Implementation and Verification of a Pollutant Loading Model for the Little Crum Creek Watershed

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E90 Project Proposal

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Abstract

Pollutant loading models for the constructed wetlands site in Crum woods, as well as the entire Little Crum Creek watershed will be developed using AVGWLF software. Additionally, the accuracy of the wetlands model (and, time permitting, the Little Crum Creek model) will be tested by taking flow and pollutant loading data at the site. Once completed, the results of the Little Crum Creek watershed model will be run through StormWISE in order to determine the most cost-effective locations for pollutant removal. The academic goal is to use knowledge of environmental modeling, GIS software, and watershed management to produce information that may be useful to local organizations interested in cost-effective pollutant reduction.

Introduction

This project will take place in three segments, with possible extension to a fourth if time permits. First, a hydrologic model using the program AVGWLF will be developed for the area drained by the C40 stream at the constructed wetlands location in Crum Woods. Then, flow and pollutant loading data will be taken at the C40 site in order to test the accuracy of the AVGWLF model. Currently, the final segment of the project involves expanding the model at C40 to cover the entire Little Crum Creek watershed, and using the AVGWLF output from this model in Professor McGarity's StormWISE program. If there is time, flow and pollutant loading data will be taken at a location within the Little Crum Creek watershed in order to evaluate the accuracy of the AVGWLF and StormWISE results. The short-term benefits of the project are clear—in addition to providing the college with information regarding the pollutant loading present at the wetlands site, the analysis of the Little Crum Creek watershed will identify the primary stormwater management problems in the area. This information could potentially be used by local groups, such as the Chester-Ridley-Crum Watersheds Association, that are interested in cost-effective pollutant reduction. Project costs are expected to be minimal, as much, if not all, of the equipment and software required for the completion of this project is already property of the department; the primary resource needed will be time.

This introduction is followed by three sections:

1. A technical discussion, which includes background information on the constructed wetlands site, an overview of nonpoint source pollution and

the practices used to combat it, and a detailed description of the models and software that will be used.

2. The project plan, in which the steps of the project are laid out in explicit detail.
3. The next section, project qualifications, outlines why I am capable of completing this project.
4. A complete list of project activities, and the corresponding CPM diagram and Gantt chart.
5. An appendix, which includes results from a directed reading done this semester with Professor McGarity.

Technical Discussion

In recent years, nonpoint source pollution control has risen to the forefront of water quality improvement in the United States. Put simply, nonpoint source pollution describes all diffuse activities or processes which introduce contaminants (both natural and resulting from human activity) into water bodies, causing a decrease in water quality. It is differentiated from point source pollution in that there is no specific location (such as a pipe) from which the contaminants originate. Often, agricultural and urban environments are considerable sources of nonpoint source pollution due to erosion and impervious surface runoff, respectively.

The three pollutants that are most commonly associated with nonpoint source pollution are nitrogen, phosphorus and total suspended solids (or sediment). Nitrogen and phosphorus occur naturally in the environment, but only in small quantities. In fact, the scarcity of these nutrients is often a limiting factor in plant growth in many ecosystems. Increased nitrogen and phosphorus concentration is largely affected by both urban and agricultural land use; specifically, the use of manure to fertilize cropland has been shown to significantly increase nitrogen concentrations in nearby streams. Urbanization, which is typically accompanied by an increase in impervious surfaces, can result in a considerable rise in phosphorus load exported via stormwater runoff. Excessive nutrient loading due to these factors can remove the limits on plant growth, causing eutrophication, which in turn may result in undue amounts of plant decay and the anoxic conditions that are a product of this decay. Erosion due to storm flow is also a major contributor to sediment pollution.

Since the area of study for this project is located within a largely urban environment, the remainder of this discussion will focus primarily on measuring and treating nonpoint source pollution from urban areas. The United States Environmental Protection Agency (EPA) has classified seven categories of best management practices (BMPs) for controlling nonpoint source pollution from urban areas. These are outlined in Chapter 5 of a 2005 document released by the EPA titled *National Management Measures to Control Nonpoint Source Pollution from Urban Areas*, and are summarized here:

1. Infiltration practices, which capture runoff and store it for several days before allowing it to infiltrate into the soil;
2. Vegetated open channel practices, in which runoff is captured and treated through infiltration, filtration or temporary storage;
3. Filtering practices, which capture runoff and filter it through a bed of sand, organic material, soil, or other media;
4. Detention ponds or vaults, in which runoff is temporarily detained in order to ensure a constant discharge flow rate;
5. Retention ponds, which use a permanent pool, extended detention basin, or shallow marsh to remove pollutants;
6. Constructed wetlands, which are designed to maintain a somewhat natural habitat while at the same time reducing pollution; and
7. Other practices, which consist of designs that have not been extensively tested.

The choice of which type of BMP to use in a particular location is a complicated one, and must take into account pollutant removal efficiency, cost of implementation, and future cost of maintenance, among other factors. As there has been no conclusive evaluation of the nutrient removal efficiency of the constructed wetlands site in the Crum, I would like to continue research in this area as a part of my project. Previous attempts to do this have been hampered by either the recent construction of the wetland or time constraints; I hope to start taking measurements early in the semester so that I will be able to accumulate a large bank of data from which to determine this efficiency. A larger sample size will also increase the accuracy of the data, which will make for better comparison with the model outputs.

Two separate pollutant loading models will be implemented as a part of this project. The first is a rather basic export coefficient model. Export coefficients measure the nutrient mass load per unit area per unit time—for example, kg of pollutant/ha/yr. These unit loads are heavily dependant on land use. Ideally, if export coefficients are to be used in a study, actual values should be derived for the individual lakes and watersheds; however, this often requires a great deal of time, expense and effort that is not generally available to those performing the study. Instead, values from the literature are used to reasonably approximate the loading values by land use. Beaulac and Reckhow (1982) performed a comprehensive literature review of these loading estimates and found them to be sufficiently accurate, provided that they are carefully applied. For this project, since time is the most significant constraint, values from the literature will be used whenever an export coefficient model is used.

The other model that will play a large role in this project is the Generalized Watershed Loading Function[1] (GWLF) model; specifically, a version that has been integrated with ArcView GIS software and is known as AVGWLF. The GWLF model uses land-use data, nutrient loading parameters and local weather data as inputs, and from this simulates runoff, sediment and nutrient (nitrogen and phosphorus) loadings for a watershed. It is a combined distributed/lumped parameter model in that for surface areas, it allows multiple land-use scenarios, but each area is assumed to be homogeneous in terms of its attributes. Loads from each area are aggregated into a watershed total, ignoring any spatial routing possibilities. In 2002, a method for deriving the required input data using GIS software was developed by researchers at Penn State University. Statewide GIS data sets are loaded, and the user is prompted to give any other relevant information about the area in question, such as growing season dates, manure application dates, and start and finish points for the weather data simulation. These responses, along with the selected study watershed boundary, are used to estimate values for the GWLF model parameters. GWLF is then run, either from within ArcView itself, or as a separate entity. AVGWLF has been described by the US EPA as a good "mid-level" model; additionally, the default parameters within the model were determined using data from watersheds throughout Pennsylvania. This makes the model an attractive choice, as it is likely that these parameters will be representative of the study area. Furthermore, AVGWLF output is suitable for use by StormWISE, a screening model that will be used as well in the project.

In addition to the two pollutant loading models, StormWISE, an optimization screening model that prioritizes second-order stream watersheds based on cost-effectiveness

[1] All AVGWLF description adapted from Evans et al. (2002)

of nonpoint source pollution reduction. StormWISE was developed in 2005 by Professor McGarity along with members of the Springfield Township Environmental Advisory Commission. Essential in the formulation of the model is a BMP management – cost tradeoff equation that is similar in form to the Langmuir surface saturation equation. The particular relationship used by StormWISE is found below:

$$f = \frac{X}{H + X}$$

where: f = fraction of land treated by BMPs
X = resources devoted to BMPs ($1000), and
H = resources required to treat one-half of the land area ($1000).

This equation is the centerpiece of the optimization model, which also incorporates information regarding pollutant loading, runoff, land use and nonpoint pollutant reduction. Much of this data can be obtained from AVGWLF output (or that of a similar model). Final StormWISE output includes the amount in tons of pollutant reduction (for nitrogen, phosphorus and total suspended solids), the cost of this reduction, and the subwatershed within which this reduction will take place.

Project Plan

<u>Phase One</u>

Objective:

Implement a pollutant loading model of the area drained by C40.

Approach:

This will first involve procuring Digital Elevation Map (DEM) data for the Lansdowne quadrant from USGS (or other reputable source), and clipping it so that it only covers the municipality of Swarthmore. Then, the TauDEM extension of MapWindow will be used to delineate the drainage area from the DEM. Land use area data will be approximated from recent aerial photography, and input into AVGWLF along with the delineated drainage area. Additionally, export coefficients will be determined based on existing data from the literature, and used to calculate yearly loads based on the following equation:

$$L = \left(\sum_{i=1}^{n} \sum_{j=1}^{m} A_{ki} \cdot E_{ki} \right) + a$$

where

L = nutrient loss (kg/yr)

A = area of a discrete land use (ha)

E = export coefficient for a specific land use class (kg/ha/yr)

m = number of discrete land use patches

n = number of land use classes

a = artificial inputs (e.g. sewage, industrial, etc.) (kg/year)

Once these two tasks have been completed, their output will be compared.

Ouput:

Simulated pollutant loading data from two separate models (AVGWLF and export coefficient) for total nitrogen, total phosphorus and total suspended solids at the constructed wetlands site. These two methods will then be compared; however, individual accuracy cannot be determined until the completion of phase two.

<u>Phase Two</u>

Objective:

Collect flow and pollutant loading measurements at the constructed wetlands site in order to evaluate the accuracy of the AVGWLF and export coefficient models. A further objective will be to measure the nutrient removal efficiency of the wetland.

Approach:

As I was abroad during the semester when Engineering 063: Water Quality and Pollution Control was offered, I was unable to gain the background in the physical measurement of water quality that comes as a part of the course. Thus, the first step of this process will be to become acquainted with conventional sampling techniques, proper quality assurance/quality control procedure, and the instruments in the Hicks Environmental Lab. If possible, I will begin this research over winter break so as to lessen the need for learning during the spring semester; however, I anticipate that I will need a brief, hands-on tutorial in the Environmental Lab itself before beginning any serious work.

Once the learning process has been completed, actual data measurement will begin. Since this does not depend on the completion of Phase One, it may be started at any point in the semester at which the weather conditions combined with my comfort using the instruments deem it feasible. The first step will be determining a suitable location for the placement of the autosampler (property of the Engineering Department) and to install it at that location. Once this has been done, it will be necessary to calibrate the autosampler at the site. In his E90 Project Report, Colton Bangs '07 indicated that this was necessary but that he did not have the time to perform such a task. Since accuracy in data is paramount, I will attempt to calibrate the instrument before seriously employing it. After calibration has been completed, data will be collected for an as yet undetermined amount of time (this will be in the final draft), with the hope of catching at least one storm event so that the wetland's performance under stress can also be gauged.

After enough data has been collected, the pollutant loading data will be extrapolated to a year's time period and compared with the output from the AVGWLF and export coefficient models. The accuracy of each method will be analyzed, and if the results are satisfactory, steps will continue toward implementing the model for the Little Crum Creek watershed. Nutrient removal efficiency for the site will be calculated and compared to values obtained by Colton Bangs '07 and Marc Jeuland '01.

Output:

Actual pollutant loading data for the wetlands site, as well as nutrient efficiency removal values. Additionally, the former will be compared to the simulation models from Phase One, and the latter to previously obtained efficiency values. The accuracy of the AVGWLF model will determine whether the model is again used for the Little Crum Creek watershed.

<u>Phase Three</u>

Objective:

Implement a pollutant loading model for the Little Crum Creek watershed. Determine the sub-basins within this watershed that provide the most cost-effective means of pollutant removal.

Approach:

In general, Phase Three will follow many of the same steps as Phase One. The same methods will be used to create a GIS representation of the area. Boundaries of the Little Crum Creek watershed exist in data files that come bundled with the AVGWLF program; however, it is likely that they are not detailed enough to provide comprehensive analysis of the area. A similar problem was encountered in the study of Springfield Township conducted by Professor McGarity during the development of StormWISE. Thus, additional delineation is necessary. Land use information for the area will be verified by site visits as wells as through the use of aerial or satellite photography.

The main difference, however, between Phase Three and Phase One, however, will be the use of StormWISE to prioritize sub-watersheds for cost-effective nonpoint pollution removal BMPs. The analysis using StormWISE will mirror that for Springfield Township as presented by Professor McGarity in his 2005 paper "Decision Making for Implementation of Nonpoint Pollution Measures in the Urban Coastal Zone." This will involve determining a relationship between total cost and total pollution reduction, examining how types of land use affect the cost-pollutant relationship, calculating how the composition of total sediment removal changes as the total sediment reduction requirements are changed, and finally, examining how prioritization changes as total resources allocated is increased. These results then could possibly be presented or delivered to a local organization interested in cost-effective pollutant removal in the Little Crum Creek watershed.

Output:

Simulated pollutant loading data from the AVGWLF model for the Little Crum Creek watershed. Additionally, information regarding the prioritization of subwatersheds for BMP implementation projects will be determined.

Phase Four (TIME PERMITTING)

If time remains once Phase Three has been completed, the equivalent of Phase Two will be performed for the Little Crum Creek watershed. The autosampler will be deployed at some location within the watershed, and data will be collected for the purpose of verifying the AVGWLF output. The location could potentially be selected based on the StormWISE output in order to evaluate the feasibility of BMP implementation. Obviously, there will be less time available for a study of this magnitude, and so any potential results from this segment of the project will likely be less conclusive than the results from Phase Two.

Project Qualifications

As a senior in the Swarthmore College engineering program, I am qualified to conduct the research and development necessary for the completion of a project of this scope. Past classes, including Engineering 066: Environmental Systems, an operations research/mathematical modeling class taken while abroad and a directed reading in environmental modeling, as well as a 2007 summer internship with Christopher B. Burke Engineering, Ltd., an environmental engineering firm located in Indianapolis, IN, have instilled in me sufficient knowledge of modeling techniques. Specifically, my familiarity with GIS software, having used ArcMap extensively this summer, combined with my recent participation in an introductory GIS class at Delaware Valley Community College will prove beneficial. As for AVGWLF, the other program that will play a large role in the project, the directed reading in which I am participating this semester has provided me with a valuable introduction to the workings of the software.

Resource requirements:

- Computer programs: AVGWLF, ArcView 3.2, ArcMap, MapWindow, TauDEM, StormWISE. All of these are installed on at least one computer in the solar lab.
- Data monitoring equipment: Sonde autosampler, HACH DR-890 (N, P concentrations), scale, oven (for TSS) – all available now in the Hicks Environmental Lab
- Time, of course – primarily my own, but I anticipate requiring some assistance from Professor McGarity because of my limited experience with actual physical measurement of water quality data

One potential concern is my limited experience with the actual physical measurement of water quality data (I was unable to take the Water Quality and Pollution Control class offered in the fall of 2006 because I was abroad), but I am confident that during the remainder of this semester, over winter break, and if necessary, the beginning of next semester, I will become well-versed in the appropriate methods.

Project Costs

I do not anticipate the project costs to be particularly high given that much of the software is either already installed on at least one computer in the solar lab or available for free on the internet. Additionally, all of the data monitoring equipment necessary for the second phase of the project is already owned by the department.

Project Activities and CPM

A list of applicable project activities is presented in Table 1.

Activity	Needs	Feeds	Duration	Effort	Action
A	-	C	1w	15h	Research water quality models
B	A	C,D	1w	15h	Construct GIS representation of C40 drainage area/Swarthmore College
C	B	E	2d	4h	Determine export coefficients to use and do appropriate calculations
D	B	E	1d	3h	Run AVGWLF on drainage area
E	C,D	J,Q	1w	15h	Analyze, interpret, and compare AVGWLF and export coefficient results, and document these findings appropriately
F	-	G	1w	15h	Familiarize myself with proper sampling techniques
G	F	H	1d	4h	Determine best location for autosampler and install
H	G	I	4d	8h	Calibrate autosampler at C40 site
I	H	J	As long as possible		Measure flow data; catch at least one rain event
J	E,I	Q	5d	10h	Evaluate accuracy of pollutant loading models (exports/AVGWLF)
K	I	Q	6d	12h	Analyze nutrient removal efficiency at site (BMP effectiveness)
L	J	N	1w	15h	Construct GIS representation of Little Crum Creek watershed
M	L	N	2d	6h	Verify land use in LCC watershed (through actual site visits)
N	L	O	1d	3h	Run AVGWLF on LCC watershed
O	M,N	P	2d	5h	Adjust StormWISE input and run on LCC watershed
P	O	Q	1w	20h	Analyze/interpret AVGWLF and StormWISE results
Q	K,P	-	1w	25h	Write final project report

Table 1: Project Activities

A Gantt chart for the project is presented in Figure 1. Note that since the amount of data collection at the wetlands site has not yet been determined, the end point is underestimated. It is likely, given the assumption that a large amount of data will need to be taken, that this point will be on the critical path. Additionally, a start date of two weeks into the semester is assumed for task F; however, this date may fluctuate.

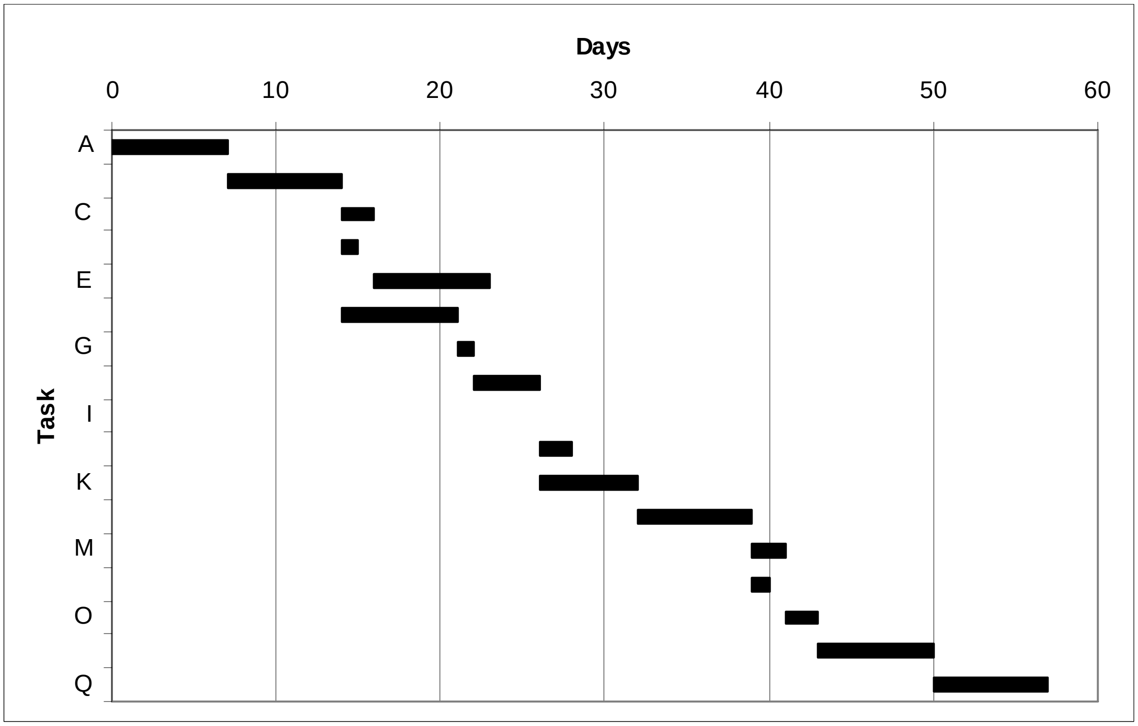

Figure 1: Gantt chart for project. Note: total time is underestimated due to uncertainty regarding the total length of time needed to record data at the wetlands site

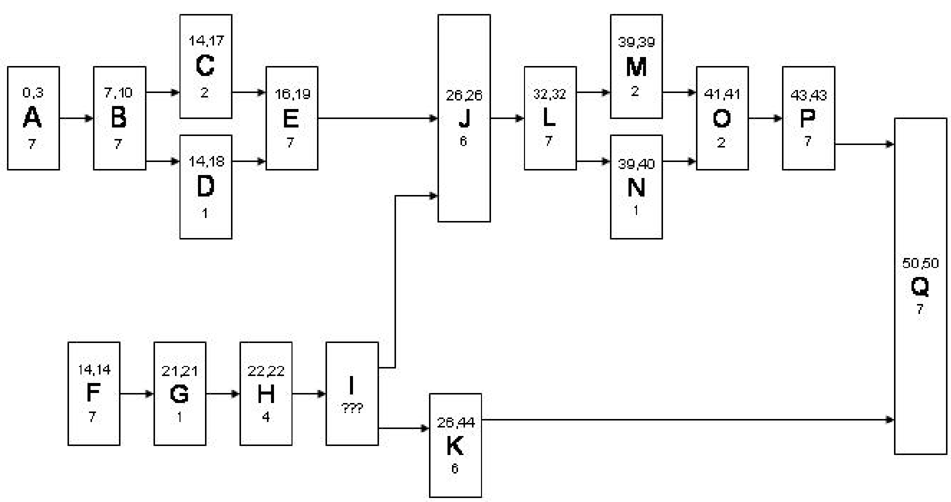

Figure 2: CPM analysis for project. Note that since the total time needed to take data is at this point unknown, a complete analysis cannot be performed.

References

Beaulac, Michael and Kenneth Reckhow, 1982. "An Examination of Land Use—Nutrient Relationships." *Water Resources Bulletin* 18(6): 1013-1024.

Evans, Barry, et. al., 2002. "A Comprehensive GIS-Based Modeling Approach for Predicting Nutrient Loads in Watersheds." *Journal of Spatial Hydrology* 2(2).

Limbrunner, James, 2007. "Watershed Models for Nonpoint Source Pollution Management Decision Support." Tufts University.

McGarity, Arthur and Paul Horna, 2005. "Decision Making for Implementation of Nonpoint Pollution Measures in the Urban Coastal Zone." Pennsylvania Department of Environmental Protection.

United States Environmental Protection Agency, 2005. "National Management Measures to Control Nonpoint Source Pollution from Urban Areas." <http://www.epa.gov/nps/urbanmm/> Accessed 13 November 2007.

Appendix A: Preliminary Results of AVGWLF Analysis of the Wetlands Area

The area drained by the C40 wetlands site was delineated using the Automatic Watershed Delineation feature of the open-source GIS program MapWindow. A shapefile representing the streams and storm sewers in the nearby area (this was approximated from a similar shapefile constructed by Colton Bangs '07 as a part of his E90 project last spring) was used to do this, as well as an outlet point that roughly indicated the location of the wetlands site. A 10x10 m DEM of the Lansdowne quadrangle was acquired from the United States Geographical Survey and clipped to include the Swarthmore College area. The drainage area that resulted from this analysis is shown in Figure 3, along with the stream shapefile and outlet point used in the delineation process.

Figure 3: Swarthmore College area. The stream layer is represented by the blue line, the drainage area by the red outline, and the outlet point is marked with a star

This watershed and shapefile then were used to run AVGWLF on the area. All the parameters were left at their default values except for the following:

- Weather data: 1981 – 1991
- Growing season: April – September
- Manure months: February, April, September, November

The Tile Drain, Water Extraction and Animal Feeding Layers were not included in the analysis, as this data does not exist for the area. Once the analysis was complete, AVGWLF was used to plot relevant stream flow (Average monthly precipitation, evapotranspiration, runoff, and stream flow – Figures 4-7) and pollutant loading (Average monthly erosion, sediment yield, total nitrogen, and total phosphorus – Figures 8-11) data.

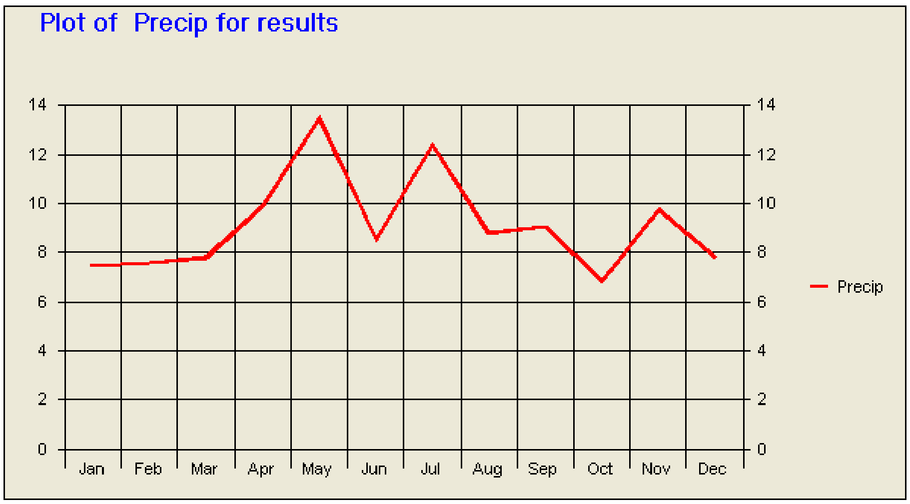

Figure 4: Average monthly precipitation (cm)

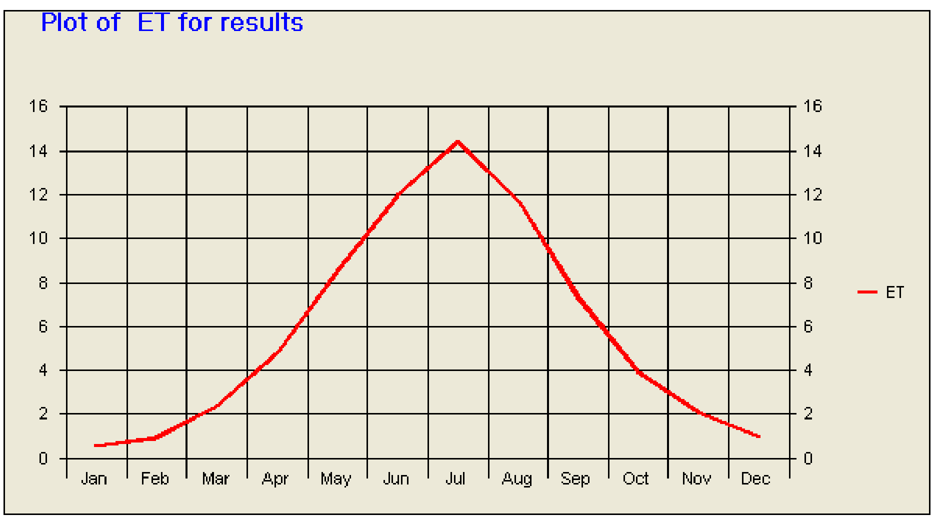

Figure 5: Average monthly evapotranspiration (cm)

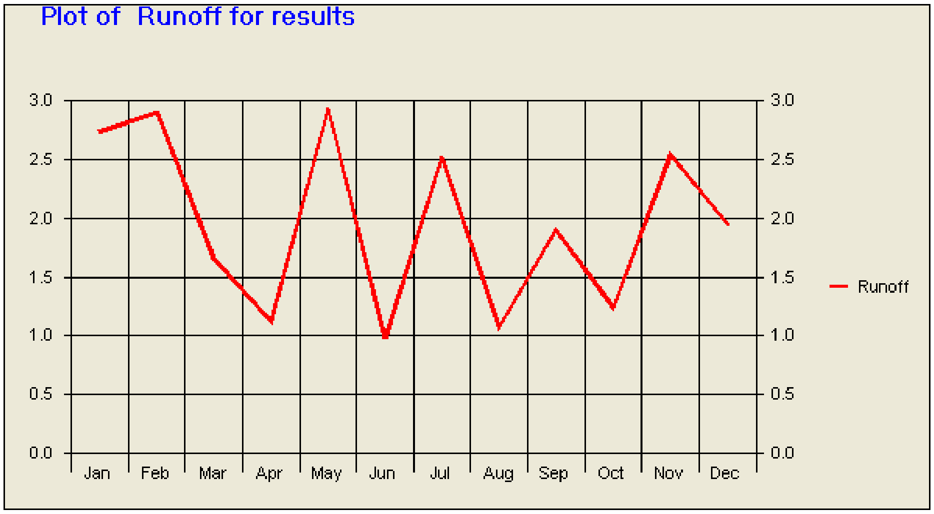

Figure 6: Average monthly runoff (cm)

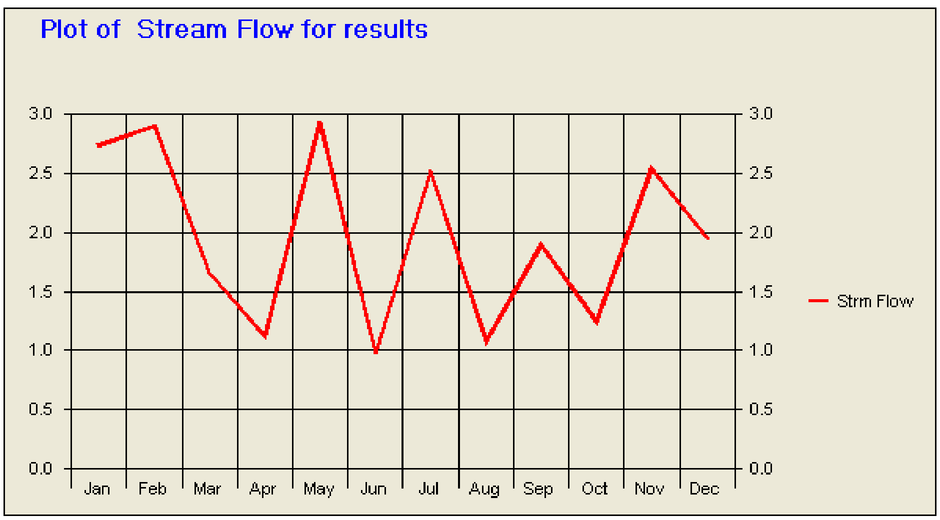

Figure 7: Average monthly stream flow (cm)

These results are fairly limited for two reasons: (1) the area of study is quite small, and (2) the tile drain and water extraction layers do not exist (the absence of the animal feeding layer is not a serious concern because there is no agricultural land in the drainage area). Since the area of study is so small, minimal variation in precipitation can cause wide fluctuations in stream flow, as in seen in Figure 6. For example, the increased precipitation in May causes the stream flow to reach its peak during the month; however, a relatively small decrease in total precipitation in June combined with an increase in evapotranspiration (as is to be expected in the summer months) results in a severe drop in stream flow between May and June. It seems likely that a larger surface area, with more diverse land uses, and inclusion of the other data layers that AVGWLF can take into consideration would result in more consistent stream flow. It is possible, though, that such erratic stream flow is a property of C40.

AVGWLF also plots pollutant loading data for the area of study. This is the information that will be tested for accuracy by taking actual measurements at the site.

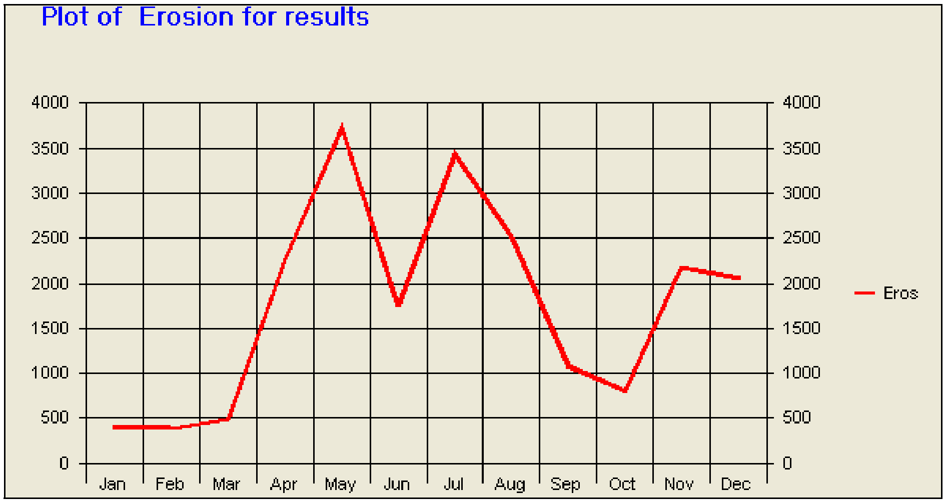

Figure 8: Average monthly erosion (1000 kg)

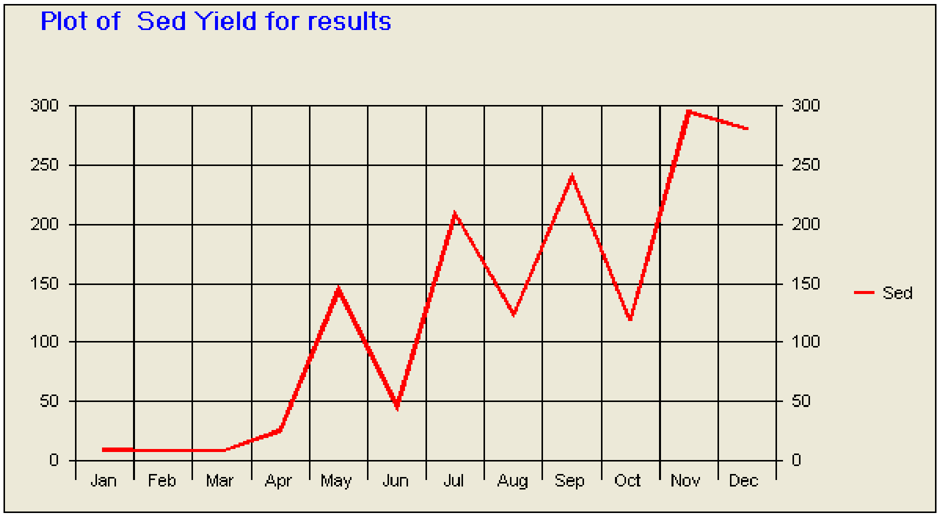

Figure 9: Average monthly sediment yield (1000 kg)

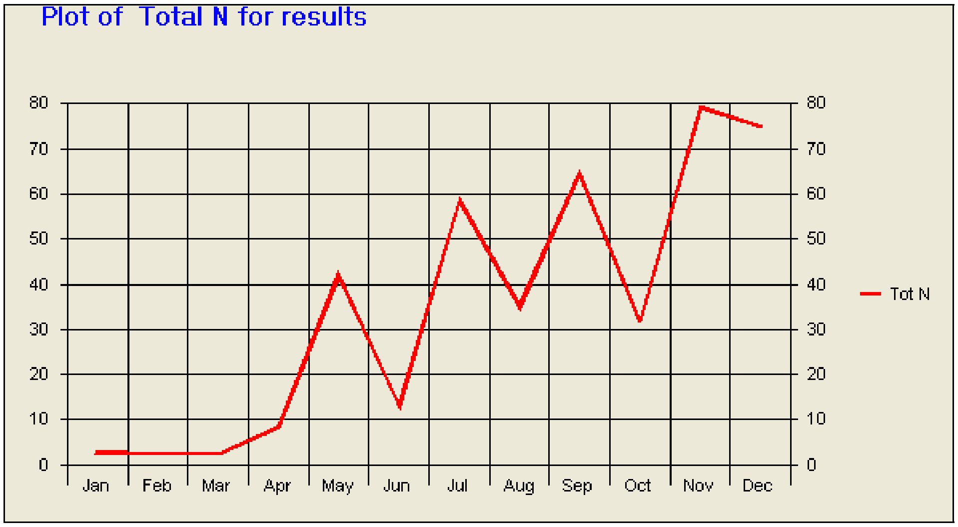

Figure 10: Average monthly total nitrogen (kg)

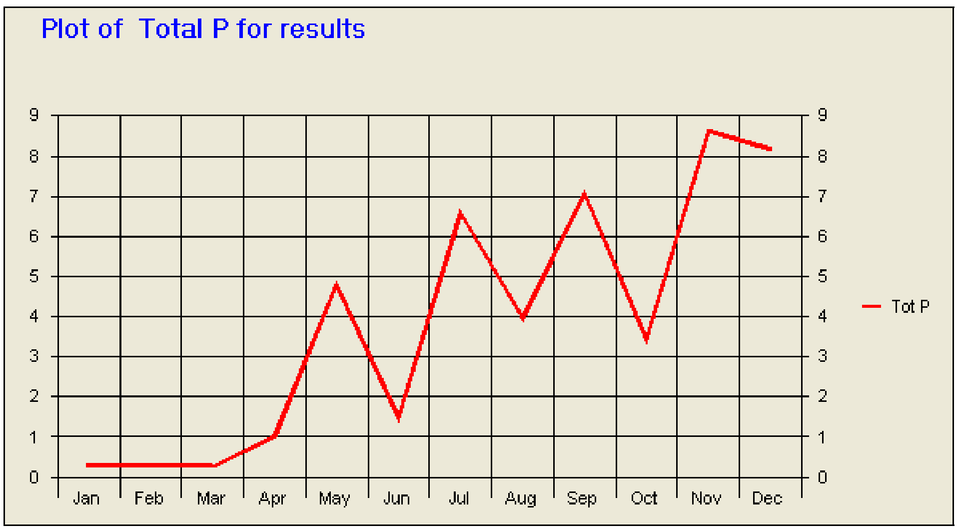

Figure 11: Average monthly total phosphorus (kg)

One interesting result of this run is that the average monthly total sediment yield, total nitrogen and total phosphorus all follow a nearly identical pattern. This is likely due to the assumption made by AVGWLF that all of the land use in the area under examination is made up of high-development urban. The wide fluctuations in average monthly pollution can be attributed, as with the variations in the stream flow data, to the small size of the drainage area.