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A COMPREHENSIVE GIS-BASED MODELING APPROACH FOR PREDICTING NUTRIENT LOADS IN WATERSHEDS

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ABSTRACT: A comprehensive, GIS-based modeling approach was developed to enable accurate prediction of nutrient loads in watersheds throughout the state of Pennsylvania; particularly those watersheds for which stream monitoring data do not exist. This approach relies on the use of statewide GIS data sets for deriving reasonably good estimates for various critical model parameters that exhibit considerable spatial variability within the state. Data manipulation and subsequent simulation modeling is managed via an interface (called AVGWLF) between a popular desktop GIS software package (ArcView) and the Generalized Watershed Loading Function (GWLF) model. The modeling approach was tested in thirty-two (32) watersheds throughout Pennsylvania, and a statistical evaluation of the accuracy of the load predictions was made. Nash-Sutcliffe coefficients of correlation derived for the calibration and verification watersheds ranged in value from 0.92 to 0.97 for both nitrogen and phosphorus when considering mean annual loads. The median N-S values for nitrogen varied between 0.64 to 0.70 for monthly, seasonal, and year-to-year load estimates; and for phosphorus they varied between 0.61 and 0.72.

KEY WORDS: GIS, watershed modeling, TMDL, nutrients, nonpoint source pollution

INTRODUCTION

The recognition of the importance of non-point sources of pollution in the U.S. has led to increased efforts over the last two decades to identify and quantify non-point source pollutant loads, especially at the watershed level. Typical techniques for determining the extent and magnitude of non-point source pollution problems include long-term surface water monitoring and computer-based simulation modeling. Due to the time and expense associated with surface water monitoring, however, simulation modeling has been relied upon more frequently to provide needed information for the development and implementation of non-point source control programs (Novotny and Olem, 1994; Deliman et al. 1999). Watershed simulation models, in fact, are commonly considered to be essential tools for evaluating the sources and controls of sediment and nutrient loading to surface waters. Such models provide a framework for integrating the data that describe the processes and land-surface characteristics that determine pollutant loads transported to nearby water bodies.

The utilization of watershed models, however, is a difficult, tedious task because of the broad spatial and temporal scales that must be considered, as well as the large amount of data that must be compiled, integrated, analyzed, and interpreted. Fortunately, the last two decades of model development have coincided with rapid advancements in the development and use of geographic information system (GIS) technology. This technology provides the means for compiling, organizing, manipulating, analyzing, and presenting spatially-referenced model input and output data. Due to the many inherent benefits, GIS software has been used to support literally hundreds of watershed modeling efforts over the last 10-15 years. Many state, regional, and federal environmental agencies, in fact, use this technology routinely to support ongoing watershed modeling and assessment programs (Samuels, 1998).

As suggested above, simulation models are being applied more frequently to “real-world” pollution problems, and given the U.S. Environmental Protection Agency’s new watershed-based emphasis, this trend is likely to continue. Similarly, given the rapid development of GIS databases throughout the country, it is also likely that GIS-based watershed modeling will become a standard analytical approach in the foreseeable future. Consequently, it will become imperative that appropriate GIS data sets which accurately reflect the spatial variability of critical model parameters be used to derive input data for such modeling efforts. This will be especially important as total maximum daily load (TMDL) assessments are performed for watersheds as required by the 1972 Clean Water Act (see Paulson and Dilks, 1996). Among other things, it is this need for “region-specific” parameterization, with emphasis on model inputs for Pennsylvania that has been addressed in the work described herein.

Over the last 5-10 years, the Pennsylvania Department of Environmental Protection (DEP) has recognized the indispensability of GIS technology, and has endeavored to integrate it into all of the agency’s internal program areas. Towards this end, Penn State has been assisting DEP in the development and implementation of various GIS-based watershed assessment tools. One such tool facilitates the use of the GWLF model via a GIS software (ArcView) interface. This tool (called AVGWLF) has recently been selected by DEP to help support its ongoing TMDL projects within Pennsylvania. The general approach in such projects is to: 1) derive input data for GWLF for use in an “impaired” watershed, 2) simulate nutrient and sediment loads within the impaired watershed, 3) compare simulated loads within the impaired watershed against loads simulated for a nearby “reference” watershed that exhibits similar landscape, development and agricultural patterns, but which also has been deemed to be unimpaired, and 4) identify and evaluate pollution mitigation strategies that could be applied in the impaired watershed to achieve pollutant loads similar to those calculated for the reference watershed. The primary bases of comparison between impaired and reference watersheds are the average annual nutrient and sediment loads estimated for each.

The primary focus of the project described herein was to develop a comprehensive modeling approach based on this GWLF/ArcView interface that enables accurate prediction of nutrient and sediment loads in watersheds throughout the state of Pennsylvania; particularly those watersheds for which historical stream monitoring data do not exist. This methodology relies on the use of statewide data sets for deriving reasonably good estimates for various critical model parameters that exhibit significant spatial variability within the state. Subsequent to developing the GIS-based modeling approach, an evaluation of its accuracy in predicting mean annual nutrient loads was conducted using data from thirty-two (32) watersheds distributed throughout the state. Although sediment loads are important with respect to DEP’s TMDL assessment activity as described above, they are not addressed in this particular paper.

THE GWLF MODEL

The core watershed simulation model for this GIS-based application is the GWLF (Generalized Watershed Loading Function) model developed by Haith and Shoemaker (1987). This particular model was chosen over others primarily because of its ease of use and reliance on data input that is generally less exotic and easier to compile than other watershed-oriented water quality models such as SWAT, SWMM and HSPF (Deliman et al., 1999). The model has also been endorsed by the U.S. EPA as a good “mid-level” model that contains algorithms for simulating most of the key mechanisms controlling nutrient fluxes within a watershed (U.S. EPA, 1999). For the purposes of this particular application, the original DOS version of the model was re-written in Visual Basic to facilitate integration with ArcView.

The GWLF model provides the ability to simulate runoff, sediment, and nutrient (N and P) loadings from a watershed given variable-size source areas (e.g., agricultural, forested, and developed land). It also has algorithms for calculating septic system loads, and allows for the inclusion of point source discharge data. It is a continuous simulation model which uses daily time steps for weather data and water balance calculations. Monthly calculations are made for sediment and nutrient loads, based on the daily water balance accumulated to monthly values.

GWLF is considered to be a combined distributed/lumped parameter watershed model. For surface loading, it is distributed in the sense that it allows multiple land use/cover scenarios, but each area is assumed to be homogenous in regard to various attributes considered by the model. Additionally, the model does not spatially distribute the source areas, but simply aggregates the loads from each area into a watershed total; in other words, there is no spatial routing. For sub-surface loading, the model acts as a lumped parameter model using a water balance approach. No distinctly separate areas are considered for sub-surface flow contributions. Daily water balances are computed for an unsaturated zone as well as a saturated sub-surface zone, where infiltration is simply computed as the difference between precipitation and snowmelt minus surface runoff plus evapotranspiration (Figure 1).

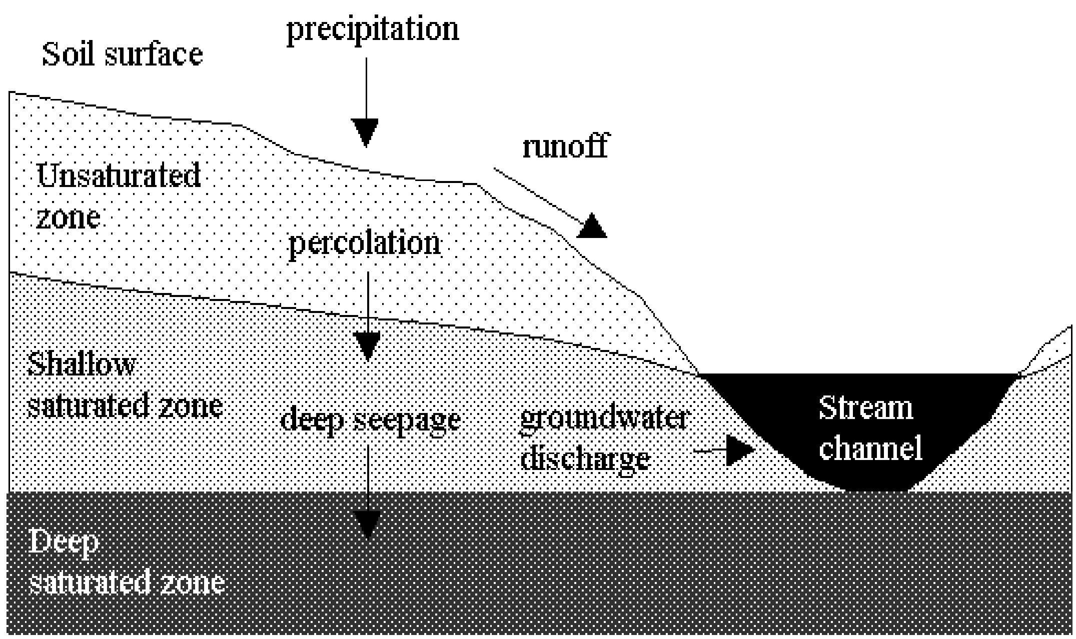


Figure 1. Sub-division of modeling components within GWLF (adapted from Haith et al., (1992)).

With respect to the major processes simulated, GWLF models surface runoff using the curve number (CN) approach with daily weather (temperature and precipitation) inputs. Erosion and sediment yield are estimated using monthly erosion calculations based on the Universal Soil Loss Equation (USLE) algorithm. A sediment delivery ratio based on watershed size and a transport capacity based on average daily runoff are then applied to the calculated erosion to determine sediment yield for each source area. Surface nutrient losses are determined by applying dissolved N and P coefficients to surface runoff and a sediment coefficient to the yield portion for each agricultural source area. Point source discharges can also contribute to dissolved losses and are specified in terms of kilograms per month. Manured areas, as well as septic systems, can also be considered. Urban nutrient inputs are all assumed to be solid-phase, and the model uses an exponential accumulation and wash-off function for these loadings. Sub-surface losses are calculated using dissolved N and P coefficients for shallow groundwater contributions to stream nutrient loads, and the sub-surface sub-model only considers a single, lumped-parameter contributing area. Evapotranspiration is determined using daily weather data and a cover factor dependent upon land use/cover type. Finally, a water balance is performed daily using supplied or computed precipitation, snowmelt, initial unsaturated zone storage, maximum available zone storage, and evapotranspiration values.

In addition to the original model algorithms described above, a stream bank erosion routine was also implemented as part of the present study. This routine is based on an approach in which monthly stream bank erosion is estimated by first calculating a watershed-specific lateral erosion rate (LER) for streams within the watershed. After a value for LER has been computed, the total sediment load generated via stream bank erosion is then calculated by multiplying the above erosion rate by the total length of streams in the watershed, the average stream bank height, and the average soil bulk density. More information on the specific details of this approach is provided in Evans (2002).

For execution, the model requires three separate input file containing transport-, nutrient-, and weather-related data. The transport (*transport.dat*) file defines the necessary parameters for each source area to be considered (e.g., area size, curve number, etc.) as well as global parameters (e.g., initial storage, sediment delivery ratio, etc.) that apply to all source areas. The nutrient (*nutrient.dat*) file specifies the various loading parameters for the different source areas identified (e.g., number of septic systems, urban source area accumulation rates, manure concentrations, etc.). The weather (*weather.dat*) file contains daily average temperature and total precipitation values for each year simulated.

GIS-BASED INPUT DATA GENERATION AND MODEL EXECUTION

As alluded to earlier, the use of GIS software for deriving input data for watershed simulation models such as GWLF is becoming standard practice due to the inherent advantages of using GIS for manipulating spatial data. In this case, a customized interface developed by Penn State for the ArcView GIS package (AVGWLF) is used to parameterize input data for the GWLF model. With this interface, statewide GIS data sets are automatically loaded, and the user is subsequently prompted to provide other information related to “non-spatial” model parameters (e.g., beginning and end of the growing season; and the months during which manure is spread on agricultural land). This information is subsequently used to automatically derive values for required model input parameters, which are, then written to the *transport.dat* and *nutrient.dat* input files needed to execute the GWLF model. Also accessed through the interface is a statewide weather database that contains over 25 years of temperature and precipitation data for seventy-eighty (78) weather stations around Pennsylvania. This database is used to create the necessary *weather.dat* input file for a given watershed simulation. A summary of the sources used to derive the input data is given in Table 1. More detailed discussions on how values are derived for each model parameter using this AVGWLF interface is provided by Evans (2002).

Upon initiating AVGWLF, statewide GIS data sets are automatically loaded. Once the required GIS themes are loaded, the user then selects a watershed for which simulation is to be performed as shown in Figure 2. The user is subsequently guided through a series of dialog screens that request information on growing season dates, manure application dates, and a beginning and end date for the simulation period. The highlighted watershed boundary and dialog screen responses are used to automatically clip out GIS data layers that are in turn used to estimate values for the various GWLF model parameters. After the required model input files have been created, the GWLF model can be run either from a button in AVGWLF (see Figure 3) or by executing the Visual Basic executable outside of ArcView. Both the *transport.dat* and *nutrient.dat* input files can be edited via the use of an edit screen (see Figure 4). Examples of model output are shown in Figures 5 and 6.

Table 1. Information sources for GWLF model parameterization.

WEATHER.DAT file	Historical weather data from National Weather Service monitoring stations
TRANSPORT.DAT file	
Basin size	GIS/derived from basin boundaries
Land use/cover distribution	GIS/derived from land use/cover map
Curve numbers by source area	GIS/derived from land cover and soil maps
USLE (KLSCP) factors by source area	GIS/derived from soil, DEM, and land cover
ET cover coefficients	GIS/derived from land cover
Erosivity coefficients	GIS/ derived from physiography map
Daylight hrs. by month	Computed automatically for state
Growing season months	Input by user
Initial saturated storage	Default value of 10 cm
Initial unsaturated storage	Default value of 0 cm
Recession coefficient	Default value of 0.1
Seepage coefficient	Default value of 0
Initial snow amount (cm water)	Default value of 0
Sediment delivery ratio	GIS/based on basin size
Soil water (available water capacity)	GIS/derived from soil map
NUTRIENT.DAT file	
Dissolved N in runoff by land cover type	Default values/adjusted using AEU density
Dissolved P in runoff by land cover type	Default values/adjusted using AEU density
N/P concentrations in manure runoff	Default values/adjusted using AEU density
N/P buildup in urban areas	Default values (from GWLF Manual)
N and P point source loads	GIS/derived from NPDES point coverage
Background N/P concentrations in GW	GIS/derived from new background N map
Background P concentrations in soil	GIS/derived from soil P loading map
Background N concentrations in soil	Based on map in GWLF Manual
Months of manure spreading	Input by user
Population on septic systems	GIS/derived from census tract map
Per capita septic system loads (N/P)	Default values (from GWLF Manual)

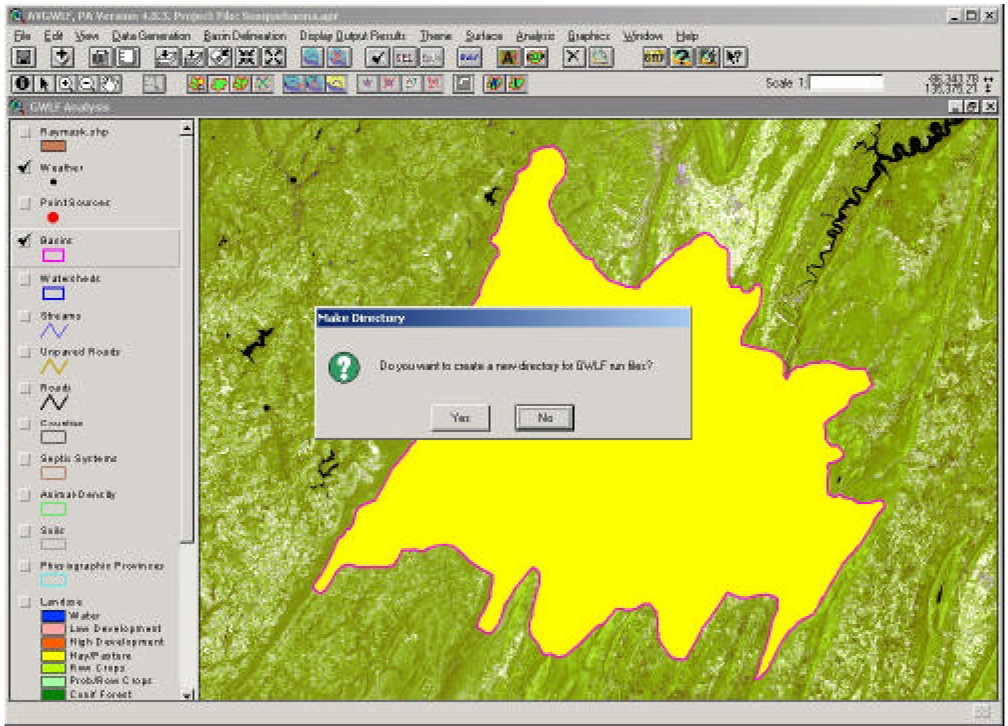


Figure 2. Selecting a watershed for simulation purposes.

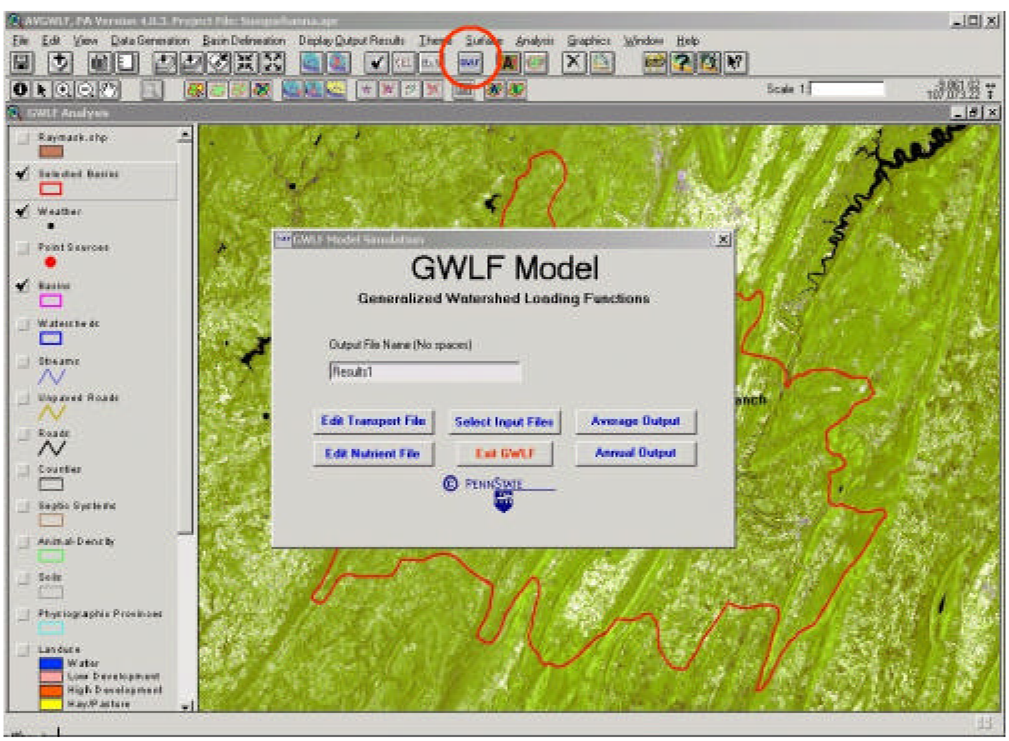


Figure 3. Executing the GWLF model within AVGWLF.

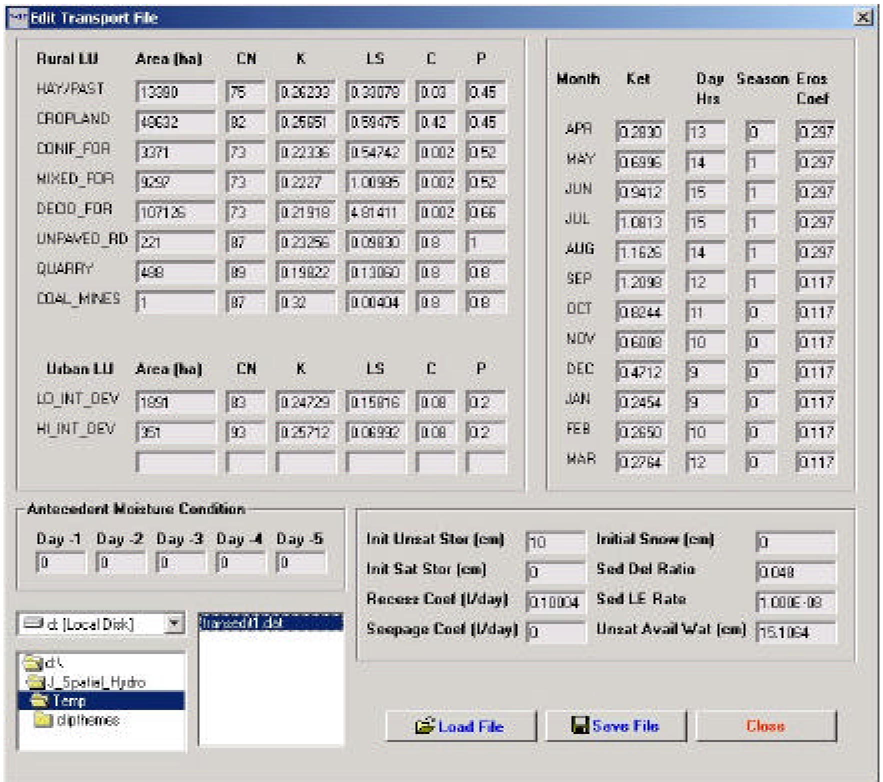


Figure 4. Example of input screen for the *transport.dat* file completed automatically by AVGWLF.

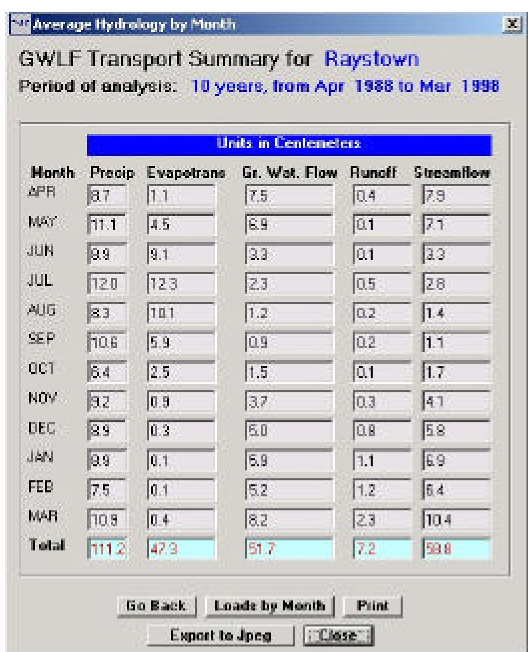
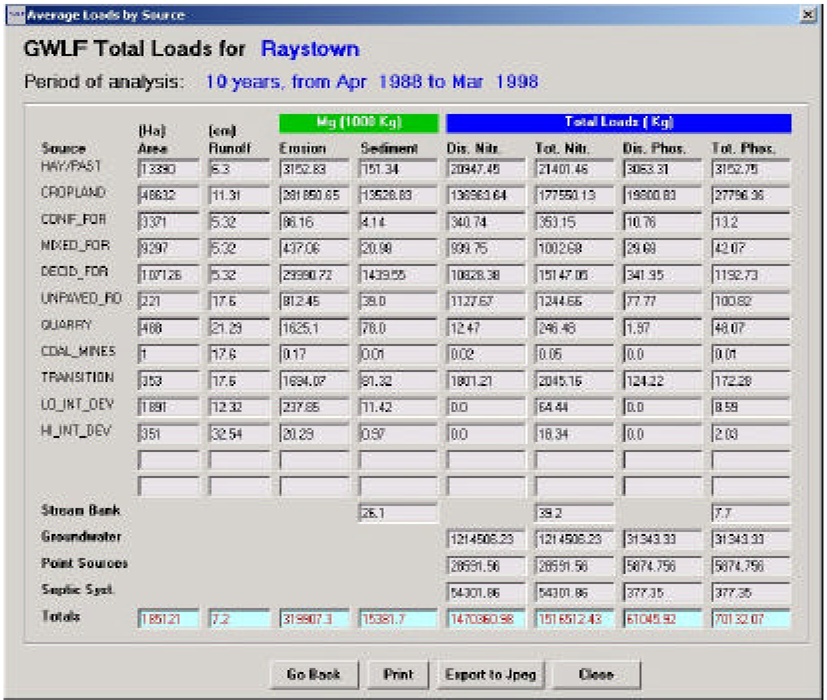


Figure 5. Example of hydrology output (mean monthly values).



Average Loads by Source

GWLF Total Loads for Raystown

Period of analysis: 10 years, from Apr 1988 to Mar 1998

	(Ha)	(cm)	Mg (1000 Kg)		Total Loads (Kg)			
Source	Area	Runoff	Erosion	Sediment	Dis. Nitr.	Tot. Nitr.	Dis. Phos.	Tot. Phos.
HAY/PAST	13390	6.3	3152.83	151.34	20947.45	21401.46	3063.31	3152.75
CROPLAND	48632	11.31	281850.65	13528.83	136963.64	177550.13	19800.83	27796.36
CONIF_FOR	3371	5.32	86.16	4.14	340.74	353.15	10.76	13.2
MIXED_FOR	9297	5.32	437.06	20.98	939.75	1002.68	29.68	42.07
DECID_FOR	107126	5.32	29990.72	1439.55	10828.38	15147.05	341.95	1192.73
UNPAVED_RD	221	17.6	812.45	39.0	1127.67	1244.66	77.77	100.82
QUARRY	488	21.29	1625.1	78.0	12.47	246.48	1.97	48.07
COAL_MINES	1	17.6	0.17	0.01	0.02	0.05	0.0	0.01
TRANSITION	353	17.6	1694.07	81.32	1801.21	2045.16	124.22	172.28
LO_INT_DEV	1891	12.32	237.85	11.42	0.0	64.44	0.0	8.59
HI_INT_DEV	351	32.54	20.29	0.97	0.0	18.34	0.0	2.03
Stream Bank				26.1		39.2		7.7
Groundwater					1214506.23	1214506.23	31343.33	31343.33
Point Sources					28591.56	28591.56	5874.756	5874.756
Septic Syst.					54301.86	54301.86	377.35	377.35
Totals	185121	7.2	319907.3	15381.7	1470360.98	1516512.43	61045.92	70132.07

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Figure 6. Example of simulated nutrient and sediment loads by source (mean annual loads).

EVALUATION OF MODELING APPROACH

Study Site Selection

In Pennsylvania, data on stream flow and water quality are collected by the U.S. Geological Survey and the Pennsylvania Department of Environmental Protection, respectively. For this study, we were interested in using watersheds where both types of data were collected during the same time period for at least six (6) years, and where there were no significant gaps in data (particularly, daily stream flow). Another requirement was that the stream flow and water quality data had to span the years 1992-1994 to coincide with the dates of the satellite data used to derive the statewide land use/cover GIS layer. A total of thirty-two (32) watersheds located throughout Pennsylvania met these requirements and were subsequently used as test sites in this study (see Figure 7). Of this total, sixteen (16) watersheds were randomly selected to be used in the calibration process, with the remaining watersheds to be used for verification purposes.

The watersheds selected collectively express the degree of variation in landscape characteristics found within the state. As shown in Tables 2 and 3, these watersheds reflect a wide range of land use and development patterns (developed vs. cultivated vs. forested vs. disturbed), and vary considerably with respect to degree of glaciation and subsurface geology. With regard to precipitation, the mean annual value for the state is 41.7 in (1059.0 mm), and ranges from about 32.3 in (820.0 mm) to 48.6 in (1234.0 mm) (Waltman et al., 1997).

Table 2. Land use/cover characteristics by watershed.

Watershed Name	Size (acres)	Percent Developed	Percent Wooded	Percent Water	Percent Disturbed	Percent Agriculture
Beech Creek	109,181	0.6	90.4	0.1	5.0	3.9
Blacklick Creek	246,963	2.5	73.9	0.6	2.3	20.7
Brodhead Creek	183,553	4.4	87.3	0.1	0.0	8.2
Casselman Creek	204,804	1.6	61.2	0.2	2.2	34.8
Chartiers Creek	175,405	17.5	48.9	0.0	1.0	32.6
Clarion River	527,497	1.1	91.8	0.4	1.1	5.7
Clearfield Creek	241,353	1.0	80.6	0.6	3.9	13.9
Codorus Creek	174,273	9.0	27.2	0.1	0.5	63.2
Conestoga Creek	303,744	9.7	25.0	0.1	0.9	64.3
Conewago Creek	326,715	2.7	32.4	1.0	0.2	63.8
Conodoguinet Creek	324,367	5.0	32.8	0.8	0.1	61.3
Driftwood Branch	190,104	0.4	96.5	0.1	0.4	2.6
Fishing Creek	231,548	0.6	68.8	0.1	0.3	30.2
Juniata R./Raystown Br.	460,165	1.2	64.6	0.4	0.5	33.4
Kettle Creek	157,297	0.0	95.9	0.2	0.7	3.2
Loyalsock Creek	278,480	0.2	88.6	0.1	1.0	10.1
Lycoming Creek	137,300	0.5	85.6	0.1	0.4	13.4
Neshaminy Creek	131,792	20.2	37.6	0.0	1.1	41.1
Oil Creek	208,888	1.0	76.9	0.1	0.3	21.8
Penns Creek	198,556	0.3	70.3	0.5	0.2	28.7
Pine Creek	630,630	0.2	88.5	0.3	0.5	10.5
Redbank Creek	340,213	2.2	70.9	0.2	1.8	24.9
Schuylkill River	224,279	3.8	74.8	1.8	5.0	14.6
Sherman Creek	154,269	0.2	69.2	0.1	0.2	30.3
Slippery Rock Creek	260,127	1.5	57.2	1.1	1.4	38.7
Spring Creek	54,935	6.1	44.0	0.3	0.1	50.0
Swatara Creek	365,545	5.7	43.8	0.9	0.8	48.8
Tioga Creek	282,692	0.4	64.2	0.1	1.2	34.1
Towanda Creek	176,328	0.3	68.6	0.1	0.0	31.0
Tunkhannock Creek	264,777	1.5	68.0	1.9	0.0	28.6
Yellow Breeches Creek	137,490	6.1	56.2	0.1	0.4	37.2
Young Woman Creek	29,549	0.0	99.7	0.1	0.0	0.2

Table 3. Geologic characteristics by watershed.

Watershed Name	Percent Carbonate	Percent Cong[1]	Percent IBS[2]	Percent Meta/Ig[3]	Percent Sandstone	Percent Shale	Glaciated
Beech Creek	0.3	-	34.7	-	64.1	0.9	No
Blacklick Creek	-	-	98.1	-	1.9	-	No
Brodhead Creek	-	-	41.5	-	47.2	11.3	Half
Casselman Creek	-	-	84.6	-	15.4	-	No
Chartiers Creek	-	-	94.6	-	-	5.4	No
Clarion Creek	-	-	43.0	-	57.0	-	No
Clearfield Creek	-	-	87.7	-	12.3	-	No
Codorus Creek	12.3	9.5	-	71.1	1.5	5.6	No
Conestoga Creek	57.8	8.3	16.3	6.7	9.2	1.7	No
Conewago Creek	9.8	5.6	-	31.8	23.2	29.6	No
Conodoguinet	39.0	-	5.5	2.7	8.1	44.7	No
Driftwood Branch	-	-	48.1	-	51.9	-	No
Fishing Creek	-	-	41.5	-	56.9	1.6	No
Juniata/Raystown	11.3	-	49.5	-	23.1	16.1	No
Kettle Creek	-	-	44.7	-	55.3	-	No
Loyalsock Creek	-	-	42.8	-	57.2	-	Partial
Lycoming Creek	-	-	48.8	-	51.2	-	Partial
Neshaminy Creek	1.8	1.7	-	2.6	46.9	47.0	No
Oil Creek	-	-	30.4	-	47.9	21.7	Half
Penns Creek	23.7	-	-	-	46.7	29.6	No
Pine Creek	-	-	47.0	-	53.0	-	Partial
Redbank Creek	-	-	75.8	-	24.2	-	No
Schuylkill River	1.4	-	54.2	-	35.7	8.7	No
Sherman Creek	9.7	-	23.9	-	39.0	27.4	No
Slippery Rock	-	-	76.1	-	22.3	1.6	Half
Spring Creek	83.1	-	-	-	11.6	5.3	No
Swatara Creek	14.8	0.7	54.0	2.0	12.2	15.3	No
Tioga Creek	-	-	66.3	-	33.7	-	Half
Towanda Creek	-	-	60.0	-	40.0	-	Half
Tunkhannock	-	-	100	-	-	-	Yes
Yellow Breeches	39.8	1.1	3.2	45.1	-	10.8	No
Young Woman	-	-	13.5	-	86.5	-	No

[1]Conglomerate
[2]Interbedded sedimentary rock
[3]Metamorphic/igneous

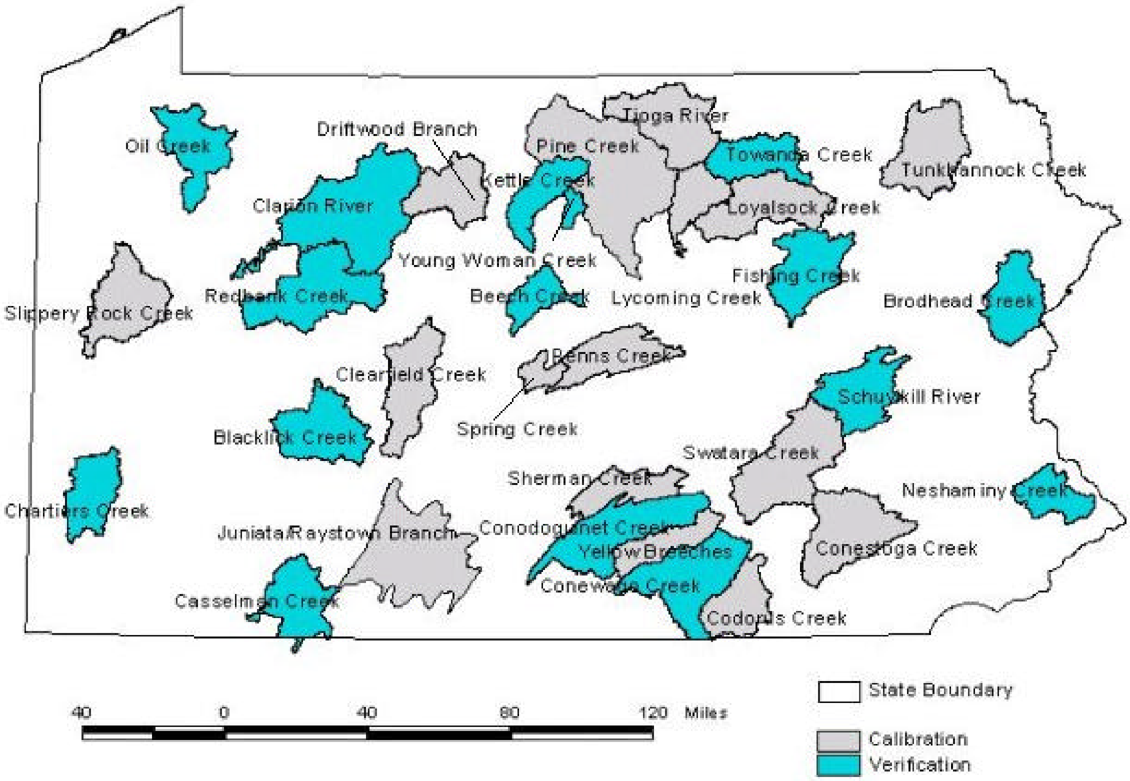

Figure 7. Location of calibration and verification watersheds.

Calculation of Historical Nutrient Loads

For both the calibration and verification watersheds, historical water quality data were compiled for either the period 1990-1996 or 1987-94, depending upon the availability of data. Historical water quality and stream flow data were then used to derive total nitrogen and phosphorus loads for each watershed which could be compared against simulated loads produced via the use of the GWLF model. Nutrient concentration data were extracted from a CD database product developed by EarthInfo, Inc. (1996). Databases are available for every state in the country, and include monitoring data compiled from various government sources such as USGS, EPA, and state environmental agencies. Daily stream flow data for each watershed were downloaded from USGS's Internet site (www.water.usgs.gov).

To derive historical nutrient loads, relatively standard mass balance techniques as described by Lane (1975), DeLong and Wells (1987), and Mattikalli and Richards (1996) were used. First, the in-stream nutrient concentration data and corresponding flow rate data were used to develop load (mass) versus flow relationships for each watershed for the period for which water quality data were compiled. Daily stream flow data for the watershed and period of interest were then downloaded from the U.S. Geological Survey's Internet site, and daily nutrient loads for each relevant time period were subsequently computed for each watershed using the appropriate load versus flow relationship (i.e., "rating curves"). Loads computed in this fashion were used as the "observed" loads against which model-simulated loads were compared.

GWLF Modeling, Calibration and Verification

In recognition of the variable quality of some of the model input data, some effort was expended in the model calibration step to "fine tune" the algorithms used to estimate various input parameters. The primary parameters adjusted during this calibration activity included those that affected stream flow (i.e., ET cover coefficient), upland erosion (particularly USLE factors "C" and "P"), sediment loads from stream bank erosion (i.e., lateral erosion rate of stream banks), background concentrations of nitrogen and phosphorus in groundwater, and average soil phosphorus concentration. These parameters were considered to be the most critical ones affecting nutrient load simulations as reported by Evans (2002), Lee et al. (2000), and Schneiderman et al. (1998) that could at the same time be easily estimated using readily available data. During the calibration process, an attempt was made to adjust these parameter values (or algorithms used to estimate these values) in a way that would achieve an overall "best fit" between the simulated and observed nutrient loads for the sixteen calibration watersheds. Values for more difficult to calculate parameters (at least using automated GIS-based routines) such as basin recession coefficient, groundwater seepage coefficient, and event mean nutrient concentrations for assorted land use/cover types were based on those given by Haith et al. (1992) as being reasonable for most locations in the northeast part of the United States. More detailed information on the calibration process in provided by Evans (2002).

Subsequent to this preliminary calibration effort, additional AVGWLF model simulations were performed for the remaining sixteen verification watersheds to evaluate how well the modeling procedure works in watersheds not considered in the original calibration effort. All simulations were performed for the same period in which historical water quality sample data were compiled, as described earlier. Model input files in each case were created using the AVGWLF model interface which automatically assigns parameter values using the GIS data layers and default values as discussed earlier.

RESULTS AND DISCUSSION

The GWLF model calculates nutrient loads on a daily basis, but provides output on a monthly and annual basis. The primary emphasis of this research was to statistically evaluate observed and predicted mean annual nutrient loads since this is the basis for comparing "impacted" and "reference" watersheds in the TMDL assessments being conducted in Pennsylvania. In the interest of determining the utility of the GIS-based modeling approach for other time periods, statistical analyses were performed using monthly, seasonal and year-to-year modeling results as well. Plots of the observed versus simulated mean annual nutrient loads for each of the thirty-two watersheds used in the calibration and verification steps are provided in Figures 8 through 11.

To assess the correlation, or "goodness-of-fit", between observed and predicted values for mean annual nitrogen and phosphorus loads the Nash-Sutcliffe statistical measure recommended by ASCE (1993) for hydrological studies was used. With the Nash-Sutcliffe measure, an R^2 coefficient is calculated using the equation $R^2 = 1 - [\sum(Q_o - Q_p)^2 \; / \; \sum(Q_o - Q_a)^2]$, where Q_o is the observed value, Q_p is the predicted value, and Q_a is the average of the observed values. Coefficient (R^2) values equal to 1 indicate a perfect fit between observed and predicted data, and R^2 values equal to 0 indicate that the model is predicting no better than using the average of the observed data. (Note: throughout the remainder of this text, the term "N-S" will be used in place of "R^2" to differentiate the Nash-Sutcliffe coefficient from more traditional regression and correlation coefficients). For comparison purposes, "one-to-one" lines and R^2 values that one would obtain via traditional least-squares regression are also shown on Figures 8 through 11.

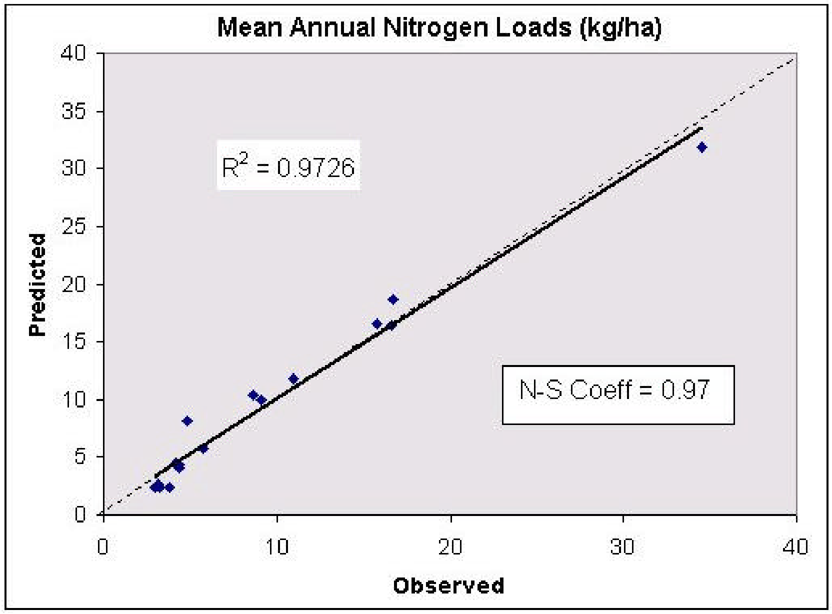

Figure 8. Comparison of nitrogen loads for the sixteen calibration watersheds.

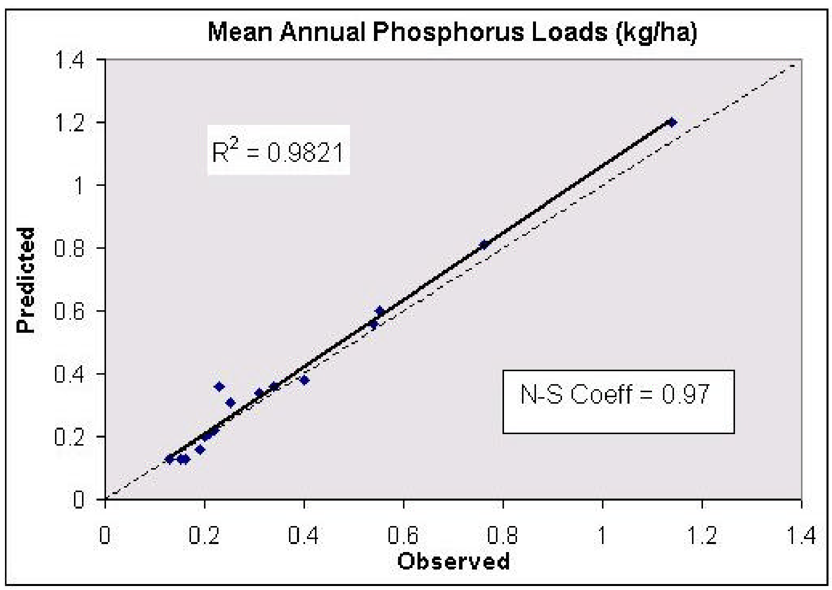

Figure 9. Comparison of phosphorus loads for the sixteen calibration watersheds.

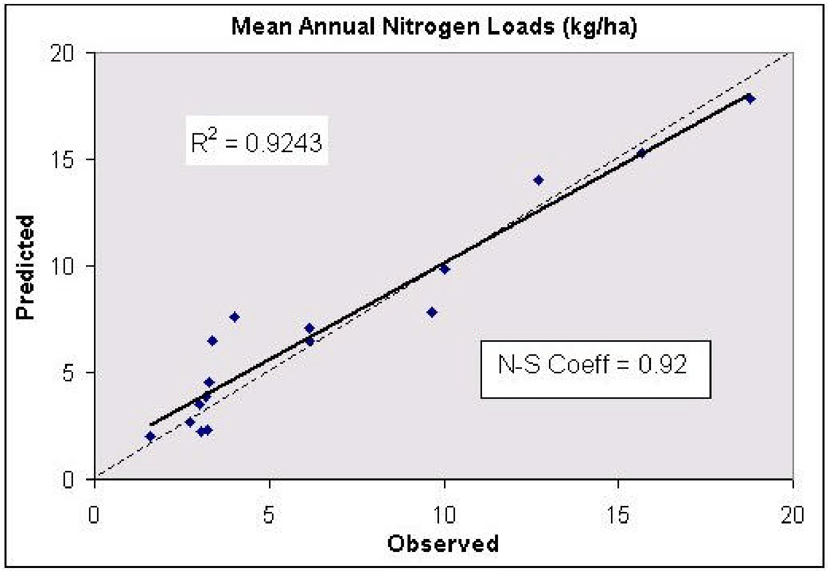

Figure 10. Comparison of nitrogen loads for the sixteen verification watersheds.

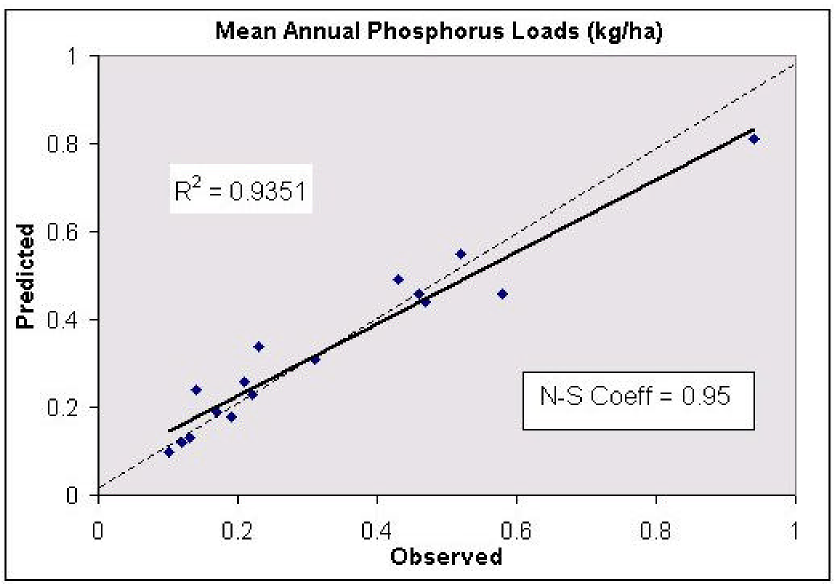

Figure 11. Comparison of phosphorus loads for the sixteen verification watersheds.

In this case, simulated and observed mean annual nutrient load values were pooled separately for both calibration and verification watersheds. Nash-Sutcliffe (N-S) coefficients were then calculated for each group for both N and P by comparing the simulated and observed mean annual nutrient loads for each watershed against the average (i.e., mean) value of the observed mean annual nutrient loads in each group. During the calibration step, an N-S value of 0.97 was calculated for both the total nitrogen and total phosphorus loads. In the verification step, N-S values of 0.92 and 0.95 were calculated for total nitrogen and total phosphorus loads, respectively.

As was done with the comparison of mean annual loads between watersheds, Nash-Sutcliffe coefficients for monthly, seasonal and yearly nitrogen and phosphorus loads were also calculated individually for each of the calibration and verification watersheds. These coefficients are shown in Table 4. From this table, it can be seen that model accuracy varied somewhat by watershed, pollutant and time period. However, as evidenced by the large number of positive values and the relatively high median values, the AVGWLF approach, on average, was much more accurate than just using the mean monthly, mean seasonal or mean annual observed load for each watershed. Using the non-parametric Mann-Whitney test, the median monthly values for nitrogen were not found to be significantly different from the median seasonal values at the 95% confidence interval. Similarly, the median seasonal values were not found to be significantly different from the median annual values, and the median monthly values were not found to be significantly different from the median annual values. Therefore, although it appears that some modeling accuracy is lost as one moves from estimating monthly nitrogen loads to estimating yearly loads based on the decreasing N-S values, these differences are not statistically significant ($p = 0.246$).

With phosphorus, however, the results based on the Mann-Whitney test showed that the difference between median monthly values and median seasonal values was weakly significant ($p = 0.0649$). The difference between median seasonal and median annual values was not significant ($p = 0.4602$), but the difference between median monthly and median annual values was significant ($p = 0.0433$). These results suggest that, at least for phosphorus, modeling accuracy improves slightly as one moves from evaluating shorter to longer time periods with AVGWLF.

CONCLUSIONS

As illustrated by the model calibration and verification results, the AVGWLF approach, overall, appears to provide reasonably good estimates of mean annual nutrient loads in watersheds exhibiting a wide range of landscape characteristics in Pennsylvania. Nash-Sutcliffe coefficients derived for the thirty-two calibration and verification watersheds were extremely good, and ranged in value from 0.92 to 0.97 for both nitrogen and phosphorus. The AVGWLF approach also appeared to satisfactorily simulate variations in nutrient loads on monthly, seasonal, and year-to-year time frames. The median N-S values for nitrogen varied between 0.64 to 0.70 for monthly, seasonal, and year-to-year load estimates; and for phosphorus they varied between 0.61 and 0.72. Although there appeared to be some variability between time periods for nitrogen, these differences were determined to not be statistically significant. However, the results for phosphorus suggest that modeling accuracy improves as one moves from evaluating shorter to longer time periods with AVGWLF. Also, as shown in Table 4, the majority of the calculated N-S coefficients for both nutrients were consistently above 0, which means that AVGWLF almost always provided a better estimate than just the mean monthly, seasonal or annual load in the test watersheds. Since historical water quality measurements are routinely not available for most watershed studies in Pennsylvania, the potential benefit of using AVGWLF in such situations cannot be underestimated.

Table 4. Summary of calculated Nash-Sutcliffe coefficients.

WATERSHED	N-mo	N-seas	N-ann	P-mo	P-seas	P-ann
Beech Creek (V)	0.52	0.38	0.31	0.54	0.62	0.95
Blacklick Creek (V)	-1.03	-2.36	-11.85	-0.81	-1.36	-7.08
Brodhead Creek (V)	0.21	0.26	-0.06	0.44	0.70	0.59
Casselman Creek (V)	0.80	0.92	0.94	0.59	0.91	0.92
Chartiers Creek (V)	0.40	0.46	0.55	0.69	0.75	0.44
Clarion River (V)	0.79	0.85	0.87	0.72	0.82	0.73
Clearfield Creek (C)	0.84	0.87	0.93	0.73	0.78	0.90
Codorus Creek (C)	0.77	0.80	0.89	-0.49	-0.15	0.89
Conestoga Creek (C)	0.75	0.75	0.66	0.10	0.52	0.80
Conewago Creek (V)	0.59	0.72	0.77	0.22	0.28	-0.01
Conodoguinet Creek (V)	0.81	0.83	0.90	0.66	0.82	0.77
Driftwood Branch (C)	0.73	0.81	0.66	0.74	0.84	0.62
Fishing Creek (V)	0.55	0.34	0.86	-0.99	-1.22	0.46
Juniata/Raystown Br. (C)	0.71	0.72	0.66	0.65	0.80	0.90
Kettle Creek (V)	0.50	0.54	0.26	0.64	0.73	0.74
Loyalsock Creek (C)	0.52	0.25	-1.14	0.66	0.58	0.19
Lycoming Creek (C)	0.69	0.62	0.08	0.62	0.69	0.82
Neshaminy Creek (V)	0.47	0.41	0.65	0.57	0.59	0.40
Oil Creek (V)	0.57	0.37	0.01	0.54	0.67	0.85
Penns Creek (C)	0.65	0.67	0.79	0.64	0.66	0.85
Pine Creek (C)	0.72	0.71	0.14	0.68	0.65	0.08
Redbank Creek (V)	-0.89	-2.35	-9.46	0.00	-0.30	-2.36
Schuylkill River (V)	0.76	0.70	-0.02	0.67	0.78	0.74
Sherman Creek (C)	0.71	0.65	0.68	0.64	0.50	0.62
Slippery Rock Creek (C)	-1.10	-1.72	-4.49	-0.46	-0.49	-2.13
Spring Creek (C)	0.14	-0.07	0.06	0.07	0.31	0.74
Swatara Creek (C)	0.77	0.78	0.85	0.55	0.69	0.61
Tioga River (C)	0.82	0.86	0.95	0.64	0.76	0.92
Towanda Creek (V)	0.40	0.39	0.41	0.47	0.69	0.78
Tunkhannock Creek (C)	0.82	0.88	0.63	0.46	0.40	-0.49
Yellow Breeches Creek (C)	0.70	0.52	0.83	0.71	0.72	0.67
Young Woman Creek (V)	0.70	0.60	-0.13	0.82	0.81	0.70
Median Value	0.70	0.64	0.64	0.61	0.68	0.72

The results suggest that this approach in which “standardized” statewide GIS data layers, weather station data, and default values are used can sufficiently discern annual nutrient load differences between watersheds that reflect a wide range of physical factors, but may not be sufficiently “sensitive” to adequately capture the temporal variability of nutrient loads exhibited within individual watersheds in some cases. That is not to say that GWLF cannot be used to simulate such loads given adequate calibration. Recent work by the one of the authors (Chang et al., 2001) and others (e.g., Dodd and Tippett, 1994; and Lee et al., 2000) indicates that this indeed is possible. In this particular study, a fair amount of effort was expended in adjusting key GWLF model parameters in order to optimize results in Pennsylvania. Given this, it is likely that similar model adjustments would be needed to obtain satisfactory results in other geographic locations, particularly if landscape and climatic conditions differ substantially from those found in Pennsylvania.

The AVGWLF methodology is relatively new and was still undergoing some slight revisions at the time this paper was prepared. However, given Pennsylvania's urgent need to conduct TMDL assessments within a relatively short period of time, this methodology is now being used for practical applications. It is expected that AVGWLF will continually evolve as newer input data sets are developed and as improved parameterization algorithms are identified and implemented.

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