	0	0	0	0
1	15	0	0	0	0	0	0	0	0	0	0	0	0
1	16	0	0	0	0	0	0	0	0	0	0	0	0
1	17	0	0	0	0	0	0	0	0	0	0	0	0
1	18	0	0	0	0	0	0	0	0	0	0	0	0
1	19	0	0	0	0	0	0	0	0	0	0	0	0
1	20	0	0	0	0	0	0	0	0	0	0	0	0
1	21	0	0	0	0	0	0	0	0	0	0	0	0
1	22	0	0	0	0	0	0	0	0	0	0	0	0
1	23	0	0	0	0	0	0	0	0	0	0	0	0
1	24	0	0	0	0	0	0	0	0	0	0	0	0

Figure 7. SSSN *LC_RUSLE_Outputs* Results Sheet displaying daily land surface erosion calculations for pervious and impervious portions of each land use; combined pervious and impervious calculations by land use are also available

C. *Final Model Results: Yearly Loads*

The need that this model answers is primarily one of predicting total yearly sediment loads on small suburban watersheds, similar to the Little Crum Creek watershed. Thus, the results of most importance are the yearly loads of each pollutant, which are available separated by process model in *All_Process_Models* and aggregated in *Aggregate_Results_Manual*. Most users are assumed to want to couple the SSSN outputs with a cost allocation optimization model such as StormWISE, which is why this model is coupled with StormWISE in a logical way. However, the individual results are made available in the case that the model outputs will be used in another model or for another purpose. Moreover, these predictions are useful as targets for pollutant removal and for defining removal percentages as might be required by future TMDL legislation. The average yearly contributions from each process model can be found tabulated below.

Table 3. Average Yearly Sediment Loads Predicted by Process Models in SSSN			
Calculation Method	Total Sediment Load (metric ton)	Total Phosphorous Load (kg)	Total Nitrogen Load (kg)
Build-up/ Wash-off	133	2991	346
Land Surface Erosion (RUSLE)	113	0.8	8.0
Bank Erosion	38	0.3	2.8
All Process Models	284	2992	356

The total yearly load for each of the years of data, as well as the average over the ten years of prediction, are shown in the following table, along with those predicted for the same data set by McGarity (2009) for the same watershed, for comparison.

Table 4. Total Average Yearly Loads Predicted For Little Cum Creek Watershed			
	TSS-KG	TN-KG	TP-KG
McGarity (2009)	114388	2576	299
McGarity (2009) with Stream Bank Erosion	252164	2576	299
SSSN	283897	2999	349

As expected, the values calculated by SSSN are considerably larger than those predicted by the build-up/ wash-off model alone used by McGarity (2009), which was nearly identical to the one used as the process model in SSSN. The load predicted by SSSN is approximately double that predicted using the build-up/ wash-off model alone, due to the inclusion of land surface and stream bank erosion. McGarity (2009) also included a rudimentary stream bank erosion model in calculations for the total yearly load based on a fraction of runoff contributing to sediment erosion from observational data. This stream bank erosion model effectively doubled the load of sediment, but did not address any additional loads of nitrogen or phosphorous due to this process.

The StormWISE_Setup macro allows the user to also obtain export coefficients and event mean concentrations for each land use based on calculations averaged over the entire watershed. The base case run of SSSN on the Little Crum Creek produced the following export coefficients and event mean concentration values for each land use.

Table 5. Export Coefficients and Event Mean Concentrations for Little Crum Creek Base Case

		Export Coefficients			Event Mean Concentrations		
Land Use	Runoff(cm)	TSS-KG (kg/ha)	TN-KG (kg/ha)	TP-KG (kg/ha)	TSS-KG (mg/L)	TN-KG (mg/L)	TP-KG (mg/L)
Forest/ Wetlands	13	51.37	0.43	0.04	38.57	0.32	0.03
Developed Wooded/ Fields	19	211.3	2.73	0.33	110.9	1.43	0.17
Developed Low Intensity	26	382.1	3.03	0.31	146.0	1.16	0.12
Developed Medium Intensity	34	400.7	7.77	0.99	117.9	2.29	0.29
Developed High Intensity	42	611.3	9.90	1.12	144.0	2.33	0.26

These can be compared to the export coefficients, total loads, and event mean concentrations produced by implementing only the build-up/ wash-off portion of the model as summarized by McGarity (2009). The following table has been reproduced below using data presented in the report to show the increase in characteristic loads generated by SSSN.

Table 6. Export Coefficients and Event Mean Concentrations for Little Crum Creek From McGarity (2009)							
		Export Coefficients			Event Mean Concentrations		
Land Use	Runoff(cm)	TSS-KG (kg/ha)	TN-KG (kg/ha)	TP-KG (kg/ha)	TSS-KG (mg/L)	TN-KG (mg/L)	TP-KG (mg/L)
Forest/Wetlands	11	35.88	0.38	0.04	31	0.34	0.03
Developed Wooded/Fields	15	110	2.16	0.26	72	1.42	0.17
Developed Low Intensity	23	156	32.65	0.27	67	1.15	0.12
Developed Medium Intensity	30	210	6.73	0.86	70	2.26	0.29
Developed High Intensity	40	266	9.06	1.02	66	2.27	0.26

The base case calculated using SSSN suggests significantly higher event mean concentrations and export coefficients for the watershed across the board. This reflects the increased loads due to consideration of the land surface erosion (RUSLE) model, which almost doubles the total yearly load calculated from build-up/ wash-off alone. Neither set of calculations considers the load from stream bank erosion, as this was not calculated by land use, though theoretically the model could be extended to allow this.

Use of the SSSN model provides an alternative to the predictions previously made for this watershed which considers more of the processes observed during storm events in the Little Crum Creek. The best available numerical models were integrated into a framework for load calculation which will hopefully prove more accurate for this watershed. The bank erosion model in SSSN is based on a far more widely accepted method of calculation than the model implemented previously. The addition of land surface erosion reflects observed phenomena within the watershed, as well, as loose soil is often eroded from the surfaces of playing fields, construction sites, lawns, and similar pervious areas.

Based on the event mean concentrations observed from five monitoring sites presented by McGarity (2009), the predicted loads from SSSN provide similar event mean concentrations to those observed, an certainly take into account the stream bank erosion phenomena observed during particularly large storms. However, the fact that stream bank erosion is not included in any of the event mean concentration calculations due to its removal from land use classification may make comparison to observed data difficult. Additional analysis of the contributing areas of each land use type and the total stream length in the contributing area to each of these sites might provide further insight into the accuracy of these predicted event mean concentrations. Nonetheless, SSSN provides a useful model for use with the Little Crum Creek Watershed.

D. *Integration with StormWISE Decision Framework*

The SSSN model has been integrated into the StormWISE resource allocation optimization model developed by McGarity (2009) in its most current version, also programmed in Visual Basic for Applications. The modular object-oriented programming technique used has allowed the SSSN modules to be used by the StormWISE program as a preprocessing step, creating loads and export coefficients for input. This allows a user to input basic spatial data about the watershed to be modeled and receive output data regarding optimal resource allocation.

This effectively eliminates the need for a separate pollutant loading model to be run on a watershed, considerably streamlining and simplifying the process of finding ways to improve water quality in small suburban watersheds. The modular setup of the program additionally allows users the freedom to use either of the models independently, as the inputs for the pollutant loading model and optimization model are read in separately; the pollutant loading model reports results to the sheet used for optimization model input, but the values can be manually changed, as well.

The modular structure of the SSSN model will allow for future changes to be made to the StormWISE program quite easily. Most class modules are general enough to be used in contexts entirely separate from their original intended use, so long as the same data collection and calculation structure is useful. Many basic data structures have been augmented with additional functionality, but their structure allows them to be used in a way that only utilizes some portion of this functionality as needed.

Of particular interest to the development of StormWISE, most of the pollutant calculation classes will allow for inclusion of more pollutants than just suspended solids, nitrogen, and phosphorous. Future development could allow the analysis of trace metals, aromatic hydrocarbons, or any number of other indicators of water quality or environmental degradation. The addition of a stream model could even allow the analysis of biochemical oxygen demand sources and decay in the watershed, and the most cost-effective way of remedying a related problem.

DESIGN CRITERIA FULFILLMENT

The design aspects of this project fulfill requirements set out by the Engineering Department of Swarthmore College as well as the criteria for educational objectives set out by the Accreditation Board for Engineering and Technology (ABET). Considerable portions of the program framework and formulation required the collection, analysis, and decision-making processes inherent in any design project. The framework for data collection and processing was created to allow users an elegant input interface while allowing future developers the flexibility to re-use code in portions and make adjustments to the to the model goals.

This project involved research, design, design implementation, and public outreach segment, mimicking the process used by professional engineers working in an academic research context. The sustainability of the model was considered when developing the object-oriented framework, as re-use of the code is a viable option. In this way, the needs of the modelers of today are met while increasing the resources available to future modelers working on similarly modular projects.

The goals set out at the beginning of this project were met and surpassed. A working model based on the best available numerical approximation methods was created to describe the physical processes of pollutant erosion and deposition in small suburban watersheds. The developed model is simple enough in its input requirements that a user minimally fluent in ArcGIS or other GIS software should be able to create the necessary input data for the watershed to be modeled. Beyond the original proposal, this model was successfully integrated with the current version of the StormWISE software package for resource allocation optimization. The structure of the code will allow for one or more of the process modules to be update or removed from the prediction module and additional process modules can be incorporated if that is deemed necessary.

FUTURE WORK AND APPLICATIONS

Unfortunately, the creation of this or any model does not answer all of the questions posed about the physical processes observed in nature; thus, further development of portions of this model and the StormWISE framework for which it was designed will be necessary. Future directions the SSSN/StormWISE project should take will depend on the needs of the watershed managers and stakeholders of the Little Crum Creek whose support has made this project possible. Nonetheless, several interesting extensions have been identified in the process of developing this model.

Event mean concentrations characteristic of suburban land uses could be developed from data created by applications of this model to numerous similar suburban watersheds to determine the effect of scale on load calculations, and create a database of characteristic values so that those without experience in modeling and GIS data manipulation could use optimization models like StormWISE.

Currently, the stream bank erosion model outputs are included in StormWISE as an additional source of sediment and nutrients, but the problems related to this process are not addressed by the cost optimization model in StormWISE, since all BMPs are assumed to be implemented on a land use area. Since bank erosion loads are not associated with any land use, the effect of implementing BMPs on the land surface is not reflected in the load prediction for bank erosion. However, since bank erosion is directly related to the volume of runoff, a removal target for the optimization model, any runoff reduction will decrease volumetric stream flow. In some cases, this would allow the daily average volumetric flow to drop below the threshold value, thereby negating bank erosion for that storm. Thus, stream bank erosion seems to take on attributes of a feedback loop. If such a recursive relationship could be derived and included in the StormWISE optimization model, it would greatly increase the accuracy of the suggested investment levels.

As discussed above, the flexible nature of object-oriented programming allows that the model can be used in portions or in its entirely; one of the loading modules can be easily removed or disregarded. In addition, modules, classes, and functions can be added to make an even more descriptive model. Many can also be used to collect and store data of any type; thus, they could be used for a purpose requiring a similar structure but one completely unrelated to water quality. This sustainable code design will allow for future development of the model and of StormWISE. It is highly suggested than anyone considering using the model explore the code, as the true functionality of these classes far exceeds the few calculations for which they are used in this model.

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Soil Data Mart of the National Resources Conservation Service, United States Department of Agriculture. http://soildatamart.nrcs.usda.gov/ Data received 15 July 2008.

Weather Data Federal Climate Complex Global Surface Summary of Day Data, Version 7. National Oceanic and Atmospheric Administration. ftp://ftp.ncdc.noaa.gov/pub/data/gsod/

APPENDICES

Appendix A

Rudimentary Description of Calculation of GIS-Based Multiplication Factors for the Revised Universal Soil Loss Equation: Little Crum Creek Watershed

Average Soil Erodibility Factor *(K)*

For calculation of one K-value per Drainage area

1. Download or open data file for Delaware County, PA or watershed of interest from http://soildatamart.nrcs.usda.gov
2. Extract all files from the zipped folder, including the zipped soildb_US_2002 (this is a SSURGO Data Package and provides average *K*-values for each soil type)
3. Open a new ArcMap document and add a shapefile of the watershed, including delineated drainages.
    a. Add the soilmu_a_pa045 file from the "spatial" folder extracted.
    b. Change the representation of this layer to "categories" using "unique values" and value field "musym"; add all values (i.e. AgB2, BrD, etc.)
4. In the Spatial Analyst Toolbox, expand "Zonal" and double-click "Tabulate Area".
    a. Input raster of feature zone area: drainage area shapefile
    b. Zone field: Id
    c. Input raster or feature class data: soilmu_a_pa045
    d. Class field: musym
    e. Save output table wherever is useful. Click OK.
5. Go to source tab in the ArcMap document. Right-click on the table you just made.
    a. Select Data > export data
    b. Change extension from ".dbf" to ".xls" and note where it is saved. Click OK.
6. Open Excel and the table created wherever it was saved.
    a. Create two columns at the end of the table, one called "Total Area" and one called "Weighted K-Val"
    b. Add one row called "K-Val"
7. Navigate to the folder containing soil data. Double-click on the Microsoft Access Application file "soildb_US_2002". Allow it to run, and click okay or ignore all warnings.
    a. Paste the address of the \tabular folder in the soil data folder you downloaded. Make sure it ends in \tabular.
8. Soil Reports window will appear. Select all Map Unit Symbols which appear in the excel file under Report Name
    a. Select Physical Soil Properties
    b. Click "Include Report Description"
    c. Click Generate Report. This will give you a table of soil properties. Use the K_w values for the first 0-10inches or so
9. Under each soil type in the ArcGIS-generated table, paste the corresponding K_w value from the report
    a. Multiply the area by the corresponding K-value for each soil type and all for each drainage and divide by the total area in the drainage (first column). This is a list of the desired K-values. This will give an average for the drainage.

Average Length-Slope Factor *(LS)*

1. With an ArcMap document open with DEM open, enable the Spatial Analyst toolbar by selecting View>Toolbars>Spatial Analyst
2. Calculate the slope:
    a. From Spatial Analyst Toolbar, select Surface Analysis>Slope
    b. Give the calculation the name "slope", and make permanent
    c. Calculate:
        i. Select Raster Calculator from Spatial Analyst Toolbar
        ii. build the following expression:
        FlowAccumulation(FlowDirection([elevation])
    d. Click "evaluate", make the calculation permanent, then rename "flowacc"
3. Build expression on Raster Calculator:
    a. Pow([flowacc] * resolution / 22.1, 0.6) * Pow(Sin([slope]) * 0.01745 / 0.09, 1.3))
    where "resolution" is 30 for 30m raster (for LCC)
    b. Click "evaluate", make calculation permanent and change name to "lsfac"
4. To get LS, use Zonal Statistics tool and tabulate by "musym" (soil type) or other zone type

Useful tutorial for *LS* and *K* calculation found online:
http://skagit.meas.ncsu.edu/~helena/gmslab/reports/CerlErosionTutorial/denix/Models%20and%20Processes/RUSLE3d/ArcView/ArcView_computing_rusle_using_gis.htm

Appendix B

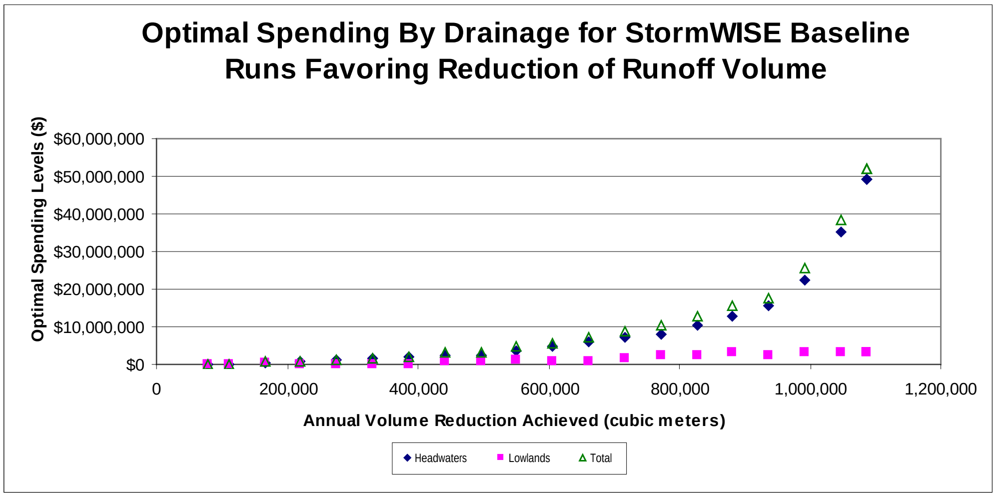
Class Modules and Brief Descriptions of Primary Functionalities

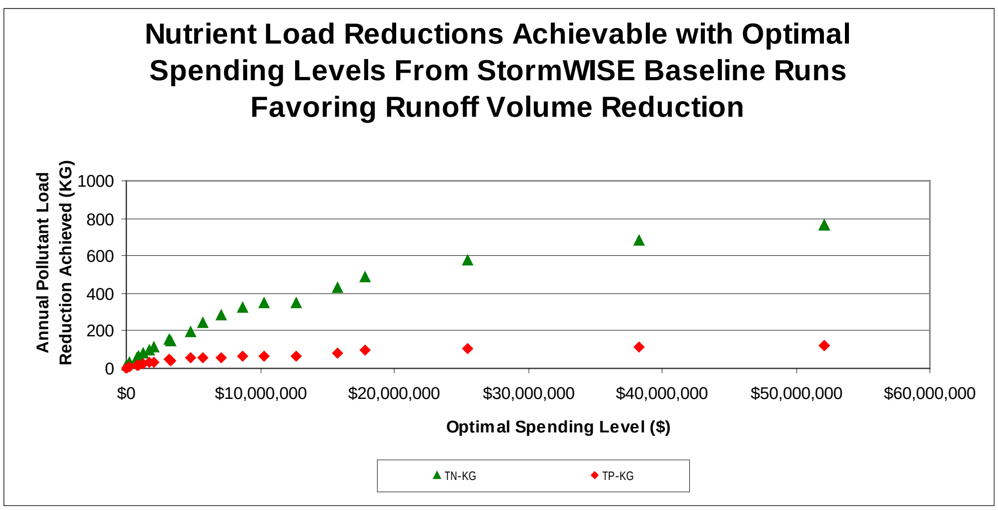
Table B 1. Primary Functionalities of VBA Modules in SSSN	
Class Modules	**Description**
Array1DClass	Contains an array of doubles and a setClass of names/descriptors
Array1DClassGeneral	Contains an array of variants and a setClass of names/descriptors
Array1DDrainageClass	Contains an array of drainageClass objects and a setClass of names; building block of watershed
Array1DLUClass	Contains an array of Land Use Classes and a setClass of descriptors
Array2DClass	Contains an array of Array1DClasses and a setClass of names/descriptions
Array2DClassGeneral	Contains an array of Array1DGeneralClasses and a setClass of names/descriptions
Array2DRUSLEClass	Contains an array of RusleFactorsClasses, lookup functions
BankErosionDataClass	Contains all functions and properties associated with Bank Erosion Calculations, data input retrieval, daily calculation arrays, etc. also properties of particulate nitrogen and phosphorous. Concentrations in soil for use in RUSLE
DayDatArrayClass	contains an array of DayDatClasses and descriptors, lookup functions
DayDatClass	Contains an array of daily data, the number of data, and functions to aggregate into a MonthDatClass
DrainageClass	Contains all functions and data organizing a drainage area; building

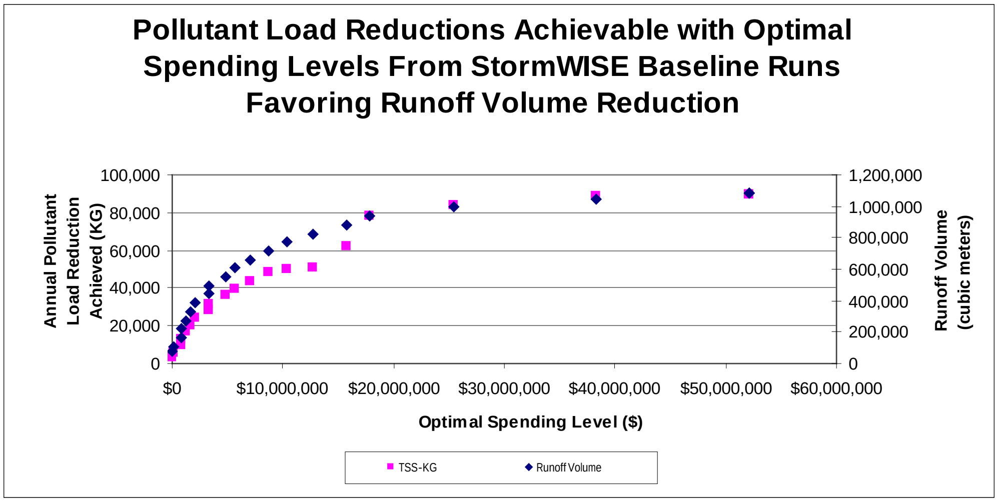
	blocks of a watershedClass, as well as runoff and washLoadClasses for each land use in the drainage
DrainageRunoffClass	Contains an array of the runoff calculations for each land use in the drainage; a property of the DrainageClass; Calculates Runoff Using SCSMethodClass contained within
DrainageWashLoadClass	Contains an array of build-up/wash-off calculations for each land use in the drainage and the functions to calculate the wash-off loads for each land use
MonthDatArrayClass	contains an array of monthDatClasses; lookup and aggregation functions
MonthDatClass	Contains an array of monthly data, lookup and aggregations functions, and conversion to yearDatClass by addition of monthly data
RunQualDataClass	Contains data acquisition functions for the watershed areas and build-up/wash-off calculations
RUSLEClass	Contains all data and functions related to calculation of RUSLE, including an array of RUSLEFactorsClasses, a daily RUSLERClass, and data input and output functions, aggregation on daily and monthly basis, etc.
RUSLEfactorsClass	Contains an array of RusleLandUseFactorsClasses and lookup functions (one per drainage)
RUSLELandUseFactorsClass	Contains one land use's RUSLE factors: area, C, P, average K, etc. One per land use per drainage zone
RUSLERClass	Contains functionality to calculate and store a daily rainfall erosivity factor based on precipitation data
WatershedClass	Contains all data and functions for RUSLE, Bank Erosion, and wash-off calculations, as well as aggregation between the processes on daily, monthly, yearly bases
WatershedEMCClass	Calculates an event mean concentration for each day of runoff (currently malfunctioning)
WatershedLoadingsClass	Creates and organizes data for output to StormWISE, including Wash-off and RUSLE
YearDatArrayClass	Contains an array of yearDatClasses
YearDatClass	Contains an array of yearly data and description, as well as an averaging function
Process Modules	
Main	Contains individual process modules to be run individually
BankErosion	Contains process module for Bank Erosion (also can be cut from StormWISE Input
RUSLE_Data_From_Watershed	Gets areas and land uses and sets up input sheet for RUSLE (run before StormWISE_Input to set up RUSLE for a different set of drainages)
RUSLE	Calculates only the RUSLE
StormWISE_Setup	Calculates and outputs all Data

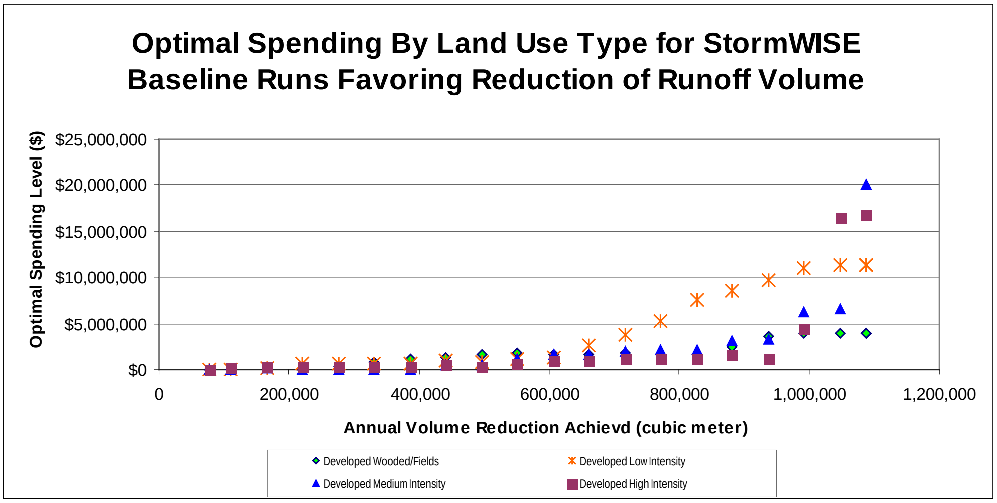
Appendix C
Updated StormWISE Results Presented to Little Crum Creek Stakeholders' Meeting
30 April 2009

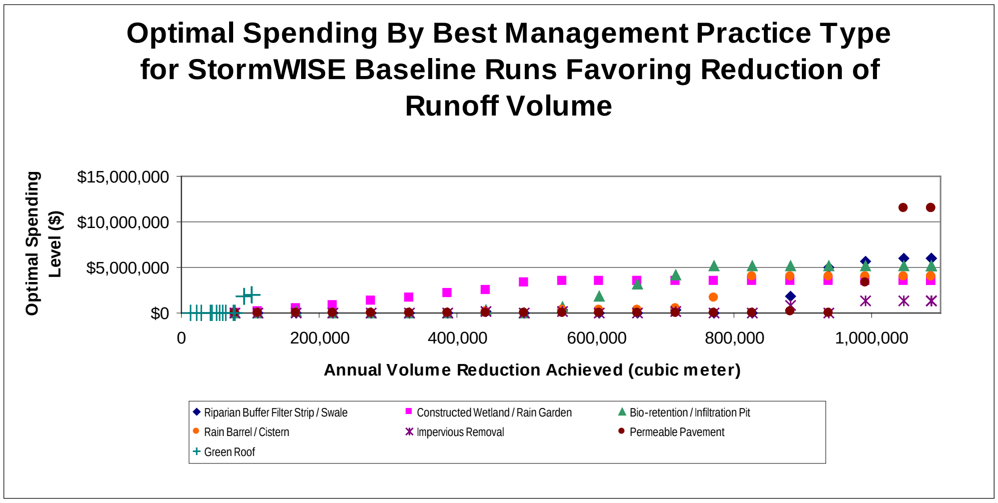
StormWISE Results Favoring Reduction of Runoff Volume



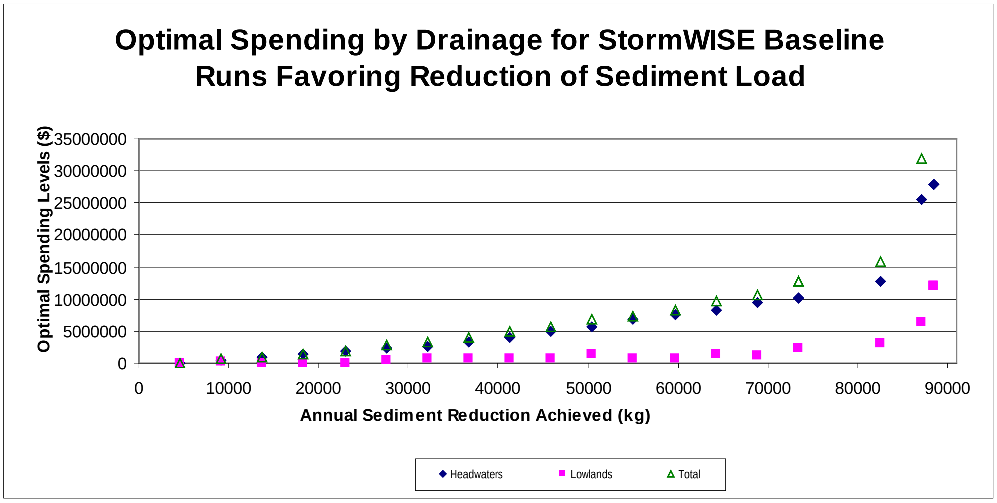


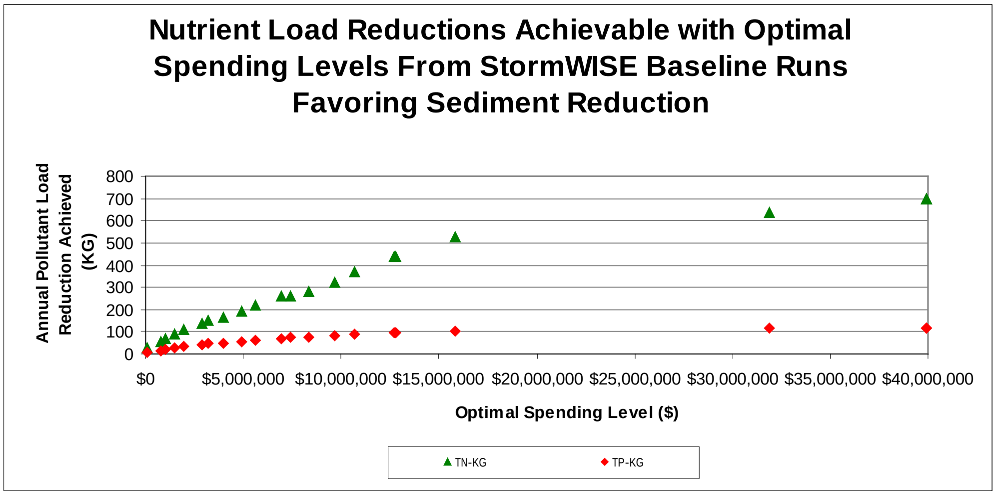

Pollutant Load Reductions Achievable with Optimal Spending Levels From StormWISE Baseline Runs Favoring Runoff Volume Reduction
Annual Pollutant Load Reduction Achieved (KG)
Runoff Volume (cubic meters)
Optimal Spending Level ($)
TSS-KG
Runoff Volume

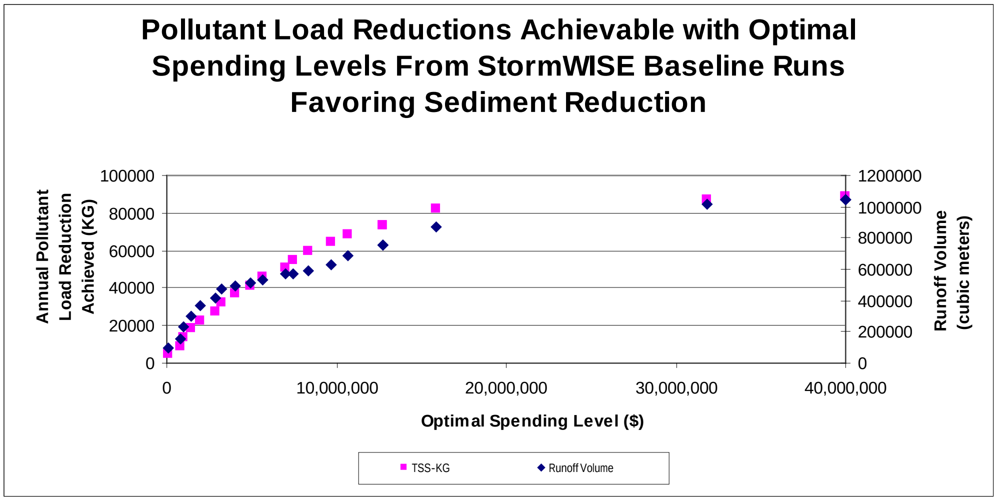

Optimal Spending By Land Use Type for StormWISE Baseline Runs Favoring Reduction of Runoff Volume
Optimal Spending Level ($)
Annual Volume Reduction Achievd (cubic meter)
Developed Wooded/Fields
Developed Low Intensity
Developed Medium Intensity
Developed High Intensity

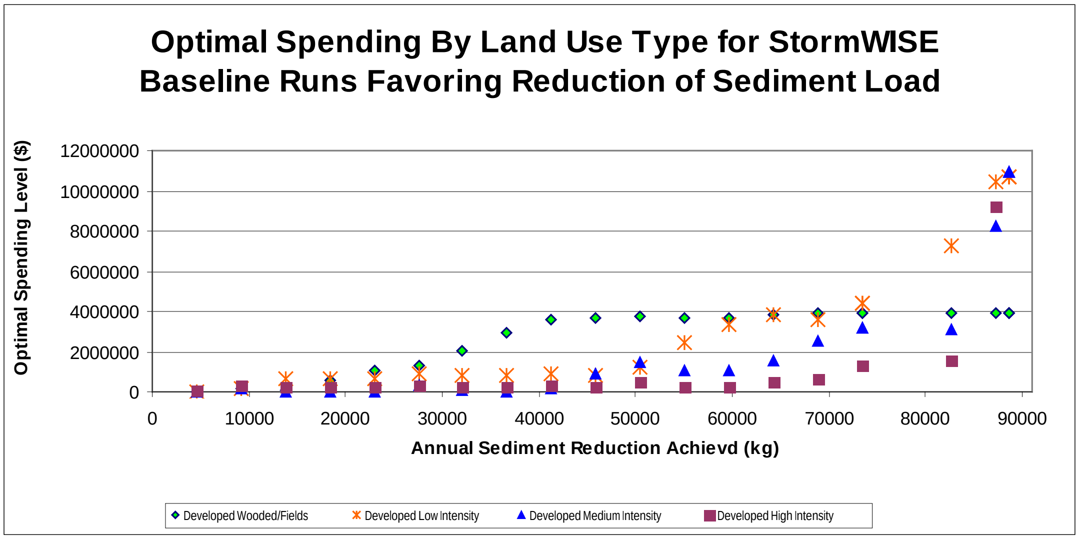

Optimal Spending By Best Management Practice Type for StormWISE Baseline Runs Favoring Reduction of Runoff Volume
Optimal Spending Level ($)
Annual Volume Reduction Achieved (cubic meter)
Riparian Buffer Filter Strip / Swale
Constructed Wetland / Rain Garden
Bio-retention / Infiltration Pit
Rain Barrel / Cistern
Impervious Removal
Permeable Pavement
Green Roof

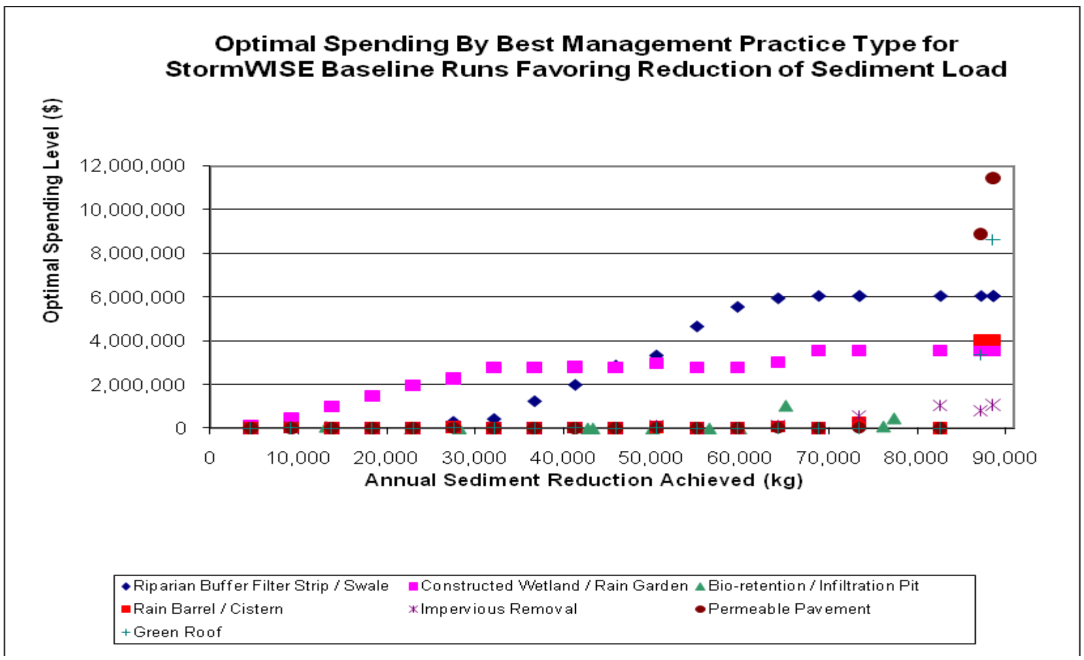
StormWISE Results Favoring Reduction of Sediment








Optimal Spending By Land Use Type for StormWISE Baseline Runs Favoring Reduction of Sediment Load
Optimal Spending Level ($)
12000000
10000000
8000000
6000000
4000000
2000000
0
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Annual Sediment Reduction Achievd (kg)
Developed Wooded/Fields
Developed Low Intensity
Developed Medium Intensity
Developed High Intensity


Optimal Spending By Best Management Practice Type for StormWISE Baseline Runs Favoring Reduction of Sediment Load
Optimal Spending Level ($)
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
Annual Sediment Reduction Achieved (kg)
Riparian Buffer Filter Strip / Swale
Constructed Wetland / Rain Garden
Bio-retention / Infiltration Pit
Rain Barrel / Cistern
Impervious Removal
Permeable Pavement
Green Roof