Case Study

Nutrient Loads to Cayuga Lake, New York: Watershed Modeling on a Budget

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Abstract: Nutrient loads were estimated for the 34 watersheds draining into Cayuga Lake, New York, through use of a watershed model. Financial and human resources were very limited for the project, but significant cost savings were achieved through project decisions. Chief among these were selection of a watershed model that did not require calibration and use of historic water quality monitoring data for model testing. Savings were also obtained by extrapolating soil properties from related information (nutrient contents from organic matter), substituting literature concentrations for missing point source data, extrapolating septic system performance from one area to another, and use of synthetic weather data generated from a model. None of the decisions was remarkable in itself, but together, they permitted a watershed study and its associated modeling to be accomplished with modest resources. **DOI: 10.1061/(ASCE)WR.1943-5452.0000198.** *© 2012 American Society of Civil Engineers.*

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Introduction

Watershed modeling is often expensive and time consuming. The development of land use databases, collection of water quality and hydrologic data for model calibration and testing, and measurement of model input parameters are major activities required for watershed modeling. Resource needs are compounded when comparative evaluations are necessary for multiple watersheds. Watershed modeling may not be for the faint hearted; neither would it appear appropriate for small nongovernment organizations (NGOs) with limited funds. However, it is not impossible. This paper describes a very large modeling effort by a very small NGO and the compromises and shortcuts required by limits of money and time.

Cayuga Lake, shown in Fig. 1, is a large water body in the Finger Lakes region of central New York State. It is approximately 60 km long, with an average width of about 2.8 km and maximum depth of more than 130 m. The lake's drainage area, which covers 1,871 km^2 (excluding the lake surface and drainage areas of adjacent Finger Lakes, which are connected through the Seneca-Cayuga Canal) contains portions of 44 communities and 6 counties and has an economy that includes significant agricultural, education, tourism, manufacturing, and service sectors. Overall land uses are 52% agriculture, 34% forest and brush, 12% urban, and the remaining 2% other rural uses, such as water, disturbed, and cleared areas.

Although the water quality of Cayuga Lake is generally good, sediment and phosphorus inputs are considered long-term threats (Genesee/Finger Lakes Regional Planning Council 2000), particularly in the shallow northern and southern portions. Swimming is prevented at the southern end due to sediment-induced turbidity, and the Draft Cayuga Lake Watershed Restoration and Protection Plan identifies management of phosphorus as a high priority (Genesee/Finger Lakes Regional Planning Council 2001). The New York State Department of Environmental Conservation has listed the southern end of Cayuga Lake as an 'impaired segment requiring the development of total maximum daily loads (TMDLs) associated with phosphorus, sediment, and pathogens (New York State Dept. of Environmental Conservation 2010).

In spite of the threat posed by contaminants to the lake's value as a regional economic, recreational, and ecological resource, only the sketchiest information is available for nutrient loads to the lake. The only comprehensive data come from one year of water quality monitoring nearly 40 years ago (Likens 1974a, b). Planning studies have recognized the need for up-to-date information on nutrient loads to Cayuga Lake, but the means of generating the information have not been apparent. Counties, cities, and towns within the drainage basin have strong planning, health, and public works departments, but there is no organization with significant administrative and budgetary responsibilities for the lake, and this has made initiation of basin-wide studies very difficult. Even without such institutional limitations, determining the magnitudes and locations of nutrient loads to the lake would be a daunting task. The only practical way to complete the inventory is through modeling of the 34 watersheds draining into the lake, but no models are in place. The land use, soils, and topographic data required for modeling are sparse at best. Available geospatial data resources cover only a small portion of the basin area and fail to include essential information related to crops, erosion, and septic systems. Few water quality data are available for model calibration or testing.

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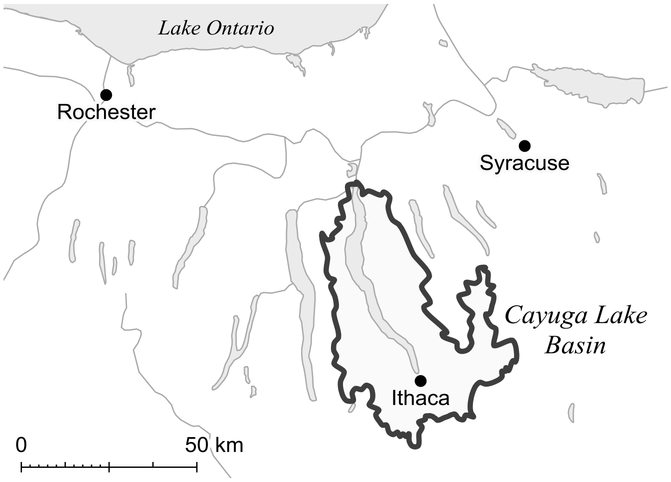

Fig. 1. The Cayuga Lake basin and the Finger Lakes of upstate New York

There is one small NGO, the Cayuga Lake Watershed Network (CLWN), whose mission includes a broad concern for "threats to Cayuga Lake and its Watershed." The Network has no legal mandates for lake or watershed protection and very limited funding. It does, however, have several hundred dues-paying members, most of whom share a strong affection for the lake and its surrounding lands. The organization, which is headquartered at Wells College in the lakeside community of Aurora, NY, is fairly visible with biannual workshops, informative publications, and programs to support agricultural efforts to minimize pollution. Faculty and students at Cornell University are also active in CLWN, and this connection provided the impetus for a joint study by the Network and Cornell's Department of Biological and Environmental Engineering funded for US$25,000/year over three years by federal formula funds from the Cornell University Agricultural Experiment Station. The purposes of the study were to (1) estimate annual mass loads of N and P to Cayuga Lake, and (2) determine the sources of these loads.

Given the limited nature of existing watershed information, the study objectives were very ambitious. CLWN staff had little experience in geographic information system (GIS) design or watershed modeling, and US$75,000 was not much of a budget for 34 watersheds comprising nearly 2,000 km^2. Engineering students would provide some of the missing technical skills but typically could devote no more than several hours per week to the work. Nevertheless, as is documented in this case study, the project was completed successfully on time and within budget. This success was due to a series of decisions related to model selection, GIS development, parameter estimation, and model testing, each of which recognized the constrained resources. None of the decisions were remarkable in themselves, but together they demonstrate that watershed studies and their associated modeling can be accomplished with modest resources.

The remaining portions of this paper describe the major decisions and compromises required to carry out the study. Model testing and study results are also presented.

Methods: Cost-Effective Modeling Decisions

Selection of a Watershed Model

The largest savings in time and costs were realized by the decision to use a watershed model that did not require calibration. Calibration is a process whereby certain model input parameters are estimated by adjusting their values until model water quality predictions approximate observations from event-based monitoring. The obvious drawback to parameter estimation by calibration is the need for time-consuming and expensive monitoring. Furthermore, although calibration is often seen as a means of ensuring model accuracy, this is not necessarily the case. Calibration may reflect an incomplete model in which selected watershed processes are not related directly to measureable physical, chemical, or biological phenomena. Unless calibration is followed with a validation stage in which predictions are compared with a second set of observations, there is little assurance that the fitted parameter values are generally applicable.

The generalized watershed loading functions (GWLF) model, version 3 (GWLF30) (Haith et al. 2010) was selected for the study. The model is based on a daily hydrologic model that computes surface runoff, evapotranspiration, soil moisture, and streamflow from daily precipitation and temperature. Nutrient loads are determined for runoff, groundwater discharge, and on-site wastewater systems. Point sources are specified as input data. Although the model can be calibrated when sufficient monitoring data are available, calibration is not a requirement. The model has significant credibility in the northeastern United States because of previous experience with it in the region. The model was originally developed and tested for the West Branch Delaware River in Delaware County, NY (Haith and Shoemaker 1987; Haith et al. 2010). It was subsequently used for other New York waters, including the Hudson River (Swaney et al. 1996), Keuka Lake (Landre 1996), and New York City reservoir watersheds (Schneiderman et al. 2002). There have also been applications in Maine (Runge et al. 1992), Massachusetts (Matteo et al. 2006), Pennsylvania (Chang et al. 2001), Maryland (Lee et al. 2001), and North Carolina (Research Triangle Institute 1994). The model has been adopted as a watershed tool for developing TMDL allocations in Pennsylvania (Evans et al. 2002) and is being adapted for similar purposes in the New England states (Mulcahy 2007).

Design of a GIS

It is virtually impossible to carry out extensive watershed modeling without a GIS. The absence of such a database was the principle impediment to the Cayuga Lake project. In addition, once such a database was developed, it would have uses far beyond watershed modeling as a standalone planning and research tool for CLWN, Cornell researchers, and local planning agencies. Accordingly, the GIS construction was the first project priority and accounted for a significant portion of the project budget, including the contracting of a GIS specialist through CLWN.

To meet the data input requirements of the GWLF model, a number of new geospatial data layers describing land use, land cover, soil characteristics, climate, wastewater management, topography, and hydrology were created. Whereas some data layers could be synthesized from existing geospatial data resources acquired from local, state, or federal government agencies, a number of new data layers were created by interpretation of aerial imagery or other geospatial analysis techniques. Complete technical documentation of the data sources and methods are described in the final project report (Haith et al. 2009).

Given the limited project budget, the development of suitable land use and land cover information presented the most significant challenge. Although automated classification algorithms exist, these techniques cannot produce sufficiently accurate and detailed land use and cover data, particularly for urban land classes. Manual digitization, in contrast, can result in very accurate and highly resolved land classifications, but can be both time consuming and prohibitively costly. Ultimately, a novel approach drawing on the strengths of both approaches was used.

Small extent urban land uses, such as residential, commercial, and institutional areas, were manually digitized from high resolution aerial imagery acquired from the New York State Digital Orthoimagery Program (NYSDOP). Forest cover types were classified using a supervised maximum likelihood classification method (Jensen 1996) on a pair of medium-resolution Landsat 5 images captured in the summer and early winter of 2004. Agricultural land cover types were derived from the Cropland Data Layer produced by the USDA National Agricultural Statistics Service, which is primarily generated by an automated classification process informed by field observations. Ultimately, these individual data layers were merged to create a single multiresource, hierarchical classification of land use and cover types for the Cayuga Lake basin. This and other geospatial data layers created for this project have been made available to local government planning agencies and online through the Cornell University Geospatial Information Repository (http://cugir.mannlib.cornell.edu).

Weather Data

Weather data are often taken for granted in watershed modeling studies, but the provision of consistent and accurate records is difficult, particularly in multiwatershed studies. Obvious choices would appear to be historic records for locations central to each watershed. Records should be as long as possible, and when all watersheds drain to a common water body such as Cayuga Lake, the records should be concurrent so that nutrient loads from each watershed are comparable. These requirements are not easily met, and even when appropriate historic records are available, time-consuming analyses are necessary to replace missing data and eliminate spurious entries.

A more practical approach is to use a weather generator that can produce records of arbitrary length with the same statistical properties as the actual historic data. The USCLIMATE software package (Hanson et al. 1994) was used in this study to generate 100-year daily weather records for each of the 34 watersheds. These records were keyed to five regional weather stations; that is, the generated records duplicated the historic (1971–2000) mean annual precipitation amounts.

Water Quality Data for Model Testing

The most expensive component of most watershed studies is water quality monitoring, both for model calibration, if required, and model validation, or verification of the accuracy of model predictions. The more-or-less standard approach is to perform continuous event-based sampling for several years at the watershed outlet, run the watershed model for these same years, and compare model and monitoring results. As described previously, when the model requires calibration, the monitoring data is divided into two sets, one each for calibration and validation.

Neither time nor money was sufficient for monitoring in the Cayuga Lake study, but some historic data were available. Although the Likens (1974a, b) 1970–1971 monitoring described previously did not emphasize storm event sampling, it did include weekly or biweekly samples, and as a result may well have included some high flows associated with storms. Although this is the only such monitoring of overall nutrient loads to the lake to the authors knowledge, extensive monitoring, including storm event sampling, has taken place in Fall Creek, the largest of the Cayuga Lake watersheds. Total and dissolved phosphorus were measured in Fall Creek for 20 months in 1972–1974 (Johnson et al. 1976) and dissolved nitrogen sampling was performed from 1972 through 1995 (Bauters and Eckhardt 2001).

The historic data could be used for validation if the watershed model could be run for comparable time periods. Unfortunately, the land use conditions, agricultural practices, and wastewater discharges for these earlier periods are largely unknown, and there were no possible means of modeling daily or monthly loads comparable to the historic measurements. However, would comparisons of annual means be equally invalid? Certainly, annual means based on the current (2002–2006) watershed information would likely be different than those from earlier times, but how different? If model means differed greatly from the historic values, it would likely indicate problems with the model, and conversely, if the two sets of means were relatively close, it would provide at least some confidence in model results.

The most serious limitation of means comparisons is failure to test a model's ability to capture variability, particularly seasonal and annual changes in streamflows and loads. Although previous applications of the GWLF model has indicated good performance in modeling such variability, it is not guaranteed. Nonetheless, model testing by comparisons with historic mean loads was the only option available. It stopped short of a complete model validation, but it did provide evidence of model credibility. In addition to saving the costs of a monitoring program, it allowed the same model results used for the load estimates to be used in the testing; no separate model runs were required for model validation.

Land Use Classes

The land use/land cover (LU/LC) spatial data layer of the Cayuga Lake GWLF database consists of 11 classes—agricultural, commercial, disturbed, forest/brush, industrial, institutional, outdoor recreation, residential, transportation, urban, and water. These are further broken down into 139 subcategories of LU/LC, each of which has distinctive characteristics with respect to hydrology, erosion, and nutrient loss. Although it is impractical to model this many categories, if for no other reason than the difficulties in presenting and interpreting results, the numerous subcategories were derived to preserve options for future uses of the data.

Selection of LU/LC categories is a critical decision in any watershed modeling study—it involves tradeoffs between model accuracy, usefulness of results, and level of effort. The 139 categories were aggregated into the 15 rural and 7 urban land uses shown in Table 1. The urban uses were further divided into pervious and impervious portions, resulting in a total of 29 distinct types. Although this would have exceeded the allowable land uses in earlier versions of GWLF, GWLF30 can handle up to 50 types.

Selections and aggregations of LU/LC categories are always arbitrary to some extent, but the decisions were generally dictated by differences or similarities in model input parameters. For example, the four major crop categories differ significantly in runoff curve numbers, erosion variables, and nutrient runoff concentrations. Orchards and vineyards are combined because both have large grassy areas between trees and vines. Forest areas are divided between deciduous and conifer because of differences in evapotranspiration cover coefficients. The farmstead category was created to include the variety of impervious surfaces (such as building roofs, barn yards, and paved areas) in agricultural areas. The urban divisions, including the pervious/impervious breakdowns, correspond to differences in nutrient accumulation rates on these surfaces.

Impervious surfaces estimates were problematic. In the process of assembling the GIS, impervious surfaces were manually digitized from aerial imagery. However, manual digitization is a

Table 1. Major Land Uses in the Cayuga Lake Basin

Land use type	Area (ha)	Percentage of watershed
Rural		
Corn	18,639	10.0
Hay and small grain	29,401	15.7
Soybeans	2,096	1.1
Alfalfa	11,791	6.3
Pasture and grass	29,427	15.7
Other crops	4,780	2.6
Orchards and vineyards	377	0.2
Farmstead	1,075	0.6
Inactive agriculture	2,477	1.3
Tree farms	332	0.2
Brush	12,590	6.7
Deciduous forest	24,161	12.9
Conifer forest	5,960	3.2
Mixed forest	19,561	10.5
Disturbed land	376	0.2
Urban		
Industrial—pervious	337	0.2
Industrial—impervious	388	0.2
Commercial—pervious	249	0.1
Commercial—impervious	644	0.3
Institutional—pervious	628	0.3
Institutional—impervious	338	0.2
Outdoor recreation—pervious	970	0.5
Outdoor recreation—impervious	95	0.1
High density residential—pervious	5,088	2.7
High density residential—impervious	3,836	2.1
Medium density residential—pervious	1,052	0.6
Medium density residential—impervious	282	0.2
Low density residential—pervious	7,779	4.2
Low density residential—impervious	1,164	0.6
Summary		
Agriculture	97,586	52.2
Forest and brush	62,604	33.5
Other rural	2,853	1.5
Urban	22,850	12.2
Total modeled area	185,893	99.4
Total watershed area	187,066	100.0

time-intensive process and the process was completed for only 10 of the 34 watersheds. As an alternative, impervious surfaces were estimated for each urban surface by using default impervious percentages from the New York State Stormwater Management Design Manual (Center for Watershed Protection 2003). These values are listed in Table 2. The accuracy of these default values was evaluated by comparing the total impervious surface areas used in simulations with the digital imaging results for the 10 watersheds. As shown in Table 3, the default values used in the simulations exceeded the manually measured values by an average of 50%, and, assuming similar errors in all 34 watersheds, this likely produced corresponding overestimates in urban runoff loads.

Table 2. Impervious Percentages for Urban Land Uses

Land use category	Percentage impervious	Corresponding New York State stormwater management category
Industrial	54	Light industrial mean
Commercial	72	Commercial mean
Institutional	35	Institutional mean
Outdoor recreation	9	Open urban land
Low-density residential	13	Mean of 1 and 2 acre (0.4 and 0.8 hectare) residential
Medium-density residential	21	Mean of 1/2, 1/4, 1/8 acre (0.2, 0.1, 0.05 hectare) residential
High-density residential	43	Mean of town homes and multifamily residential

Table 3. Comparison of Default Impervious Areas Used in Watershed Simulations with Those Obtained from Aerial Imagery

	Percentage impervious	
Watershed	Aerial imagery	New York State stormwater defaults
Cayuga Village area	5.4	8.1
Glen/Dean creeks area	1.7	2.4
Great Gully	1.2	1.6
King Ferry Station area	1.7	3.4
Lavanna area	1.2	1.7
Little Creek area	2.9	3.6
Paines Creek	1.4	1.8
Red Creek	1.3	2.5
Union Springs area	2.9	4.1
Yawger Creek	1.7	2.0
Mean	2.1	3.1

Parameter Estimation

Two types of input parameters are required by GWLF. Transport parameters are used to compute water balances and sediment movement. Values must be provided for runoff curve numbers, evapotranspiration coefficients, groundwater discharge constants, universal soil loss equation variables, and sediment delivery ratios. Nutrient parameters are required to determine N and P loads from runoff, groundwater discharge, and point sources. Data are necessary for dissolved concentrations in rural runoff and groundwater, solid concentrations in sediment, accumulation rates on urban surfaces, populations served by on-site or septic wastewater systems, and monthly discharges from point sources. Values for many of these parameters were available from the GWLF users' manual (Haith et al. 2010) or could be computed with the GIS. However, some inputs related to dissolved and solid concentrations, septic systems, and sewage treatment plants were not readily available and approximate or indirect estimation methods were necessary.

Dissolved Concentrations in Runoff

Event mean dissolved N and P runoff concentrations were required for each of the rural land uses in Table 1. Additional concentrations were required for land uses subject to winter manure spreading. Some of these data were available as default values from the GWLF manual (Haith et al. 2010), but others required assumptions or interpretations. Thus, it was assumed that values for soybeans and other crops are the same as those for corn, brush, is the average of hay and forest, inactive agriculture is comparable to brush, and disturbed land is equivalent to fallow. Other values were more of a stretch. Farmstead concentrations were assumed to be similar to commercial values reported in the National Urban Runoff Program (Stahre and Urbonas 1990). Assuming that fertilizer applications on fruits are comparable to those on field crops, the mean of fallow and corn concentrations were used for orchards and vineyards.

When manure is applied in the winter, runoff nutrient concentrations are typically much larger than otherwise. The manure remains on top of the frozen soil and there is no plant uptake of nutrients. For this reason, GWLF uses different concentrations in winter runoff for rural land uses that receive winter manure. Input data must specify which uses are receiving the manure, months of application, and the new concentrations. On the basis of conversations with Cooperative Extension personnel in Cayuga, Tompkins, and Seneca counties, it was determined that winter manure spreading by dairy farmers in the eastern Cayuga Lake watersheds generally occurs following the cleaning out of storage facilities in late winter (March). It was estimated that 25% of the corn and 30% of the hay/small grains receive this manure in the eastern watersheds. Dairy farms are generally smaller in the western and southern watersheds, and farmers are more likely to spread manure through the winter (January through March). It was estimated that manure was spread during the winter on 50% of corn and hay/small grains in these watersheds.

Field experiments conducted in Cayuga County in the 1970s were relied on to estimate dissolved nutrient concentrations in runoff from winter manure spreading (Klausner et al. 1976). Manure was applied to corn land at 35, 100, and 200 Mg/ha. Dissolved runoff losses of *N* and *P* were measured during January, February, and March of 1972, 1973, and 1974. The 35 Mg/ha rate produced a mean *N* input of 170 kg/ha, and because this would be sufficient for the crops grown in the area, it was assumed that the concentrations measured for that rate (8.3 mg/L for *N* and 2.4 mg/L for *P*) are typical of the values that would occur in winter runoff from corn, hay, and small grains lands throughout the Cayuga Lake watershed. The actual concentrations used as GWLF inputs were weighted averages of manured and unmanured areas.

Nutrients in Sediment

Solid-phase nutrients in rural runoff are calculated in GWLF as sediment load times an average nutrient concentration in the sediment. The GWLF input files require specification of these concentrations for each watershed being modeled. An obvious, if expensive, approach is a soil sampling and testing program for each modeled watershed. This was beyond the study's means, so extrapolations from limited previous sampling of area soils were relied on.

Arnold (1968) and Prince and Raney (1961) reported nitrogen and/or organic matter contents for samples from 10 of the soil associations in the Cayuga Lake drainage basin. In eight of the cases, only organic matter was measured. From this meager information, *N* and *P* contents were assigned for the soils in the 34 Cayuga Lake watersheds. The first step was to estimate *N* and *P* for the 10 sampled soils. For most of these soils, nitrogen was determined as 5% of organic matter (Brady 1990). Phosphorus was estimated using the ratio of soil *P* to *N* (0.43) for upstate New York determined from national soil maps (Mills et al. 1985). The second part of the procedure was to identify a predominant soil association for each watershed and assign *N* and *P* contents based on similarities to the sampled soils. In most cases, the watershed soils corresponded to one or more of the samples. In other cases, values for geographically nearby associations were used.

The final step was to adjust soil *N* and *P* concentrations to reflect differences between in situ soils and sediment. Nutrient concentrations in the latter are higher than soil values because erosion processes selectively prefer particles that are lighter (such as organic matter) and/or have greater surface areas than the in situ soils. On the basis of the GWLF User's Manual suggestion (Haith et al. 2010), sediment nutrient levels were assumed to be double the soil levels.

Point Sources

Significant *N* and *P* point sources to Cayuga Lake are eight municipal wastewater treatment plants (WWTPs), all of which have biological systems achieving secondary levels of treatment. In addition, several of the plants have advanced treatment for *P* removal. As with weather data, WWTP information is often taken for granted, mainly because of monitoring and reporting required by the National Pollutant Discharge Elimination System (NPDES). The presumption is warranted in the case of discharge volumes and conventional contaminants (such as pH, suspended solids, and biochemical oxygen demand), but nutrient data are often lacking in the NPDES reports. Reports for five of the plants included effluent *P* concentrations, but none provided the appropriate *N* data. In all cases, mean concentrations calculated from the monthly samples were multiplied by daily discharge and 30.5 days to obtain mean monthly *N* and *P* loads. For the three plants with missing *P* concentrations, a mean *P* concentration of 2.5 mg/L for U.S. secondary treatment plants reported in the survey from Stoddard et al. (2003) was used. Similarly, the Stoddard et al. (2003) value of 18.3 mg/L of effluent *N* was used for all eight WWTPs.

Septic Systems

One of the unique features of the GWLF model is that it includes *N* and *P* loads to surface waters from on-site wastewater management systems. Each of these systems is assumed to consist of a septic tank and leaching field, and four types of septic systems are provided for: normal, short-circuited, ponded, and direct discharge.

A normal septic system is a system whose construction and operation conforms to recommended procedures such as those suggested by U.S. EPA design manual for on-site wastewater disposal systems (U.S. EPA 1980). The effluent percolates into the soil and enters the water table. Except for removal by plant uptake, *N* is transported to the stream by groundwater discharge. Phosphorus is adsorbed by the soil and does not reach streams. Short-circuited systems are close enough to surface waters (<15 m) that negligible soil adsorption of *P* takes place. Ponded systems have failed adsorption fields and resulting surfacing of the effluent, which reaches streams in overland flow. The only nutrient removal for both short-circuited and ponded systems is through plant uptake. Direct discharge systems are illegal systems without leach fields that discharge septic tank effluent directly into surface waters with no nutrient removal.

Input data requirements for GWLF on-site wastewater calculations are per capita daily *N* and *P* in domestic wastewater and taken up by plant growth on leaching fields and the watershed populations served by each of the four types of septic systems. Default values for the per capita data are available in the GWLF manual (Haith et al. 2010), but the population numbers must be determined for the modeled watersheds. An appropriate septic system survey was impossible due to the high cost.

Total populations in each watershed served by septic systems were determined through geospatial data analysis. First, the locations of all residential structures were mapped from aerial imagery. The extents of existing sewer services were then determined by digitizing sewer district maps provided by the utilities. All the residential structures not located within the boundaries of the sewer districts were assumed to require on-site wastewater management systems, The number of residents per residential structure and, hence, the number of residences per on-site wastewater management system, were estimated using TIGER/Line Shapefiles from the U.S. Census Bureau for the 2000 census (U.S. Census Bureau 2012).

Apportioning the unsewered populations among the four system types required additional assumptions. Health Department data for six towns in Cayuga County indicated a mean septic system failure rate of 4.2% (Genesee/Finger Lakes Regional Planning Council 2000). There were no comparable data for other Cayuga watershed counties, so the 4.2% failure rate was assumed for all watersheds.

These failures most likely corresponded to the visible ponded category used in GWLF. For the remaining categories, it was assumed that the nonnormal systems would follow a distribution similar to that found in the West Branch Delaware River Watershed (Haith et al. 2010): 10% ponded, 1% short-circuited, and 3% direct discharge. Thus, there are 1/10 as many short-circuited as ponded systems, and 3/10 as many direct discharge as ponded systems. Applying these fractions to the Cayuga Lake systems, 94.1% normal, 4.2% ponded, 0.4% short-circuited, and 1.3% direct discharge values were obtained.

Study Results

Nutrient Loads and Sources

Input data files were prepared and 100-year simulations were run for each of the 34 Cayuga Lake watersheds listed in Table 4 and shown in Fig. 2. Table 4 presents the calculated mean annual *N* and *P* loads to the lake from the watersheds as well as breakdowns of major land uses. Not surprisingly, the largest watersheds (Cayuga Inlet, Fall Creek, and Salmon Creek) provide the major nutrient loads. The watersheds range from highly agricultural [Hicks (81.8%) and McDuffie (82.6%)] to fairly urban [Lansing (45.3%) and Minnegar Creek (48.4%)]. Predominantly forested areas are somewhat rare, although two watersheds, Cascadilla Creek and Six Mile Creek, have more than 60% forest and brush area. Both watersheds are also in the most urbanized section of the basin, at the southern end of Cayuga Lake.

For the purposes of management, it makes sense to focus on the largest contributors to nutrient loads. However, the ranking of loads can be ambiguous. Table 5 lists the relative watershed loads in two ways—as percentages of the total and as unit loads (kg/ha). From this information, it is clear that Cayuga Inlet and Fall Creek are the largest sources of *N* and *P*, respectively. However, in neither case are these watersheds the most intense nutrient contributors, as indicated by unit loads. The Cayuga Inlet unit *N* load (11.1 kg/ha) exceeds the mean for the Cayuga basin (8.3 kg/ha) but is less than several small watersheds [e.g., Lansing (20.6 kg/ha) and Minnegar (13.5 kg/ha)]. The Fall Creek unit *P* load (0.51 kg/ha) is actually less than the basin mean (0.52 kg/ha) even though that watershed is the largest mass contributor (17.3%) of *P* to the lake.

Yet another way to focus management efforts is to examine the relative sources within watersheds. Table 6 shows the breakdown of source categories for the three largest watersheds and the Cayuga basin as a whole. The watershed land uses range from the highly urban and forested Cayuga Inlet to the mostly agricultural Salmon Creek. With respect to *N*, hydrologic sources (runoff, groundwater discharge) are relatively minor in the urbanized watershed but are

Table 4. Major Land Uses and Mean Annual Nutrient Loads from Cayuga Lake Watersheds

Watershed	Area (ha)	Major Land Use: Agriculture (%)	Major Land Use: Forest/Brush (%)	Major Land Use: Urban (%)	Nitrogen load (Mg/year)	Phosphorus load (Mg/year)
1. Barnum Creek area	928	72.2	15.3	10.6	8	0.5
2. Big Hollow area	2,348	69.4	14.7	9.8	21	1.4
3. Bloomer/Mack creeks area	1,824	73.7	16.1	6.7	16	1.1
4. Canoga Creek area	2,777	66.4	10.3	20.1	20	1.5
5. Cascadilla Creek	3,665	21.3	60.8	16.7	14	1.1
6. Cayuga Inlet	24,081	28.9	55.1	14.6	267	12.6
7. Cayuga View area	573	42.9	38.2	17.5	4	0.6
8. Cayuga Village area	680	48.1	22.6	27.8	5	0.3
9. Fall Creek	33,086	48.2	39.7	10.7	244	16.9
10. Glen/Dean creeks area	1,902	73.6	16.4	8.6	18	1.0
11. Glenwood Creek area	2,484	46.5	32.2	19.7	17	1.1
12. Great Gully	3,989	77.2	13.0	5.4	38	2.4
13. Groves/Powell creeks area	1,587	76.1	11.1	10.3	15	1.0
14. Gulf Creek area	1,843	39.7	40.6	18.2	16	0.8
15. Hicks Gully	1,070	81.8	9.3	6.2	9	0.6
16. Interlaken area	6,851	65.8	19.0	11.6	47	3.6
17. King Ferry Station area	4,797	61.6	21.2	10.7	32	2.3
18. Lake Ridge Point area	3,409	46.7	30.9	15.1	25	1.7
19. Lansing Area	3,088	31.3	21.9	45.3	64	2.8
20. Lavanna area	1,507	72.3	16.0	5.9	15	1.3
21. Little Creek area	1,631	70.5	12.8	14.6	16	0.9
22. McDuffie Town area	1,538	82.6	8.3	7.4	14	0.9
23. Minnegar Creek area	766	35.9	13.4	48.4	10	1.0
24. Paines Creek	3,945	73.1	18.9	5.9	39	2.3
25. Red Creek	1,611	72.3	17.6	7.7	14	0.9
26. Salmon Creek	23,375	68.0	22.9	7.4	226	13.3
27. Schuyler Creek area	1,899	72.6	11.6	12.1	18	1.5
28. Sheldrake Creek	2,411	72.9	15.7	8.3	22	1.5
29. Six Mile Creek	13,411	21.1	62.9	15.0	50	4.5
30. Taughannock Creek	17,295	48.1	39.1	11.4	101	7.2
31. Trumansburg Creek	3,501	59.8	24.6	13.8	29	1.7
32. Union Springs area	3,791	72.5	9.2	15.1	42	2.8
33. Willow Creek area	3,052	49.7	34.0	14.6	22	1.4
34. Yawger Creek	6,351	78.7	11.2	6.4	59	3.6
Total	187,066	52.2	33.5	12.2	1556	98

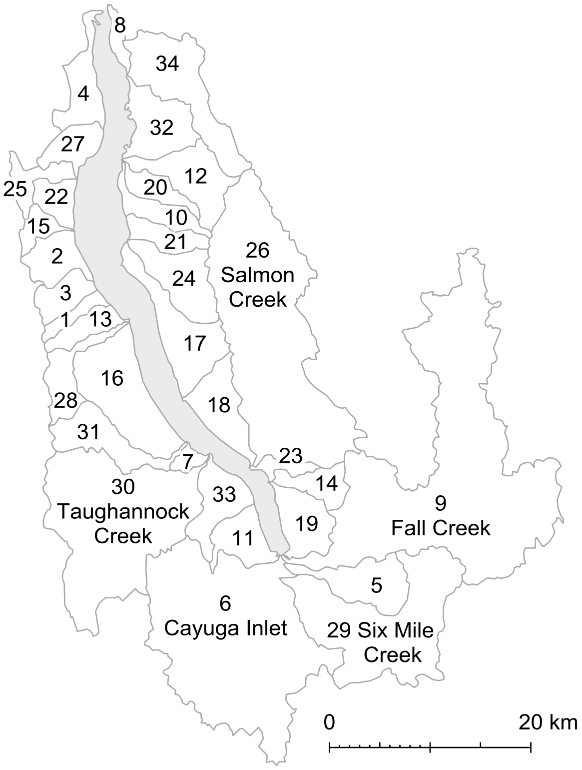

Fig. 2. Cayuga Lake watersheds

much more significant in the two more agricultural watersheds, Fall Creek and Salmon Creek. The high contributions from ground water in those watersheds, 55% and 72%, respectively, pose difficult challenges for management because only long-term changes in land use can reduce these loads. Conversely, runoff dominates *P* loads, and these sources can be managed by reducing runoff and/or soil erosion.

Finally, Table 7 shows the calculated nutrient loads from all 29 runoff sources, groundwater discharge, point sources, and septic systems for the entire Cayuga Basin. Disturbed land is the most intense source of *N* (35.7 kg/ha-yr) and *P* (14.3 kg/ha). Runoff sources predominate for *P*, but not for *N*. Runoff from three agricultural sources, corn, hay and small grain and soybeans runoff contributes over 40% of the total *P* load to Cayuga Lake. Two additional runoff sources, disturbed land (such as construction and mining sites) and high density residential land account for an additional 13.4% of *P*. Wastewater sources contribute 9.5% of the total *P* load.

Comparisons with Historic Monitoring Data

As described previously, historic nutrient monitoring load data were available for the lake as a whole for 1970–71 (Likens 1974a, b) and for Fall Creek, the largest watershed, in 1972–74 (Johnson et al. 1976) and 1972–95 (Bauters and Eckhardt 2001). These loads were compared with the long-term annual means generated from the GWLF model runs.

Table 5. Relative Mean Annual Nutrient Loads from Cayuga Lake Watersheds

	Nitrogen load		Phosphorus load	
Watershed	(%)	(kg/ha)	(%)	(kg/ha)
1. Barnum Creek area	0.5	9.1	0.5	0.57
2. Big Hollow area	1.3	8.7	1.4	0.60
3. Bloomer/Mack creeks area	1.0	8.8	1.1	0.60
4. Canoga Creek area	1.3	7.2	1.5	0.54
5. Cascadilla Creek	0.9	3.9	1.1	0.30
6. Cayuga Inlet	17.2	11.1	12.9	0.52
7. Cayuga View area	0.3	7.7	0.6	0.96
8. Cayuga Village area	0.3	6.7	0.3	0.44
9. Fall Creek	15.7	7.4	17.3	0.51
10. Glen/Dean creeks area	1.1	9.3	1.0	0.54
11. Glenwood Creek area	1.1	6.9	1.1	0.43
12. Great Gully	2.4	9.4	2.4	0.59
13. Groves/Powell creeks area	1.0	9.3	1.0	0.63
14. Gulf Creek area	1.0	8.7	0.8	0.42
15. Hicks Gully	0.6	8.7	0.6	0.58
16. Interlaken area	3.0	6.8	3.7	0.53
17. King Ferry Station area	2.1	6.7	2.3	0.48
18. Lake Ridge Point area	1.6	7.4	1.7	0.50
19. Lansing area	4.1	20.6	2.9	0.91
20. Lavanna area	1.0	9.9	1.3	0.86
21. Little Creek area	1.0	9.8	1.0	0.57
22. McDuffie Town area	0.9	9.3	1.0	0.61
23. Minnegar Creek area	0.7	13.5	1.0	1.24
24. Paines Creek	2.5	9.9	2.4	0.59
25. Red Creek	0.9	8.6	0.9	0.55
26. Salmon Creek	14.5	9.7	13.6	0.57
27. Schuyler Creek area	1.2	9.6	1.5	0.77
28. Sheldrake Creek	1.4	9.0	1.5	0.61
29. Six Mile Creek	3.2	3.7	4.5	0.33
30. Taughannock Creek	6.5	5.8	7.3	0.41
31. Trumansburg Creek	1.8	8.2	1.7	0.47
32. Union Springs area	2.7	11.2	2.9	0.74
33. Willow Creek area	1.4	7.1	1.4	0.46
34. Yawger Creek	3.8	9.3	3.7	0.57
Total	100.0	8.3	100.0	0.52

It is difficult to compare historic and current Cayuga basin land use distributions due to differences in categories. Likens (1974a)'s reported Cayuga basin land uses of 48% active agriculture and 31% forested are similar to the current values of 52% and 34% for agriculture and forest and brush, respectively. However, the earlier data included 16% abandoned or inactive agricultural and 2% residential lands but no urban category, which currently constitutes 12% of the basin.

Hydrologic conditions during the 1970–71 monitoring appear to have been very similar to those obtained in the simulations. Tributary flows into the lake during the year of monitoring were 43.6 cm/year, very close to the mean watershed value of 42.9 cm/year from model runs. Precipitation values were also quite similar at 96.5 and 94.7 cm/year for 1970–71 and the 100-year mean, respectively. However, the 76.1 cm/year Salmon Creek streamflow reported by Likens appears to be an error. Although there is no permanent flow gauge in Salmon Creek, the USGS did measure flows for the four year period 1965–68 (USGS 2012): 15.8, 36.3, 32.4, and 44.4 cm for these four years. Annual precipitation for these same years, as measured at Cortland, NY, was 86.1, 103.1, 100.3, and 119.4 cm. For the August 1970 through July 1971 monitoring period, Cortland, NY, precipitation was 112.8 cm. Based on these data, the reported August 1970 through July 1971 streamflow of 76.1 cm is highly improbable.

The error in the Salmon Creek streamflow is compounded because flows for the unmonitored areas were extrapolated from Salmon Creek values. As a result, the reported loads for a total area of 68,600 ha, or 37% of the Cayuga Lake watershed, appear to have been greatly overestimated. On the basis of historic records, the watershed mean annual streamflow of 43.6 cm is a more realistic estimate of Salmon Creek streamflow for the monitoring period.

Table 6. Relative Sources of Mean Annual Streamflow Nutrient Loads in the Cayuga Lake Watershed and Three Largest Watersheds

Land use/source	Cayuga Lake Basin (%)	Cayuga Inlet (%)	Fall Creek (%)	Salmon Creek (%)
Areas				
Agriculture	52	29	48	68
Forest and brush	33	55	40	23
Other rural	2	0	0	1
Urban	12	15	11	7
Total Nitrogen				
Runoff				
Agriculture	15	6	16	17
Forest and brush	1	1	1	0
Other rural	1	1	1	1
Urban	6	6	6	3
Groundwater discharge	51	12	55	72
Point sources	15	61	4	0
Septic systems	12	14	17	7
Total	100	100	100	100
Total Phosphorus				
Runoff				
Agriculture	47	27	50	53
Forest and brush	3	4	2	1
Other rural	6	11	6	4
Urban	12	15	10	7
Groundwater discharge	23	9	21	35
Point sources	7	29	9	0
Septic systems	2	4	3	2
Total	100	100	100	100

Table 7. Relative Mean Annual Nutrient Loads from Cayuga Lake Sources

	Nitrogen load		Phosphorus load	
Land use/source	(kg/ha)	(%)	(kg/ha)	(%)
Runoff Sources				
Corn	4.1	4.9	1.0	19.7
Hay and small grain	2.7	5.0	0.6	16.9
Soybeans	6.1	0.8	1.9	4.1
Alfalfa	2.0	1.5	0.2	2.1
Pasture and grass	1.0	1.8	0.1	3.1
Other crops	0.8	0.3	0.1	0.5
Orchards and vineyards	1.7	0.0	0.2	0.1
Farmstead	5.2	0.4	0.6	0.6
Inactive agriculture	0.4	0.1	0.0	0.1
Tree farms	0.8	0.0	0.2	0.1
Brush	0.3	0.2	0.0	0.4
Deciduous forest	0.1	0.2	0.0	0.7
Conifer forest	0.3	0.1	0.1	0.7
Mixed forest	0.1	0.1	0.0	0.6
Disturbed land	35.7	0.9	14.3	5.5
Industrial—pervious	0.3	0.0	0.0	0.0
Industrial—impervious	17.3	0.4	1.9	0.8
Commercial—pervious	0.1	0.0	0.0	0.0
Commercial—impervious	17.2	0.7	1.9	1.3
Institutional—pervious	0.2	0.0	0.0	0.0
Institutional—impervious	9.4	0.2	1.1	0.4
Outdoor recreation—pervious	0.2	0.0	0.0	0.0
Outdoor recreation—impervious	12.2	0.1	1.3	0.1
High-density residential—pervious	0.8	0.3	0.1	0.7
High-density residential—impervious	15.3	3.8	1.9	7.5
Medium-density residential—pervious	0.3	0.0	0.0	0.1
Medium-density residential—impervious	15.3	0.3	1.8	0.5
Low-density residential—pervious	0.2	0.1	0.0	0.2
Low-density residential—impervious	7.6	0.6	0.8	0.9
Total runoff				
Agriculture	2.4	14.7	0.5	47.0
Forest and brush	0.2	0.7	0.0	2.5
Other rural	5.0	0.9	1.9	5.5
Urban	4.4	6.5	0.5	12.5
Groundwater discharge		50.7		22.9
Point sources		14.7		7.2
Septic systems		11.8		2.3
Total		100.0		100.0

Loads for Salmon Creek and the unmonitored area were recomputed using the 43.6 cm streamflow, and they are compared with simulation results in Table 8 for the monitored nutrients: dissolved nitrogen (DN), dissolved phosphorus (DP) and total phosphorus (TP).

For the lake as a whole, historic monitored nutrient loads are somewhat higher, particularly for DN, which is almost 15% larger than the 100-year model mean. TP loads are similar, with monitored loads 6% larger than 100-year means. Ratios of DP to TP are about the same for the two cases, 59% for GWLF loads and 64% for monitored loads. The somewhat larger DP and TP loads in 1970–71 are most likely attributable to municipal wastewater treatment practices. The largest plants currently have phosphorus removal processes that would have been unlikely in the 1970s. For the individual watersheds, 1970–71 monitoring and the GWLF 100-year means are relatively close for Fall, Taughannock, and Trumansburg creeks. The largest differences are visible in Cayuga Inlet DN. This may be due to inaccuracies in this experiment's estimates of the Ithaca Wastewater Treatment Plant performance. As described previously, the plant’s NPDES permit did not include complete effluent DN information (no NO_3 data were provided), and a value acquired from the literature of 18.3 mg/L for effluent *N* was used.

Additional Fall Creek event-based monitoring of DP and TP covered the 20-month period of September 1972 through April 1974. Most of the spring runoff was captured for both years, so the 20-month load was divided by two to approximate annual means. Event-based DN load data covered the 24-year period through 1995. Monitored and simulated loads are compared in Table 9. The modeled TP values were similar to what was observed from the 1970–71 monitoring. The major discrepancy is with the relative magnitudes of DP and TP. With the 1972–74 monitoring, only 25% of the TP is in dissolved form, whereas the GWLF means indicate a 59% dissolved portion. The differences may be due to the way that wastewater phosphorus is modeled in GWLF. Wastewater DP is assumed to remain dissolved as it is transported in streamflow to the watershed outlet. In reality, much of this DP may subsequently be adsorbed by sediment, particularly during storm events. The Fall Creek sampling station is several kilometers downstream of the two wastewater treatment plant discharges and there would be ample opportunity for adsorption. The most dramatic comparison is for DN. The long-term annual means calculated by GWLF simulations and measured from monitoring are almost identical. Because these DN monitored loads are based on event sampling and also cover many years, they provide strong evidence that the GWLF model results are reasonable approximations of actual nutrient loads.

Unambiguous conclusions regarding model accuracy cannot be drawn from these comparisons with monitoring data. Given the divergent times and averaging periods, it cannot be said that the model has been adequately corroborated. Nevertheless, neither is any great evidence of error observed. Modeled and measured nutrient loads are of similar magnitudes and differences can, to

Table 8. Comparison of GWLF Simulation Results with 1970–71 Monitoring

Watershed	Dissolved nitrogen (Mg/year) GWLF 100-year mean	Dissolved nitrogen (Mg/year) Likens (1970–71)	Dissolved phosphorus (Mg/year) GWLF 100-year mean	Dissolved phosphorus (Mg/year) Likens (1970–71)	Total phosphorus (Mg/year) GWLF 100-year mean	Total phosphorus (Mg/year) Likens (1970–71)
Combined Cayuga Inlet[a]	291	197	9.5	26.5	18.2	34.2
Fall Creek	219	256	10.2	9.9	16.9	20.7
Salmon Creek	209	282	7.9	5.3	13.3	10.0
Taughannock Creek	88	97	4.3	3.4	7.2	5.1
Trumansburg Creek	26	22	1.2	3.2	1.7	3.9
Cayuga Lake	1,391	1,595	58	67	98	104

[a] Includes Cayuga Inlet, Cascadilla Creek, and Six Mile Creek.

Table 9. Comparison of GWLF Fall Creek Simulation Results with Monitoring Data

Study	Dissolved nitrogen (Mg/year)	Dissolved phosphorus (Mg/year)	Total phosphorus (Mg/year)
GWLF simulation 100-year annual mean	219	10.2	16.9
Bauters and and Eckhardt (2001) monitoring 24-year annual mean (1972–1995)	225	—	—
Johnson et al. (1976) monitoring September 1972 through April 1974	—	5.5	21.5

a degree, be explained by improved wastewater treatment and erosion control as well as reduced reliance on winter manure spreading compared with the 1970s.

Conclusions

With the persistence of a small NGO, modest but timely funding from the U.S. Department of Agriculture, and the industry of students and volunteers, the first complete inventories of the nitrogen and phosphorus sources, including runoff, groundwater, wastewater treatment plants, and septic systems for the 1,871 km^2 Cayuga Lake drainage basin have been obtained. Hydrology, including precipitation, runoff, evapotranspiration, groundwater discharge, and streamflow, were also determined, as were soil erosion rates and sediment loads. A geospatial database providing complete descriptions of the land uses, cover, soils, topography, and on-site wastewater systems for the basin was also created. Detailed descriptions of the GWLF modeling study, including data input and output files for each watershed, are contained in a final report, which is available from the corresponding author (Haith et al. 2009).

Although resources were very limited for the modeling of 34 different watersheds, significant cost savings were achieved through project decisions. Chief among these were selection of a watershed model that did not require calibration and use of historic water quality monitoring data for partial testing of the model. Savings were also obtained by extrapolating soil properties from related information (nutrient contents from organic matter), substituting literature concentrations for missing point source data, extrapolating septic system performance from one area to another, and use of synthetic weather data generated from a model.

Based on study results, mean annual TN load to Cayuga Lake is over 1,550 Mg/year, of which 1,390 Mg/year is DN. The largest portion (51%) of the TN comes from groundwater, and the second largest source (26%) is wastewater, both from sewage treatment plants (14%) and septic systems (12%). Agricultural runoff and urban runoff contribute 15% and 7%, respectively. On a per hectare basis, runoff from corn and soybeans, at 4 and 6 kg/ha-year, respectively, are the most intensive cropland sources of TN.

Mean annual TP load to Cayuga Lake is just under 100 Mg/year, of which 60 Mg/year is DP. The largest source of both DP and TP is agricultural runoff, providing 45% of the DP and 47% of the TP. Much of the latter (36% out of the 47%) comes from corn, hay, and small grains, which together make up 26% of the watershed area. Urban runoff provides 13% of the TP but negligible DP. The largest urban TP source, at 8%, is high-density impervious residential land. Groundwater discharge is an important source of DP (39%), but it is less significant for TP (23%). Wastewater provides 16% of the DP and 10% of TP.

Although this study demonstrates that watershed modeling can be undertaken with much less than ideal information, this does not mean that additional data would not be useful. With additional time and money, model credibility could be improved with up-to-date event sampling in several of the major watersheds, particularly Fall Creek and Salmon Creek. Given the importance of agricultural runoff sources, the largely anecdotal description of manure management and erosion control practices could be replaced by information from well-designed surveys. Similarly, measurements of the *N* contents of WWTP discharges might resolve the uncertainties regarding *N* loads in Cayuga Inlet. Hopefully, these and other improvements might be part of future investigations of this major New York watershed.

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