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MODELING THE HYDROCHEMISTRY OF THE CANNONSVILLE WATERSHED WITH GENERALIZED WATERSHED LOADING FUNCTIONS (GWLF)[1]

Elliot M. Schneiderman, Donald C. Pierson, David G. Lounsbury, and Mark S. Zion[2]

ABSTRACT: A previous modeling study used the Generalized Watershed Loading Functions (GWLF) model to simulate streamflow, and nutrient and sediment loads to Cannonsville Reservoir from the West Branch Delaware River (WBDR). We made several model revisions, calibrated key parameters, and tested the original GWLF model and a revised GWLF model using more recent data. Model revisions included: addition of unsaturated leakage between unsaturated and saturated subsurface reservoirs; revised timing of sediment export; inclusion of urban sediments and dissolved nutrients; tracking of particulate nutrients from point sources; and revised timing of septic system loads. The revision of sediment yield timing resulted in significant improvements in monthly sediment and particulate phosphorus predictions as compared to the original model. Addition of unsaturated leakage improved hydrologic predictions during low flow months. The other model changes improve realism without adding significant model complexity or data requirements. Goodness of fit of revised model predictions versus stream measurements, as measured by the Nash-Sutcliff coefficient of model efficiency, exceeded 0.8 for streamflow – 0.7 for sediment yield and dissolved nitrogen (N) and 0.6 for particulate and dissolved phosphorus (P). The revised GWLF model, with limited calibration, provides reasonable estimates of monthly streamflow, and nutrient and sediment loads in the Cannonsville watershed.
(KEY TERMS: modeling; nonpoint source pollution; GWLF; GIS; calibration; verification.)

INTRODUCTION

Excessive nutrient loading is the primary cause of eutrophication of freshwater lakes and reservoirs. Eutrophication of drinking water supply reservoirs impairs use due to taste and odor problems and generation of disinfection byproduct (DBP) precursors. Identifying nutrient sources and characterizing the timing of nutrient loading is essential for developing effective watershed management strategies to control eutrophication. The present requirements for developing total maximum daily load (TMDL) estimates in a timely manner and within budgetary constraints suggest that watershed modeling based on readily available data should be used to support these management decisions. In this paper we present a case study of nutrient modeling and demonstrate the effects of calibration on model performance.

The Cannonsville Reservoir of the New York City water supply, located about 100 miles northwest of New York City in the Catskill Mountains, exhibits eutrophy in most years and upper mesotrophy in other years (Effler and Bader, 1998). Eutrophication in Cannonsville Reservoir appears to be controlled by the seasonal timing of nutrient loading as well as by the overall magnitude of loads to the reservoir (Doerr *et al.,* 1998, Owens *et al.,* 1998). Cannonsville Reservoir watershed has significant agricultural land use and four incorporated villages served by sewage treatment plants. The New York City Department of Environmental Protection (NYCDEP), in cooperation with federal, state, and local governmental and environmental agencies and stakeholders, is implementing watershed management to control nutrients from nonpoint and point sources in Cannonsville and other water supply reservoir watersheds. Watershed management programs to control nutrient loads include whole farm planning, stormwater retrofitting, wastewater treatment plant (WWTP) upgrades, septic rehabilitation and replacement, and land acquisition of sensitive areas. Identifying nutrient sources and

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[2]Respectively, Research Scientist, New York City Department of Environmental Protection, 71 Smith Avenue, Kingston, New York 12401; Research Scientist, Department of Limnology, Uppsala University, Norbyvagen 20, Se 752 36 Uppsala, Sweden; and GIS Specialist and Research Scientist, New York City Department of Environmental Protection, 71 Smith Avenue, Kingston, New York 12401 (E-Mail/ Schneiderman: eschneiderman@dep.nyc.gov).

characterizing the timing of nutrient loading is essential for developing effective watershed management strategies to control eutrophication.

Watershed simulation modeling is useful for characterizing the magnitude and timing of nutrient export from a watershed. GWLF (Haith and Shoemaker, 1987; Haith *et al.,* 1992) is a lumped parameter watershed model that simulates monthly nutrient and sediment loads from nonpoint sources. GWLF was developed in the 1980s as an "engineering compromise between the empiricism of export coefficients and the complexity of chemical simulation models" (Haith and Shoemaker, 1987). The U.S. Environmental Protection Agency (USEPA) characterizes GWLF as a "mid-range" model in its compendium of tools for watershed assessment and TMDL development (USEPA, 1997), and plans to incorporate it into the BASINS Watershed Assessment Tools (http://www.crwr.utexas.edu/gis/gishydro99/epabasins/basins/sld062.htm). The model originally was applied and tested on the West Branch Delaware River at Walton, New York, the main tributary to the Cannonsville Reservoir of the New York City water supply (Haith and Shoemaker, 1987). It has also been applied to the Hudson River Basin in New York (Howarth *et al.,* 1991) and the Choptank River Basin, Maryland (Lee *et al.,* 2000).

The original application and testing of GWLF in Cannonsville Watershed (Haith and Shoemaker, 1987) demonstrated that the GWLF model could simulate monthly nutrient and sediment loads reasonably well, based on land uses and stream monitoring in the early 1980s. Since then, land use, soils, and topography data for Cannonsville Watershed have been updated in a Geographic Information System (GIS), and more current stream monitoring data for the West Branch Delaware River have been collected. This paper revisits the use of GWLF in the Cannonsville watershed. Using more recent land use and stream monitoring data, we reapplied and tested the original GWLF model. We then made several model revisions and calibrated and tested a revised GWLF model. Simulation results using the revised model are compared to simulations using the original model.

STUDY AREA

The West Branch of the Delaware River (WBDR) draining into Cannonsville Reservoir at Beerston is located in Delaware County, New York, in the Catskill Mountains (Figure 1). The WBDR upstream of Beerston is 80 km long and flows to the southwest, draining an area of 912 km^2. Elevations in the watershed range from 353 m to 1,019 m above mean sea level. Tributaries enter the river from both north and south, with tributary valley slopes typically ranging between 5 and 20 degrees. In general, the soils in the upland tributary valleys are shallow glacial tills that overlie a fragipan or bedrock, with hydrologic soil groups C and D predominating. Soils in the WBDR floodplain are somewhat deeper and well drained.

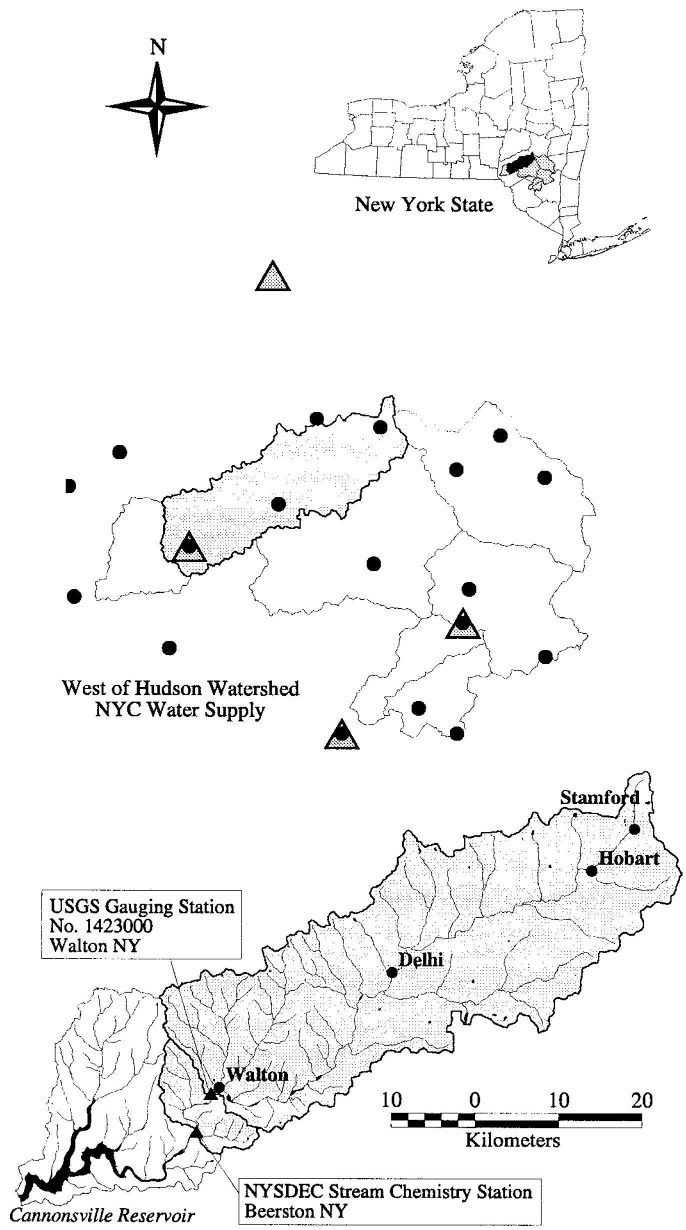


Figure 1. Upper: Position of the Beerston and Walton Drainage Areas Within the West of Hudson Watershed of the NYC Water Supply and Within NYS. Middle: Position of the Beerston and Walton Drainage Areas Within the West of Hudson Watershed of the NYC Water Supply and Showing Precipitation (circles) and Temperature (triangles) Monitoring Stations. Bottom: The Beerston and Walton Drainage Areas. (Circles indicate incorporated villages having wastewater treatment plants.)

Average annual precipitation at Walton, New York, is 107 cm/yr (Slack *et al.,* 1993). Long term average stream discharge at Walton is 16.4 m^3/sec (60.1 cm/yr, USGS, 1997). Average WBDR loads at Beerston of suspended sediment, particulate phosphorus (P), dissolved P, and dissolved nitrogen (N) (NO_x + NH_4) are 21,121 * 10^3 kg/yr, 33.9 * 10^3 kg/yr, 19.5 * 10^3 kg/yr, and 381 * 10^3 kg/yr, respectively, based on monitoring data from water years 1980 to 1982 and 1992 to 1996 (Longabucco and Rafferty, 1998).

Land use in the WBDR watershed is 70 percent forest, 28 percent active agriculture,1 percent built-up area, and 1 percent waterbodies. Agricultural land use is primarily dairy farming. An estimated permanent population of 16,338 people in the watershed increases to 19,739 during the summer months (NYCDEP, 1993). Forty-nine percent of the permanent population lives in the four incorporated villages of Walton, Stamford, Delhi, and Hobart. These villages are served by municipal WWTPs that discharge into WBDR, at an average total wastewater discharge of 1.9 MGD, based on WWTP effluent sampling by NYSDEC (Longabucco and Rafferty, 1998) and by NYCDEP (unpublished data, C. R. Cutietta-Olsen, 1997, NYCDEP, New York, New York). Landuse, soil drainage, human population, and WWTP characteristics for WBDR are given in Table 1.

METHODS

GWLF Model

A QuickBasic version of the GWLF model was obtained from D. Haith of Cornell University (GWLF version 2.0). This version was used for the simulations of the original model. To facilitate calibration and development of the revised model, the original QuickBasic version was rebuilt as an object oriented dynamic simulation program, using the Vensim Visual Modeling environment (Ventana Systems Inc., 1999). Vensim models are built on the computer screen as visual structures consisting of interconnected objects. The completed visual structure becomes the user interface for running the model, reviewing equations and relationships among variables, and viewing parameter values, model inputs, and model results as graphs or tables. In the Vensim GWLF model (Figure 2), all variables that are input or calculated in the model are stored at each time step and can be accessed as graphs or tables. Vensim also has built-in optimization, sensitivity, and statistical functions to facilitate model calibration and verification. Object oriented visual model programming greatly facilitates model development and application, and its use is becoming more widespread in environmental applications (Cassell *et al.,* 1998). The rebuilt model was tested to ensure results numerically equivalent to those of the original QuickBasic program.

TABLE 1. Land Use, Population, Point Sources, and Soils in WBDR Watershed.

Feature	Unit	WBDR
Land Use	km^2	912
forest_deciduous	%	50.30
forest_coniferous		6.26
grass_shrub		13.05
grass		26.63
corn		1.44
alfalfa		0.06
barnyard		0.04
res imperv		0.17
res perv		0.33
comm-indust imperv		0.13
comm-indust perv		0.04
road_rural		0.65
water		0.90
Soil Drainage		
A	%	4
B		6
C		68
D		22
Human Population		
Total permanent	#	16338
Total seasonal		19739
Unsewered permanent		8352
Unsewered seasonal		11425
WWTP		
	#	4
	MGD	1.9

The original GWLF model simulates a daily hydrologic water balance and monthly nutrient and sediment loads for a watershed. The hydrologic water balance estimates surface runoff from different land uses and sub-surface flows, driven by daily precipitation and air temperature. Surface runoff is estimated using the SCS Curve Number method, while sub-surface flows are based on a simple ground water flow model.

Dissolved nutrient loads (nitrogen-N, phosphorus-P) from each land use are calculated as the product of modeled surface runoff and an empirically derived nutrient concentration for each land use. Dissolved nutrient loads in subsurface flows are lumped for the watershed and calculated as the product of watershed subsurface flow and a watershed average nutrient

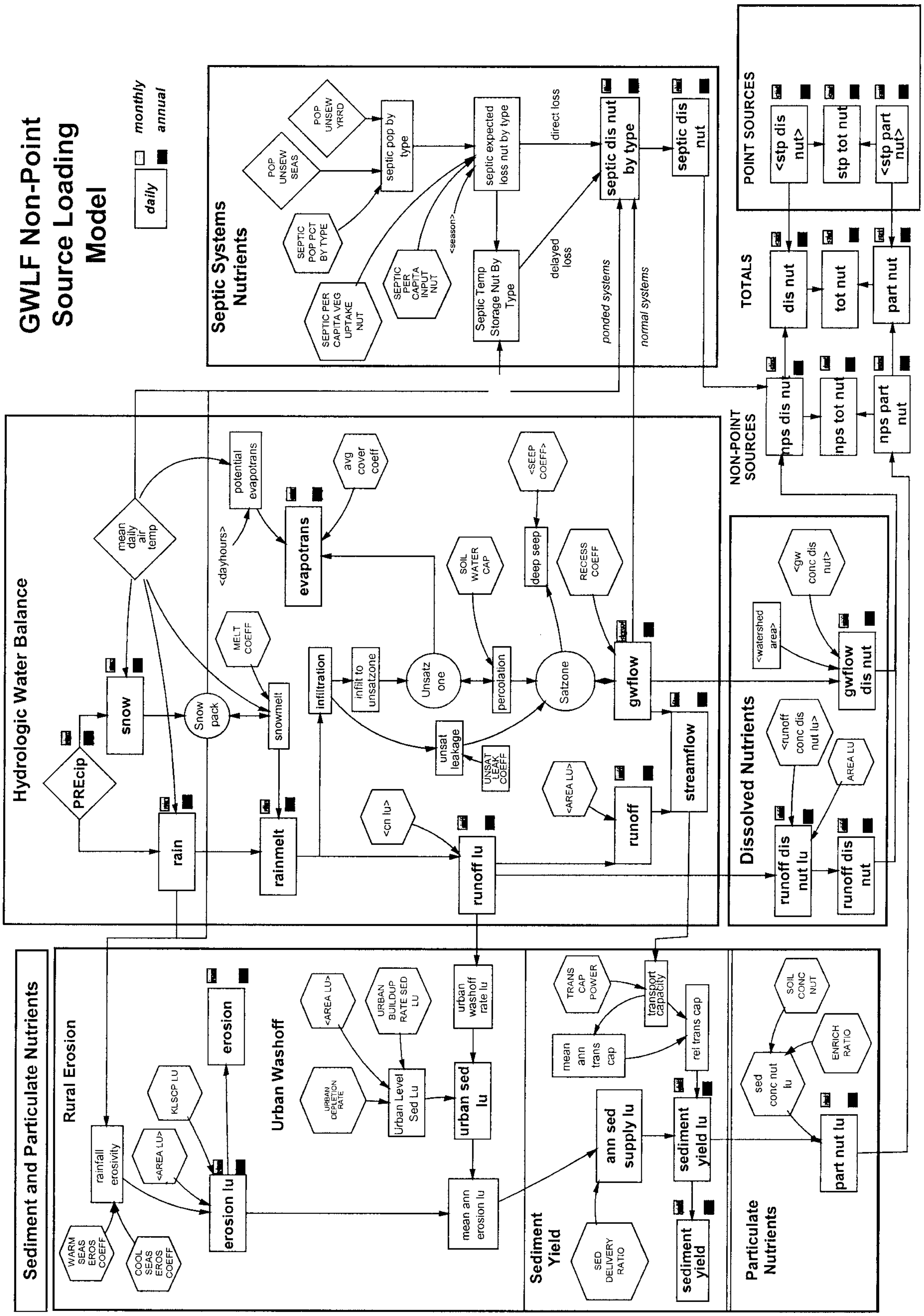


Figure 2. Vensim GWLF Model.

concentration. Dissolved nutrients from septic systems are based on estimates of unsewered population size, septic field inputs, vegetative uptake, and septic system failure rates. Sediment yield estimates are based on erosion from different land uses, calculated using the Universal Soil Loss Equation (USLE) and a sediment delivery ratio. The timing of sediment export is determined by runoff transport capacity, estimated as a power function of runoff. Particulate nutrient loads are calculated as the product of sediment yield, an empirically derived watershed wide soil nutrient concentration, and an enrichment ratio. Point source nutrient loading estimates are added to the simulated nonpoint source loads to provide estimates of total loads from the watershed. The reader is referred to the original references for a detailed model description and equations (Haith and Shoemaker, 1987; Haith *et al.,* 1992).

The revised GWLF model created in Vensim has five modifications of the original GWLF model: (a) the subsurface hydrology module was modified to allow unsaturated zone leakage due to macropores; (b) the sediment yield timing module was modified to permit carryover of transportable sediment from previous years; (c) urban loading functions were modified to permit calculation of sediment loads and dissolved nutrient loads from urban areas; (d) the point source calculations were modified to permit particulate nutrients from point sources; and (e) the septic system module was modified to permit seasonal variation in septic system failure rates and to refine the timing of septic system nitrogen export from the watershed.

(a) Unsaturated Zone Leakage. Leakage (*unsat leakage*) of *infiltration* water through the unsaturated zone (*unsatzone*) to the saturated zone (*satzone*) via macropores when *unsatzone* is below field capacity was added to the model by allowing a fraction (*unsat leak coeff*) of *infiltration* to bypass the *unsatzone* and be added to the *satzone*.

$$unsat\ leakage_t = unsat\ leak\ coeff * infiltration_t \quad (1)$$

$$unsatzone_{t+1} = unsatzone_t + infiltration_t - unsat\ leakage_t - evapotrans_t - percolation_t \quad (2)$$

$$satzone_{t+1} = satzone_t + percolation_t + unsat\ leakage_t - gwflow_t - deep\ seep_t \quad (3)$$

These equations are the same as in Haith *et al.* (1992; Equations A-27 and A-28), with the addition of *unsat leakage* and the *unsat leakage coeff*. The *unsat leak coeff* is calibrated, as described later.

(b) Sediment Yield Timing. In the original model, an annual sediment supply is calculated for a "sediment year" beginning in April and ending in March, as a fixed fraction – the sediment delivery ratio – of the sum of erosion generated during the sediment year. The sediment delivery ratio is empirically determined from annual export studies. The timing of sediment release from the basin during the sediment year is a function of the transport capacity of runoff. It is assumed that by the end of the sediment year, the supply of available sediment is exhausted; there is no carryover of sediment supply from one year to the next. The original model equations are given in Haith *et al.* (1992; Equations A-11 through A-16).

A shortcoming of the original model formulation is that an artificial discontinuity can occur at the sediment year boundary since there is no carry over of sediment supply from one year to the next. The sediment transport equations were modified to remove the sediment year boundary by expanding the annual window for sediment calculations and by representing sediment supply as a long term average. The new formulation is based on two well established empirical relationships. The first basic empirical relationship is the expression of long term average annual sediment yield from a watershed ($\bar{Y}_{ann}$) as a fraction (the sediment delivery ratio, SDR) of long term average annual erosion ($\bar{E}_{ann}$) in the watershed (Wischmeier and Smith, 1978)

$$\bar{Y}_{ann} = \bar{E}_{ann} \cdot SDR \quad (4)$$

$\bar{E}_{ann}$ is calculated as the average annual erosion summed over all land uses

$$\bar{E}_{ann} = \sum_{l} \frac{\sum_{t=1}^{n} X_{it}}{n} \cdot 365.25 \text{ days / yr} \quad (5)$$

where X_{lt} is the erosion from land use l on day t as calculated by Equation (A-11) and (A-12) in Haith *et al.* (1992), and n is the number of days over which the calculation is made. $\bar{E}_{ann}$ is calculated over a long term multi-year period.

The second basic empirical relationship is the expression of daily sediment yield (Y_t) as a power function of streamflow (Shen and Julien, 1993)

$$Y_t = k \cdot TC_t \quad (6)$$

where TC_t , the daily transport capacity of the stream, is calculated as *streamflow* (Q) to a power (tcp)

$$TC_t = Q_t^{\mathrm{tcp}} \tag{7}$$

The exponent *tcp* (trans cap power) has a default value of 1.67, as given by Haith (1985) and attributable to Vanoni (1975). We calibrated this parameter, as described later.

Equation (7) expressed in terms of long term annual averages is

$$\bar{Y}_{ann} = k \cdot \overline{TC}_{ann} \tag{8}$$

$\overline{TC}_{ann}$ is calculated as the average annual transport capacity over a long term multi-year period as

$$\overline{TC}_{ann} = \frac{\sum_{t=1}^{n} TC_t}{n} \cdot 365.25 \text{ days / yr} \tag{9}$$

Combining Equations (4) and (8) and solving for k results in

$$k = \overline{E}_{ann} \cdot SDR \cdot \frac{1}{\overline{TC}_{ann}} \tag{10}$$

The final equation for calculating daily sediment yield (Y_t) is derived by substituting k from Equation (10) into Equation (6)

$$Y_t = \overline{E}_{ann} \cdot SDR \cdot \frac{TC_t}{\overline{TC}_{ann}} \tag{11}$$

Equations (5), (7), (9), and (11) replace Equations (A-13) through (A-16) in Haith *et al.* (1992).

The revised model formulation was tested with long-term (25 year) simulations, and it was verified that a mass balance of sediment supply and sediment yield is preserved. For any particular year, the sediment yield may exceed or be less than the average annual sediment supply, depending on whether the annual transport capacity for the particular year exceeds or is less than the average annual transport capacity. The revised formulation is very similar to the original formulation that also is essentially based on Equations (4) and (6). Our purpose in making the model revision was to preserve these empirical relationships as the basis for sediment yield calculations while removing the boundary associated with the sediment year in the original model. The final design criteria for accepting the model revision over the original formulation was that the performance of the revised model was a significant improvement over the original model.

(c) Urban Loading Functions. The original GWLF model assumes that all nutrient loads from urban land uses are in particulate form. It calculates particulate loads without calculating the sediment load associated with the particulate nutrients. We added dissolved nutrient and sediment loading from urban land uses to the model. This did not involve adding new equations to the model but expanding the application of existing equations to include urban land uses. For dissolved nutrients, we used the equations for rural land use dissolved nutrient loads (Equation A-3 in Haith *et al.,* 1992) that calculate load as the product of surface runoff and an average dissolved nutrient concentration for each land use. For sediment loading from urban land uses, we use the accumulation and washoff functions given for nutrients in the original model (Equations A-17 through A-25 in Haith *et al.,* 1992), substituting sediment accumulation rates given in Haith *et al.* (1992) for particulate nutrient accumulation rates. The resultant urban sediment load (*urban sed lu*) is included in the erosion estimates from different land uses in Equation (5) above.

(d) Point Source Particulate Nutrients. The original GWLF model includes a function to input dissolved nutrient loads from point sources that are added to the nonpoint source dissolved loads. We modified this function to allow input of particulate nutrient loads from point sources. Particulate nutrients discharged to streams from point sources (*wwtp part nut discharged*) are not released from the basin instantaneously, but rather are time released as a function of stream *transport capacity*. This timing is treated the way nonpoint source sediments (Equation 11 above) are treated in the model.

$$wwtp\ part\ nut_t = \overline{wwtp\ part\ nut\ discharged}_{ann} \cdot \frac{TC_t}{\overline{TC}_{ann}} \tag{12}$$

where $\overline{wwtp\ part\ nut\ discharged}_{ann}$ is the long term average annual particulate load discharged to streams from WWTPs in the watershed.

(e) Septic Systems. The original GWLF model applies constant failure rates for failing septic systems. Professional judgment of NYCDEP engineers based on observations of failing septic systems suggests that systems that fail due to surface ponding of effluent (ponded systems) typically do not fail throughout the entire year but primarily during wet seasons. The septic system module was modified so that ponded systems only fail during predefined wet seasons. For the Cannonsville watershed the wet season was defined as April 1 through June 15 and September 15 through November 15. During other times, the ponded systems are considered to effectively function as normal systems.

The septic system module also was modified to revise the timing of release of dissolved N from normal septic systems at the basin outlet. In the original model, an annual dissolved N load from normal septic systems is calculated for each "GWLF year" beginning in April and ending in March. The portion of the annual load released during each month of the GWLF year is equivalent to the portion of annual ground water discharge for that GWLF year which occurs in that month (Equation A-37, Haith *et al.,* 1992). This formulation elicits the same artificial discontinuity at the GWLF year boundary as was previously discussed for sediment supply calculations. The normal septic system equations were modified to remove the GWLF year boundary by expanding the annual window and by representing annual dissolved N load from normal septic systems as a long-term average. Daily release of dissolved N from normal septic systems (*normal septic dis* N_t) is calculated as

$$normal\ septic\ dis\ N_t = \overline{normal\ septic\ dis\ N_{ann}} \cdot \frac{gwflow_t}{\overline{gwflow_{ann}}} \qquad (13)$$

where $gwflow_t$ is the ground water discharge on day t, $\overline{gwflow_{ann}}$ is the long term average annual ground water discharge, and $\overline{normal\ septic\ dis\ N_{ann}}$ is the long term average annual dissolved N load from normal septic systems.

The revised model formulation was tested with long term (25 year) simulations, and it was verified that a mass balance of dissolved N loading from normal septic systems was preserved. For any particular year, the normal septic dissolved N load may exceed or be less than the average annual dissolved N load from normal septic systems, depending on whether the annual ground water discharge for the particular year exceeds or is less than the average annual ground water discharge.

Input Data

Climate data were obtained from National Climate Data Center (NCDC) for precipitation and air temperature stations in the study area (Figure 1) that have been active since 1965 or earlier. Average daily precipitation for the WBDR watershed was calculated as a weighted average, with the daily precipitation value for each station inversely weighted according to the station's squared distance from the centroid of the WBDR watershed. Minimum and maximum daily air temperatures were averaged for four stations near the study area at Cooperstown, Liberty, Slide Mountain, and Walton, active since 1965 or earlier. Daily streamflow data were obtained from the USGS for the Walton Gauging Station (Station No. 1423000, active since 1950). Water chemistry data (TSS, dissolved N and P, particulate P, total N and P) were obtained from the New York State Department of Environmental Conservation (NYSDEC) for the Beerston Stream Chemistry Monitoring Station, active since October 1991 with 91 to 318 samples collected per year (Longabucco and Rafferty, 1998). Locations of these sites are depicted in Figure 1. These streamflow and water chemistry data were used for model calibration and verification.

Land use data for WBDR watershed were derived by supervised classification of 1992 and 1993 Thematic Mapper (TM) satellite imagery obtained from LANDSAT. Ten land use classes were distinguished in the image classification – deciduous forest, coniferous forest, mixed forest, grass shrub, grass, corn, alfalfa, built-up, barren, and water. Barnyard areas were estimated from farm data from the New York City Watershed Agricultural Program. Built-up areas were divided into residential and commercial/industrial categories using statistics derived from the EPA Multi-Resolution Land Characteristics (MRLC) data (http://www.epa.gov/mrlc/) and into impervious versus pervious areas using SCS Curve Number statistics (USDA-SCS, 1986). Rural road surface area outside built-up areas was estimated from New York State Department of Transportation (NYSDOT) GIS road data. Unsewered population estimates were derived from 1990 Census data, seasonal demographic data of the New York City watersheds (NYCDEP, 1993), and a GIS layer of sewer district boundaries. Point source loads from wastewater treatment plants (Figure 1) were derived from WWTP effluent sampling by NYSDEC (Longabucco and Rafferty, 1998) and by NYCDEP (unpublished data, C. R. Cutietta-Olsen, 1997, NYCDEP, New York, New York). Other GIS data layers used include USDA SSURGO soils data,10 m Digital Elevation Model (DEM) data from NYSDEC, stream networks, dwelling locations, and watershed boundary layers.

Model Parameters

Table 2 shows the GWLF model parameters used in the original and revised model applications to WBDR. A number of parameters are based on spatial, watershed specific characteristics, including parameters

TABLE 2. GWLF Parameters in Original and Revised Models.

Parameter	Description	Units	Parameter Subcategories*	In Original Model	Revised**	Notes
			Hydrologic Parameters			
Curve num lu	Runoff curve number for calculating runoff and infiltration		Forest deciduous	71.8		1, 2
			Forest coniferous	69.8		
			Grass-shrub	63.3		
			Grass	68.5		
			Corn	79.9		
			Alfalfa	77.2		
			Barnyard	92.2		
			Urban impervious	98		
			Urban pervious	74		
			Rural roads	92		
Melt coeff	For calculating snowmelt			0.45		3, 4
Soil water cap	Soil water capacity			10.9		1
Veg cover coeff	Vegetative cover coefficient for estimating evapo-transpiration		Jan, Feb, Mar,	.63,.63,.63		1, 4
			Apr, May, Jun,	.63,.99,.99		
			Jul, Aug, Sep,	.99,.99,.99		
			Oct, Nov, Dec	.99,.63,.63		
Recess coeff	Ground water recession			0.10		4, 5
Deep seep	Deep seepage loss			0		3, 4
Unsat leak coeff	Unsaturated leakage			–	0.06	5
			Dissolved Nutrient Parameters			
Runoff conc lu	Dissolved nutrient concentration in runoff	mg/l	P-forest	0.006	0.006	3, 4, 6, 10
			P-grass-shrub	0.100	0.099	
			P-grass	0.200	0.199	
			P-corn	0.260	0.258	
			P-alfalfa	0.150	0.149	
			P-barnyard	5.100	5.069	
			P-urban and roads	–	0.119	
			N-forest	0.190	0.323	
			N-grass-shrub	2.600	4.415	
			N-grass	2.900	4.924	
			N-corn	2.900	4.924	
			N-alfalfa	2.800	4.754	
			N-barnyard	29.300	49.751	
			N-urban and roads	–	1.155	
Dis nut conc factor	Factor applied to dissolved nutrient concentrations		P	1	.994	10
			N	1	1.698	
Snowmelt conc lu	Dissolved nutrient concentration in snowmelt	mg/l	P-corn	1.900	1.889	3, 4, 10, 11
			N-corn	12.200	20.716	
Gw conc	Nutrient concentration in ground water	mg/l	Dissolved P	0.010	0.010	3, 4,10
			Dissolved N	0.292	0.496	
Septic pop	Population served by septic systems	Persons	Year-round	7750		1, 7
			Seasonal	10725		
Septic input	Per capita nutrient input to septic field	kg/d-person	Dissolved P	0.0015		3, 4
			Dissolved N	0.012		
Septic uptake	Per capita nutrient removal by vegetative uptake	kg/d-person	Dissolved P	0.0004		3, 4
			Dissolved N	0.0016		
Septic failure rate	Percentage of population served by normal and failing septic systems	%	Normal	86	67.2/93.4	4, 8, 12
			Ponded	10	26.2/0.0	
			Short-circuited	1	3.3	
			Direct discharge	3	3.3	
Mean ann normal septic N	long-term annual normal septic system N load	kg/yr			29095.4	
Mean ann gwflow	Long-term annual ground water discharge	cm/yr			60.1	

TABLE 2. GWLF Parameters in Original and Revised Models (cont'd.).

Parameter	Description	Units	Parameter Subcategories*	In Original Model	Revised**	Notes
			Sediment and Solid Nutrient Parameters			
KLSCP lu	USLE erosion coefficient		Forest deciduous	0.003		1, 4, 9
			Forest coniferous	0.005		
			Grass-shrub	0.004		
			Grass	0.006		
			Corn	0.171		
			Alfalfa	0.012		
			Barnyard	0.519		
Sed del ratio	Sediment delivery ratio			0.065	0.072	1, 4, 5
Trans cap power	Transport capacity power			1.67	2.35	
Enrich ratio	Enrichment ratio			2.0	2.91	
Soil conc	Nutrient concentration in soil	mg/kg	Solid P	650		3, 4
			Solid N	1500		
Mean ann erosion lu	Average long term annual erosion	kg*10^3/yr	Forest deciduous		33170	4
			Forest coniferous		6877	
			Grass-shrub		11476	
			Grass		35124	
			Corn		54096	
			Alfalfa		167	
			Barnyard		4553	
			Res imperv		160	
			Res perv		13	
			Comm imperv		56	
			Comm perv		1	
			Road rural		157	
Mean ann trans cap	Average long-term annual transport capacity				28.1	
Mean ann WWTP part nut	Average long-term annual particulate phosphorus discharged from WWTPs	kg/yr			1762	
Urban buildup nut lu	Nutrient accumulation on urban surfaces	kg/ha-day	P-Res imperv	0.0112		3, 4
			P-Res perv	0.0039		
			P-Comm imperv	0.0090		
			P-Comm perv	0.0019		
			P-Road rural	0.0045		
			N Res imperv	0.090		
			N-Res perv	0.022		
			N-Comm imperv	0.785		
			N-Comm perv	0.012		
			N-Road rural	0.045		
Urban buildup sed lu	Sediment accumulation on urban surfaces	kg*10^3/ha-day	Res imperv	–	0.0062	3, 4
			Res perv	–	0.0011	
			Comm imperv	–	0.0028	
			Comm perv	–	0.0008	
			Road rural	–	0.0025	

*Nutrient subcategories: P is phosphorus, N is nitrogen.
**Blank indicates unchanged from value in original model.

NOTES: **(1)** GIS data analysis. **(2)** USDA-SCS, 1986. **(3)** Default/literature value. **(4)** Haith *et al.,* 1992. **(5)** Calibrated. **(6)** USEPA, 1983. **(7)** 1990 U.S. Census Bureau. **(8)** NYCDEP Engineering Division. **(9)** Wischmeier and Smith, 1978. **(10)** Calibrated factor applied to all runoff, snowmelt, and ground water dissolved nutrient concentrations. **(11)** Elevated snowmelt concentrations apply only to corn, which receives applications of winter manure spreading in Cannonsville Watershed. For other land uses, snowmelt conc lu is equivalent to runoff conc lu. **(12)** Ponded septic system failures only occur during wet season in revised model.

based on land use (*Runoff Curve Number, ET cover coefficient, KLSCP*), soils (*Runoff Curve Number, soil water capacity, KLSCP*), slope (*KLSCP*), and population (*septic population*). These parameters were derived by analysis of GIS data layers, following the indications in Haith *et al.* (1992). Other parameters were estimated by literature review as referenced in Table 2, use of default coefficients as given in Haith *et al.* (1992), or by calibration. Sediment parameters (*sed delivery ratio, trans cap power*), particulate nutrient parameter (*enrich ratio*), and dissolved nutrient parameters (*runoff conc lu, snowmelt conc lu, gw conc*) assume default values from Haith *et al.* (1992) in the original model application but were calibrated in the revised model application. Urban dissolved nutrient concentrations were taken from the Nationwide Urban Runoff Program (USEPA, 1983). The ground water recession coefficient (*recess coeff*) was calibrated in both model applications according to the method in Haith *et al.* (1992). The unsaturated leakage coefficient (*unsat leak coeff*), found only in the revised model, was calibrated. Sediment accumulation rates for urban land uses, not used in the original model, are given in Haith *et al.* (1992). For the remaining coefficients, the default values based on previous literature review as given in Haith *et al.* (1992) were used.

Revision of the sediment algorithm (Equations 4 through 11 above) results in three additional parameters in the revised model: $\bar{E}_{ann}$, $\overline{TC}_{ann}$, and $\overline{wwtp\ part\ nut\ discharged}_{ann}$. $\bar{E}_{ann}$ and $\overline{TC}_{ann}$ were estimated by simulating erosion and transport capacity for a 25 year period (1966 to 1990) and applying Equations (5) and (9). The multi-year simulation period provides estimates of long term average annual erosion and transport capacity that account for a variety of meteorological conditions. $\overline{wwtp\ part\ nut\ discharged}_{ann}$ was calculated from WWTP data for the period of record.

Model Calibration

Subsurface hydrologic flow parameters – *recess coeff* and *unsat leak coeff* – were calibrated for the revised model application using measured streamflow data for period 1961 to 1980. To calibrate the recession coefficient, all streamflow recession events were identified as periods with zero precipitation and snowmelt, based on measured daily precipitation and model estimates of daily snowmelt. For each streamflow recession event, the recession constant *r* was calculated according to Haith *et al.* (1995; Equation B-5)

$$R = \frac{\ln\left[F(t_1)/F(t_2)\right]}{t_2 - t_1} \tag{14}$$

where $F(t_1)$ and $F(t_2)$ are streamflow at the beginning and end of the recession event, and $t_2 - t_1$ is the length in days of the recession event. The recession coefficient was subsequently calculated as the average recession constant for all recession events during the calibration period. The unsaturated leakage coefficient was calibrated by an optimization procedure. The process of unsaturated leakage mainly affects streamflow during low flow periods when soils are below field capacity. The optimum leakage coefficient was therefore calculated as the value that minimizes simulated streamflow error during low flow months (streamflow less than 1 cm/month, corresponding to streamflow less than the approximate 20th percentile). The optimization was performed by running the model 40 times, varying the unsat leakage coeff from 0.000 to 0.200 by 0.005, and calculating the RMS and cumulative error for simulated versus measured monthly streamflow during low flow months for each model run. The parameter value corresponding to the minimum r^2 model performance statistic (described below in model testing) was chosen as the optimized value.

Sediment and particulate nutrient parameters – *sed delivery ratio, trans cap power,* and *enrich ratio* – were calibrated for the revised model application using monthly stream chemistry data for WBDR for period water year 1992 (October 1991 through September 1992). These parameters were optimized with the Vensim routine (Ventana Systems Inc., 1999) that performs a multi-variate optimization, varying one or more specified parameters until an optimal parameter value is identified that yields the closest fit (minimum sum of squared errors) of measured to simulated data for the calibration period. The parameters that determine sediment yield magnitude (*sed delivery ratio*) and timing (*trans cap power*) were optimized in a three step process. First, the coefficients *k* of Equation (6) and *tcp* (*trans cap power*) of Equation (7) and were optimized simultaneously to derive the pair of values that minimizes the RMS error in simulated versus measured monthly sediment yield. Second, the mean annual erosion was estimated by Equation (5) above, and mean annual transport capacity was estimated by Equation (9) above using the optimized value for *tcp*. Third, the sediment delivery ratio was calculated by solving Equation (10) for *SDR*, using the optimized value for *k*. The particulate nutrient parameter – *enrich ratio* – was optimized sequentially after the sediment parameters as the value that minimizes the r^2 in simulated versus measured monthly particulate nutrients.

Dissolved nutrient loads in GWLF are determined by parameters that specify nutrient concentrations in runoff from different land uses (*runoff conc lu, snowmelt conc lu*) and in ground water (*gw conc*). These parameters were calibrated together with a single multiplicative factor (*dis nut conc factor*) that is applied to all nutrient concentrations. In this way the relationships between concentrations associated with different land uses and ground water are maintained, as all concentrations shift up or down with the multiplicative factor. The *dis nut conc factor* was calibrated as the value that minimizes the r^2 in simulated versus measured monthly dissolved nutrients for water year 1992 (October 1991 through September 1992).

A sensitivity analysis was performed for each calibrated parameter by running the model multiple times, varying one parameter around its calibrated value while holding all other parameters constant at their calibrated values, and calculating r^2 and cumulative error of modeled versus measured monthly output data for each model run. Results of sensitivity analyses were depicted in graphs of r^2 and cumulative error as a function of varying parameter values.

Model Verification

The model was verified by comparing measured versus simulated monthly data for streamflow, dissolved P and N, particulate P, total P, and sediment. For streamflow, the verification period was 1981 through 1996. For stream chemistry variables, the verification period was wy93 through wy96 (October 1992 through September 1996). An extreme event occurred January 19 and 20, 1996. This was the streamflow of record with an estimated return period of more than 70 years (Lumia, 1998). Observed sediment yields and particulate P loads for the single month of January 1996 (59,735 * 10^3 and 89,020 kg, respectively) exceeded average annual loads (Longabucco and Rafferty, 1996). Simulation of an event of this magnitude is apparently outside the range for which the model was designed or calibrated. January 1996 was therefore excluded from the model tests for stream chemistry.

Two statistics were used as measures of model performance. The Nash-Sutcliff coefficient of model efficiency (Nash and Sutcliffe, 1970), referred to as r^2, measures the goodness of fit of model predicted versus measured data (Equation 15). The r^2 statistic can range from minus infinity to 1, with 1 indicating a perfect fit. If r^2 is less than zero, the model predicted values are less accurate than simply using the observed mean (Loague and Green, 1991).

$$r^2 = 1 - \frac{\sum (observed - predicted)^2}{\sum (observed - mean\ observed)^2} \quad (15)$$

Another goodness of fit measure is the cumulative error, or relative error (Thomann, 1982). Cumulative error is a measure of the accumulation of differences in measured versus model predicted values (Equation 16).

$$\%\ cum\ error = \frac{mean\ observed - mean\ predicted}{mean\ observed} \cdot 100 \quad (16)$$

In addition to these statistics, time series and scatter plots were made for visual inspection of differences in observed and model predicted values.

The two statistics are complementary and measure different aspects of model performance. The r^2 statistic is a measure of the proportion of the variance in observed values accounted for by the model, analogous to the coefficient of determination (Nash and Sutcliffe, 1970). It thus measures the degree to which observed and predicted time series are correlated. In contrast, the percent cumulative error statistic measures the bias of model predictions. Percent cumulative error can be zero in spite of very large deviations between observed and predicted values (low r^2). Alternatively, observed and predicted time series may track closely (high r^2) in spite of significant bias reflected in nonzero percent cumulative error. Ideal model performance will be characterized by r^2 near 1 and percent cumulative error near zero.

RESULTS

Model Calibration

Calibration of parameters in the revised model influenced model predictions of streamflow, sediment yield, particulate and dissolved nutrients. Sensitivity analyses for calibrated hydrologic and water quality parameters (Figure 3) suggest that these parameters are well-behaved with respect to the two model performance statistics. Parameter values resulting in maximum r^2 tended to coincide with the values resulting in zero percent cumulative error. Thus, calibration did not require a compromise between parameter values favoring either high r^2 or low percent cumulative error at the expense of the other.

Two hydrologic parameters were calibrated. Calibration of the *recess coeff* resulted in the same value

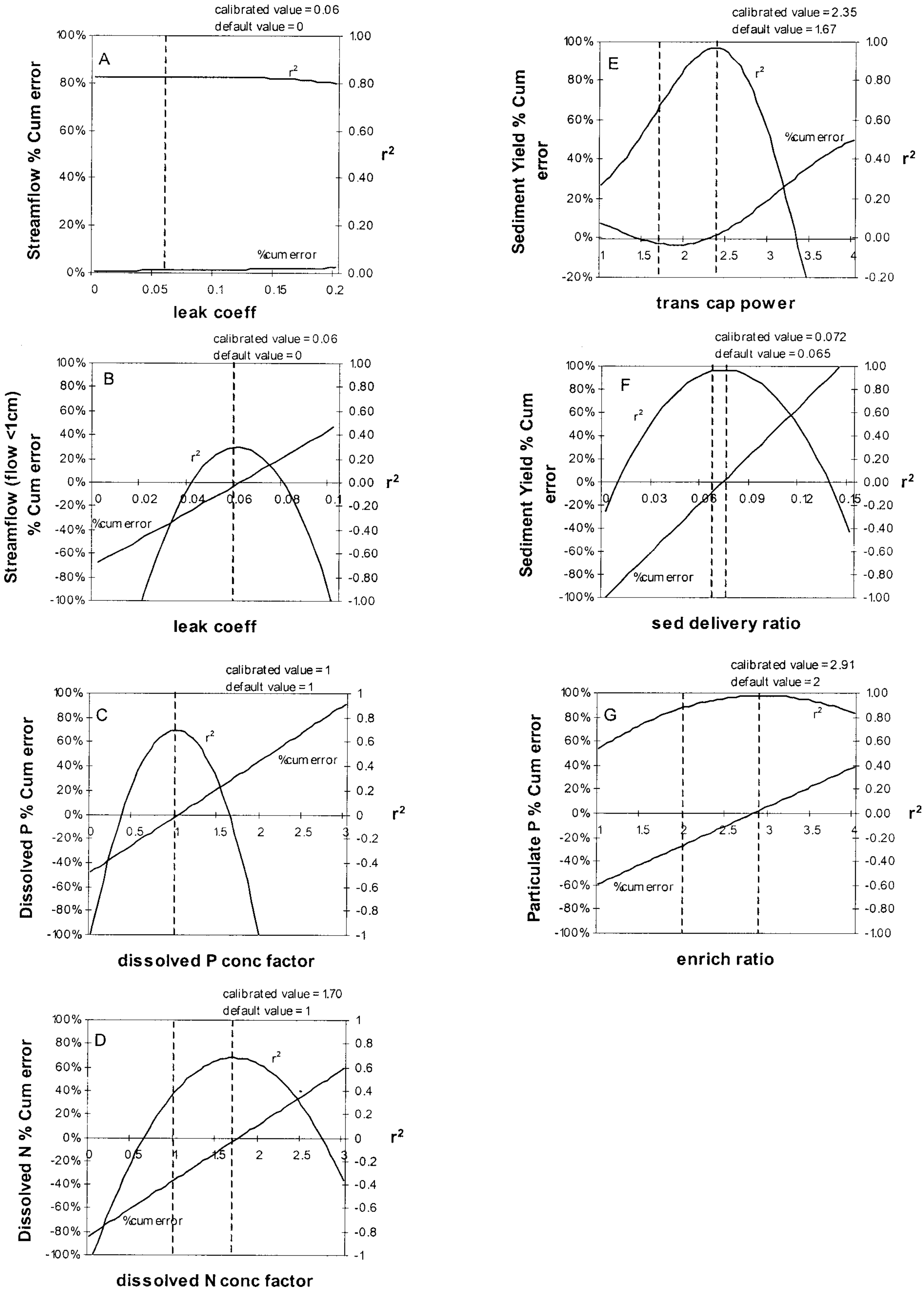


Figure 3. Sensitivity of Model Error to Varying Calibration Parameter Values.

(0.1) as the default. The *unsat leak coeff* was calibrated to a value of 0.06. Modeled monthly streamflow was found to be relatively insensitive to calibration of the *unsat leak coeff* when all months within the calibration period are considered (Figure 3A). Within a range of *unsat leak coeff* of 0 to 0.20 we observed only small changes in r^2 (3 percent) and percent cumulative error (1 percent). This is expected, since the leakage coeff mainly effects streamflow estimates during lowflow months that have a relatively small statistical effect on overall model error. With all months considered, the model predicted streamflow well (r^2 = 0.82 with default leakage coeff = 0, and r^2 = 0.83 with optimized leakage coeff = 0.06) (Figures 4A, 4C; Table 3).

Sensitivity of modeled monthly streamflow to calibration of the *unsat leak coeff* was substantial when only low flow months (flow less than 1cm) were considered (Figure 3B). Within the range of *unsat leak coeff* values between 0 and 0.1, there was considerable variation in r^2 (-2.49 to 0.30) and cumulative error (-67.12 to 46.49 percent) for predicted versus observed streamflow during low flow months. When the default value was used (*unsat leak coeff* = 0, as in the original GWLF model), modeled streamflow during low flow months was consistently underestimated (percent cumulative error = -67.12), and poorly correlated with observed streamflow. Negative r^2 (-2.49) with *unsat leak coeff* = 0 indicates that streamflow predictions during low flow months were less accurate than simply using the observed mean (Figure 4B, Table 3). These errors were reduced considerably with the *unsat leak coeff* optimized at 0.06 (r^2 = 0.30, percent cumulative error = -0.17 percent) (Figure 4D).

Sediment yield predictions were sensitive to calibration of both the *trans cap power* and the *sed delivery ratio* parameters (Figures 3E, 3F). Calibration of these parameters improved sediment yield predictions, increasing r^2 from 0.60 to 0.97 and changing percent cumulative error from -13.58 to 1.07 percent

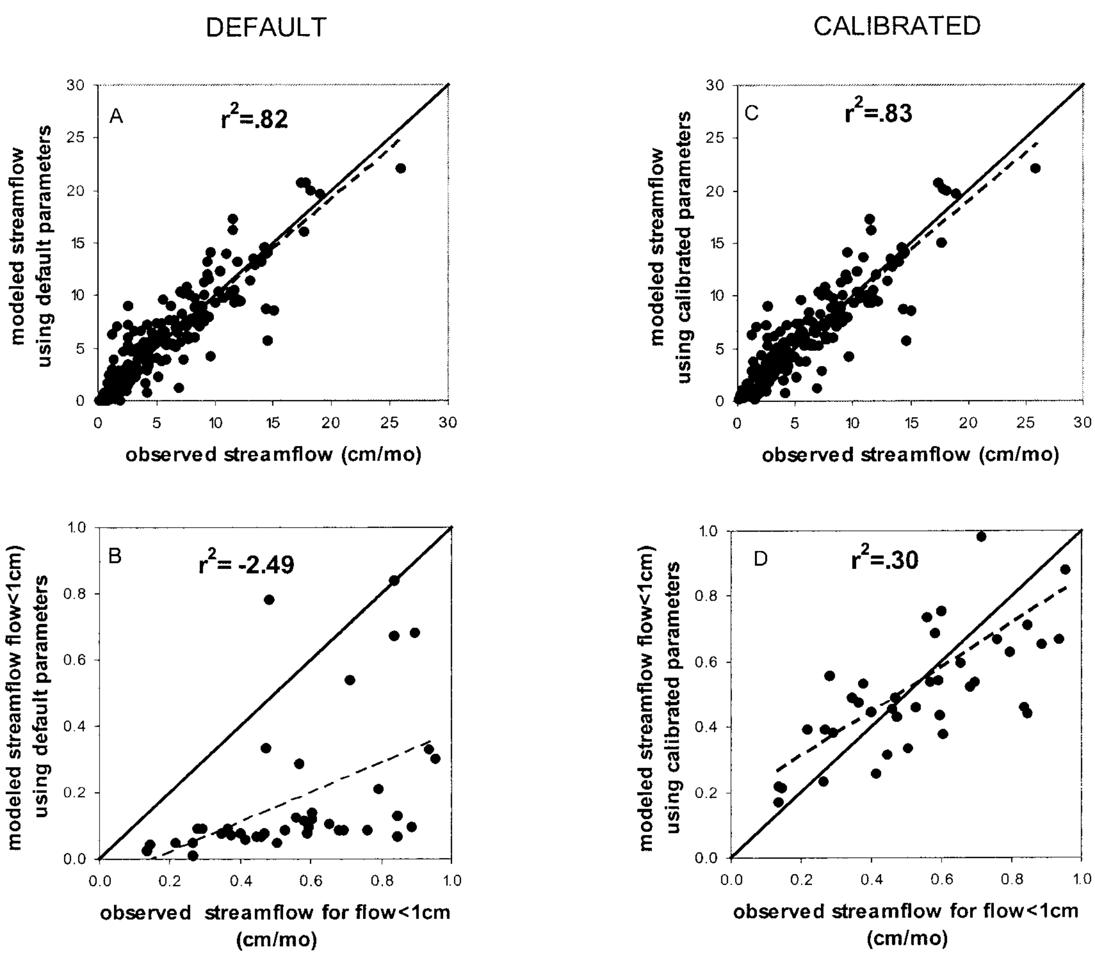


Figure 4. Correlations Between Observed and Modeled Monthly Streamflow Using Default (A, B) and Calibrated (C, D) Parameters During Calibration Period wy62-80 (solid is line of perfect fit; dashed is regression line).

(Table 3; Figures 5A, 5D). Calibration of *trans cap power* effects r^2 to a greater extent than cumulative error (Figure 3E), while calibration of s*ed delivery ratio* affects both r^2 and cumulative error (Figure 3F). The calibrated value for *sed delivery ratio* (0.072) was quite close to the default value (0.065). Thus, improvement in model predictions due to calibration of *sed delivery ratio* was minimal (r^2 increase by 0.02, percent cumulative error change = 7 percent). Most of the improvement in sediment yield predictions was from calibrating the *trans cap power*. Using the default *trans cap power* value in the model tends to overestimate sediment yield at low yields and underestimate at high yields (Figure 5A). Increasing the *trans cap power* corrects this systematic error (Figure 5D).

Particulate P predictions are sensitive to the accuracy of sediment yield estimates and to the *enrich ratio* parameter. Calibration of the sediment yield parameters alone resulted in significant increase in r^2 (from 0.44 to 0.88) and reduction in percent cumulative error (from -36.19 to -26.33). Subsequent calibration of the *enrich ratio* further increased r^2 to 0.98 and reduced percent cumulative error to 3.17 percent (Table 3). Much of the improvement in particulate P predictions was due to improvements in sediment yield predictions by calibration of sediment yield parameters. As in the case of sediment yield predictions, the model with default parameters tends to overestimate low values of particulate P and underestimate higher values, a condition that is corrected by increasing the *trans cap power* and thus improving sediment yield predictions (Figures 5B, 5E).

Improvements in particulate P due to calibration also translated into improvements in total P predictions, as particulate P is a major component of total P loads. As with particulate P, the tendency of the model with default coefficients to overestimate low values of total P and underestimate higher values was corrected by calibration (Table 3; Figures 5C, 5F).

Calibration of dissolved P concentrations resulted in values very close to the default values (*dis nut conc factor P* = 0.994) and thus provided little improvement in dissolved P predictions. Calibrated values for dissolved N concentrations were 1.698 times higher than default concentrations (*dis nut conc factor N* = 1.698). Use of the elevated dissolved N concentrations improved dissolved N predictions significantly, with increase in r^2 from 0.38 to 0.68 and change in percent cumulative error from -36.16 to -2.95 (Table 3, Figure 6).

The revised model with calibrated parameters performed well during the calibration periods, with r^2 for streamflow, sediment yield, particulate P, and total P exceeding 0.80, and r^2 for dissolved N and P near 0.70. Time series of observed and modeled streamflow using the revised GWLF model with calibrated coefficients during the calibration period wy62 to wy80 are given in Figure 7. Time series of observed and modeled sediment yield, particulate P, total P, and dissolved N and P using the revised GWLF model with calibrated coefficients during the calibration period wy92 are given in Figure 8.

TABLE 3. Summary of Revised GWLF Model Predictions, Stream Measurements, and Errors Using Default Versus Calibrated Parameters During the Calibration Period.

	Default	**Calibrated**
Streamflow (wy62-80)		
Measured mean (cm/month)	5.02	5.02
Modeled mean (cm/month)	5.06	5.08
Percent cumulative error	0.68	1.12
r^2	0.82	0.83
Streamflow (wy62-80, flow < 1 cm only)		
Measured mean (cm/month)	0.55	0.55
Modeled mean (cm/month)	0.18	0.55
Percent cumulative error	-67.12	-0.17
r^2	-2.49	0.30
Sediment Yield (wy92)		
Measured mean (kg*10^3/month)	747.32	747.32
Modeled mean (kg*10^3/month)	645.81	755.33
Percent cumulative error	-13.58	1.07
r^2	0.60	0.97
Particulate P (wy92)		
Measured mean (kg/month)	1505.55	1505.55
Modeled mean (kg/month)	960.71	1553.21
Percent cumulative error	-36.19	3.17
r^2	0.44	0.98
Total P (wy92)		
Measured mean (kg/month)	3090.48	3090.48
Modeled mean (kg/month)	2623.95	3227.09
Percent cumulative error	-15.10	4.42
r^2	0.59	0.97
Dissolved P (wy92)		
Measured mean (kg/month)	1585.00	1585.00
Modeled mean (kg/month)	1560.83	1556.54
Percent cumulative error	-1.52	-1.80
r^2	0.70	0.70
Dissolved N (wy92)		
Measured mean (kg/month)	31952.67	31952.67
Modeled mean (kg/month)	20399.33	31009.75
Percent cumulative error	-36.16	-2.95
r^2	0.38	0.68

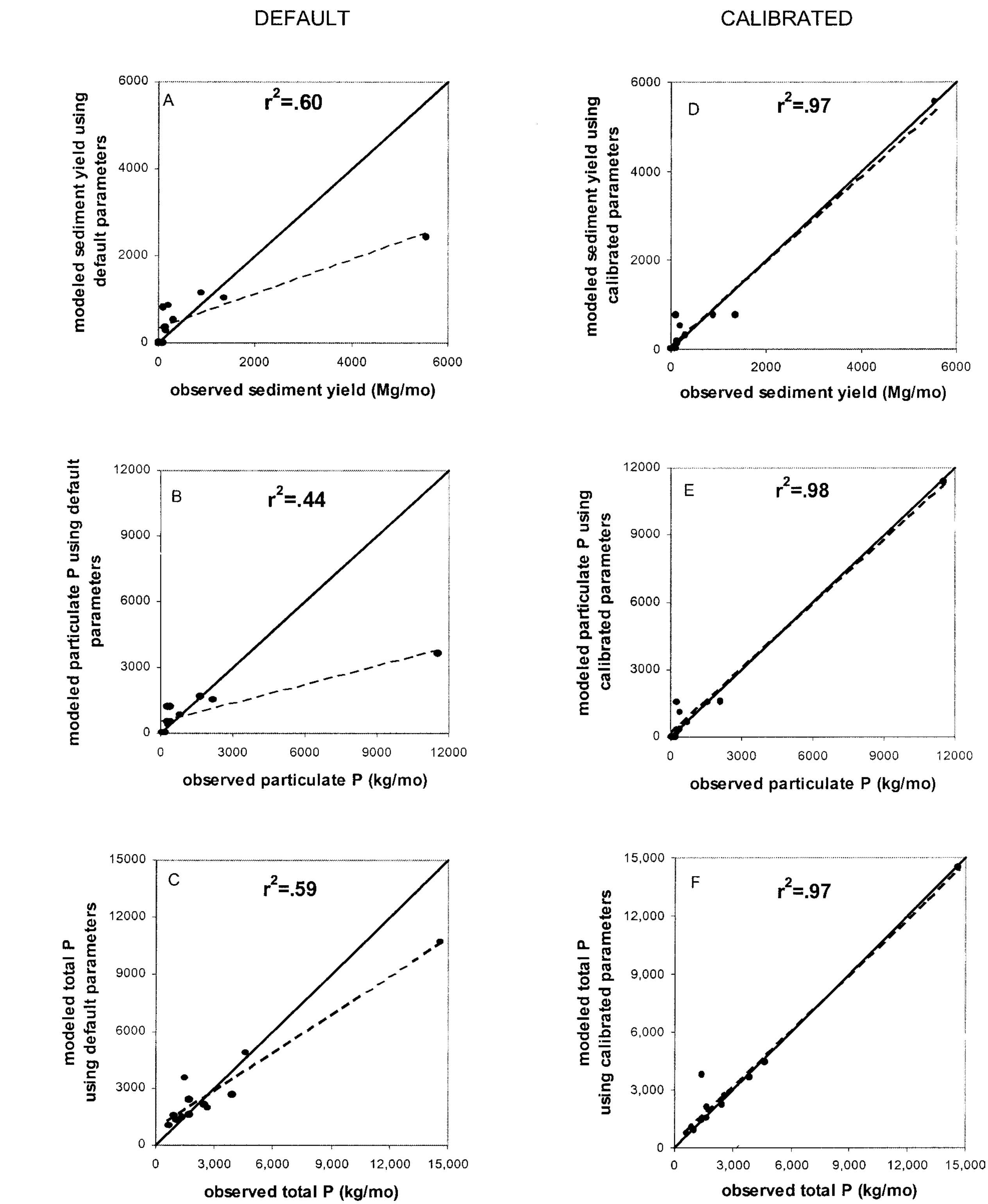


Figure 5. Correlations Between Observed and Modeled Monthly Sediment Yield, Particulate P and Total P Using Default (A, B, C), and Calibrated (D, E, F) Parameters During Calibration Period wy92 (solid is line of perfect fit; dashed is regression line).

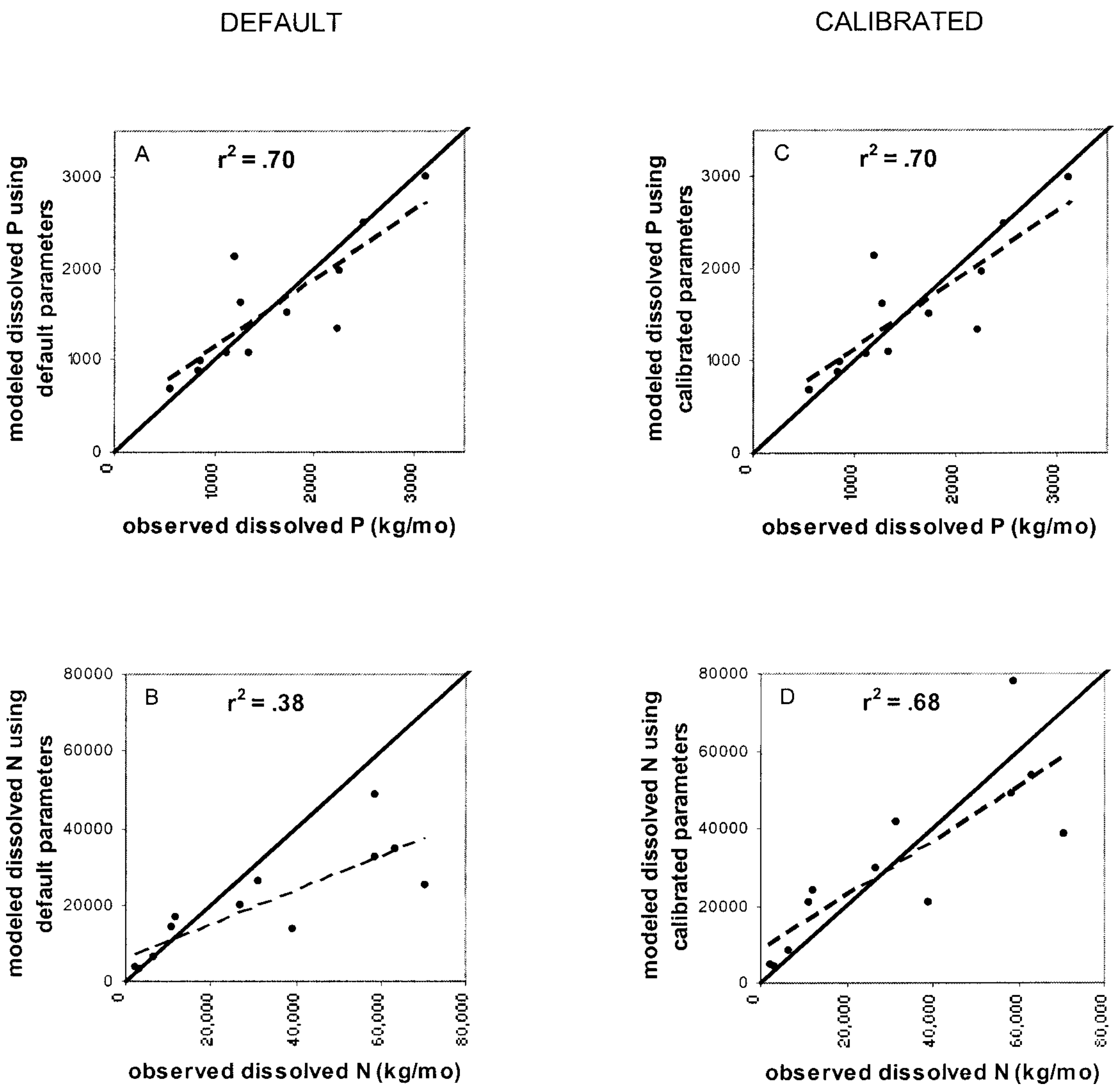
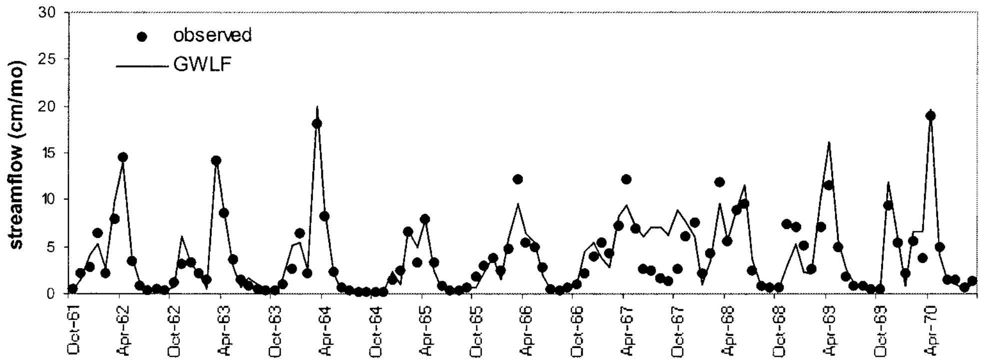


Figure 6. Correlations Between Observed and Modeled Monthly Dissolved P and N Using Default (A, B) and Calibrated (C, D) Parameters During Calibration Period wy92 (solid is line of perfect fit; dashed is regression line).

Model Verification

Performance of the revised and original GWLF model in simulating stream flow, sediment yield, and nutrient loads were compared for the verification periods. Both models predicted monthly streamflow well, with r^2 greater than 0.80 and 6 percent cumulative error (Table 4, Figures 9A, 9C). When all months during the verification period were considered, differences in r^2 (0.80 versus 0.82) and cumulative error (5.73 percent versus 6.09 percent) were marginal. Nevertheless, stream flow predictions during low flow months (flow less than 1 cm) were improved with the revised model, with substantial increase in r^2 (-2.96 to 0.20) and decrease in percent cumulative error (-62.34 percent to 2.94 percent) (Table 4b and Figures 9B, 9D). As seen in Figure 10, the underestimation of flows during low flow periods in original model predictions is corrected in the revised model predictions.

Differences in dissolved P predictions between the revised and original models were small, with equivalent r^2 values of 0.62. The percent cumulative error for dissolved P was slightly lower in the revised model (0.72 percent versus -4.17 percent). The revised model exhibited some improvement in dissolved N predictions, with a reduction in the absolute value of percent cumulative error from 26.05 percent to 17.26 percent. The r^2 values for dissolved N predictions



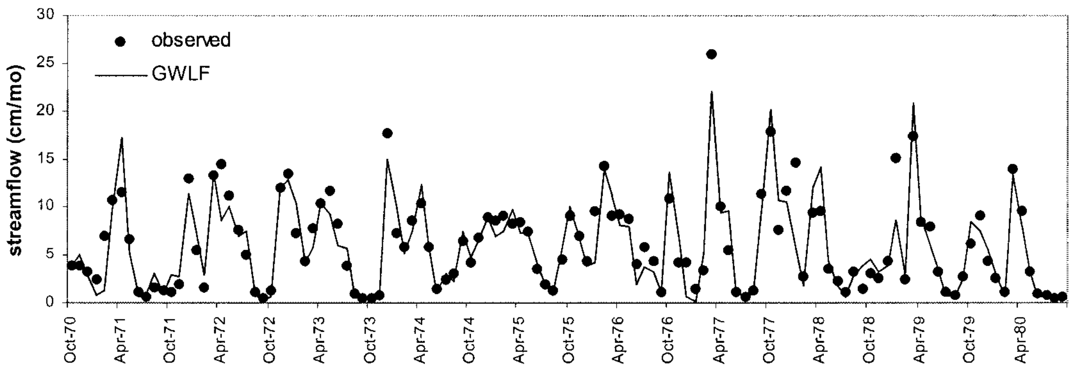


Figure 7. Time Series of Observed and Modeled Monthly Streamflow Using Revised GWLF Model With Calibrated Coefficients During the Calibration Period wy62-80.

were equivalent (0.71) for the revised and original models. These error statistics (Table 4) and inspection of the scatter plots (Figure 11) depict a reasonable fit of simulated to observed monthly estimates of dissolved nutrients.

Significant differences were found between the original and revised model predictions for monthly sediment yield. Underestimation of monthly sediment yield by the original model (percent cumulative error = -38.49 percent) was greatly reduced in the revised model predictions (percent cumulative error = -12.25 percent) (Table 4). Revised model estimates of monthly sediment yield had higher r^2 (0.75 versus 0.32 with original model) (Figures 12A, 12D). These improvements reflect not just the reduction in cumulative error but also improved timing of predictions with the revised model, as revealed by inspection of the time series graphs (Figure 13A).

Model predictions of monthly particulate P and total P, which are strongly influenced by sediment yield, were also improved by the revised model. Errors for particulate P were substantially reduced (r^2 = 0.67 vs. 0.38 with original model, percent cumulative error = -41.92 to 12.43 percent) (Table 4, Figures 12B, 12D). Errors for total P were similarly reduced (r^2= 0.72 versus 0.51 with original model, percent cumulative error = -21.14 to 12.10 percent) (Table 4, Figures 12C, 12F). As for sediment yield, these reduced errors reflect both reduced cumulative error and improved timing of predictions with the revised model, as revealed by the time-series graphs (Figures 13B, 13C).

DISCUSSION

Evaluation of Model Changes

Five revisions were made to the original GWLF model: addition of unsaturated zone leakage to the ground water hydrology module; inclusion of urban sediments and dissolved nutrients; timing of point source particulate P export; timing of sediment yield;

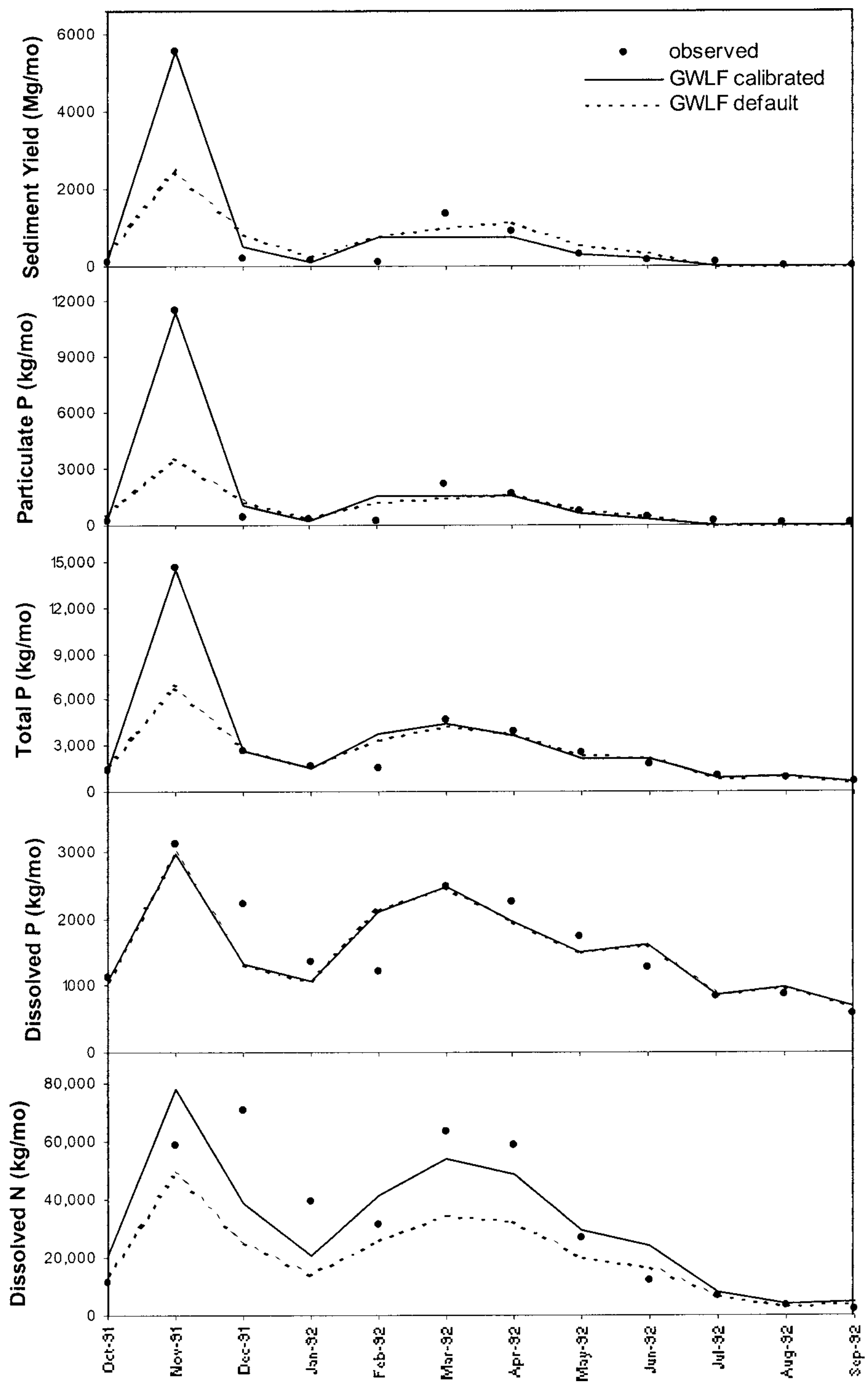


Figure 8. Time Series of Observed and Modeled Monthly Sediment Yield, Particulate and Total P Using Revised GWLF Model With Calibrated and Default Coefficients During the Calibration Period wy92.

and timing of septic system loads. Of these, the revision of sediment yield timing had the greatest effect, resulting in significant improvement of model performance. Addition of unsaturated leakage improved hydrologic predictions during low flow months. The other changes improved realism and made the model more useful for estimating effects of future land use changes or watershed management.

TABLE 4. Summary of Model Predictions, Stream Measurements, and Errors Using Original Versus Revised GWLF Model During the Verification Period.

	Original GWLF	**Revised GWLF**
Streamflow (wy81-96, all months))		
Measured mean (cm/month)	4.77	4.77
Modeled mean (cm/month)	5.05	5.06
Percent cumulative error	5.73	6.09
r^2	0.80	0.82
Streamflow (wy81-96, flow < 1 cm)		
Measured mean (cm/month)	0.58	0.58
Modeled mean (cm/month)	0.22	0.60
Percent cumulative error	-62.34	2.94
r^2	-2.96	0.20
Sediment Yield (wy93-96*)		
Measured mean (kg*10^3/month)	1160.70	1160.70
Modeled mean (kg*10^3/month)	713.95	1018.51
Percent cumulative error	-38.49	-12.25
r^2	0.32	0.75
Particulate P (wy93-96*)		
Measured mean (kg/month)	1863.27	1863.27
Modeled mean (kg/month)	1082.12	2094.81
Percent cumulative error	-41.92	12.43
r^2	0.38	0.67
Total P (wy93-96*)		
Measured mean (kg/month)	3197.62	3197.62
Modeled mean (kg/month)	2521.80	3584.44
Percent cumulative error	-21.14	12.10
r^2	0.51	0.72
Dissolved P (wy93-96*)		
Measured mean (kg/month)	1334.26	1334.26
Modeled mean (kg/month)	1278.68	1343.92
Percent cumulative error	-4.17	0.72
r^2	0.62	0.62
Dissolved N (wy93-96*)		
Measured mean (kg/month)	33237.26	33237.26
Modeled mean (kg/month)	24578.30	38974.91
Percent cumulative error	-26.05	17.26
r^2	0.71	0.71

*Excluding January 1996.

Streamflow during the low flow months of late summer and autumn tend to be underestimated in our application of the original GWLF model to the Cannonsville watershed. Similar underestimation of low flows have been observed in other applications of GWLF (Haith and Shoemaker 1987, Lee *et al* 2000). To address this tendency, we added unsaturated zone leakage to the ground water hydrology module of GWLF. Unsaturated zone leakage, or rapid transmission of infiltrating water through an unsaturated soil zone, may occur as macropore flow or by other mechanisms of preferential flow (Beven and Germann, 1982; Walter *et al.,* 2000). Incorporation of unsaturated leakage in a "crackflow" module in the SWAT model similarly improved low flow estimates (Rosenthal *et al.,* 1995). The inclusion of unsaturated zone leakage in the revised model effectively removed the underestimation bias and improved the ability of the model to simulate flows during low flow months. This improvement of streamflow estimation during low flows had little impact on annual flow and load estimates since the contribution of flows and loads during low flow periods to the cumulative loads is minimal. Nevertheless, the incorporation of unsaturated leakage, preferably calibrated to streamflow data, may be valuable for model applications where accurate simulation of monthly or seasonal differences in flow or loads is important. This is the case in the Cannonsville watershed, as nutrient loads during the growing season may be important determinants of algal growth and trophic status in the Cannonsville Reservoir (Doerr *et al.,* 1998; Owens *et al.,* 1998).

Model performance in simulating monthly sediment yield, particulate P, and total P were significantly improved by revising the algorithm controlling timing of sediment transport and calibrating the related parameters. Performance of the original model in estimating sediment yield and particulate P was weak, with r^2 below 0.40 and cumulative errors in excess of 35 percent. Model performance for total P, which is strongly influenced by the particulate P component, was also weaker than for other simulated variables. Lee *et al.* (2000) also found that GWLF performance was weaker in simulating total P in the Choptank River basin. Suspecting that the weakness in estimating sediment and particulate nutrient loads may be related to the original GWLF model not allowing carryover of sediment supply from one year to the next, we revised the algorithm to remove this restriction. This modification along with calibration of the trans cap power parameter relating sediment yield to streamflow improved model performance, increasing r^2 for monthly sediment yield, particulate and total P considerably (exceeding 0.65) and reducing cumulative errors below 15 percent.

The other model changes – urban sediment and dissolved nutrients and timing of point source particulate nutrients – add realism to the model without adding undue model complexity or data requirements. Monitoring data of the Nationwide Urban Runoff Program (USEPA, 1983) indicate that runoff from urban surfaces may contain significant concentrations of dissolved nutrients. Model sensitivity to the inclusion of urban dissolved nutrients in our application of GWLF

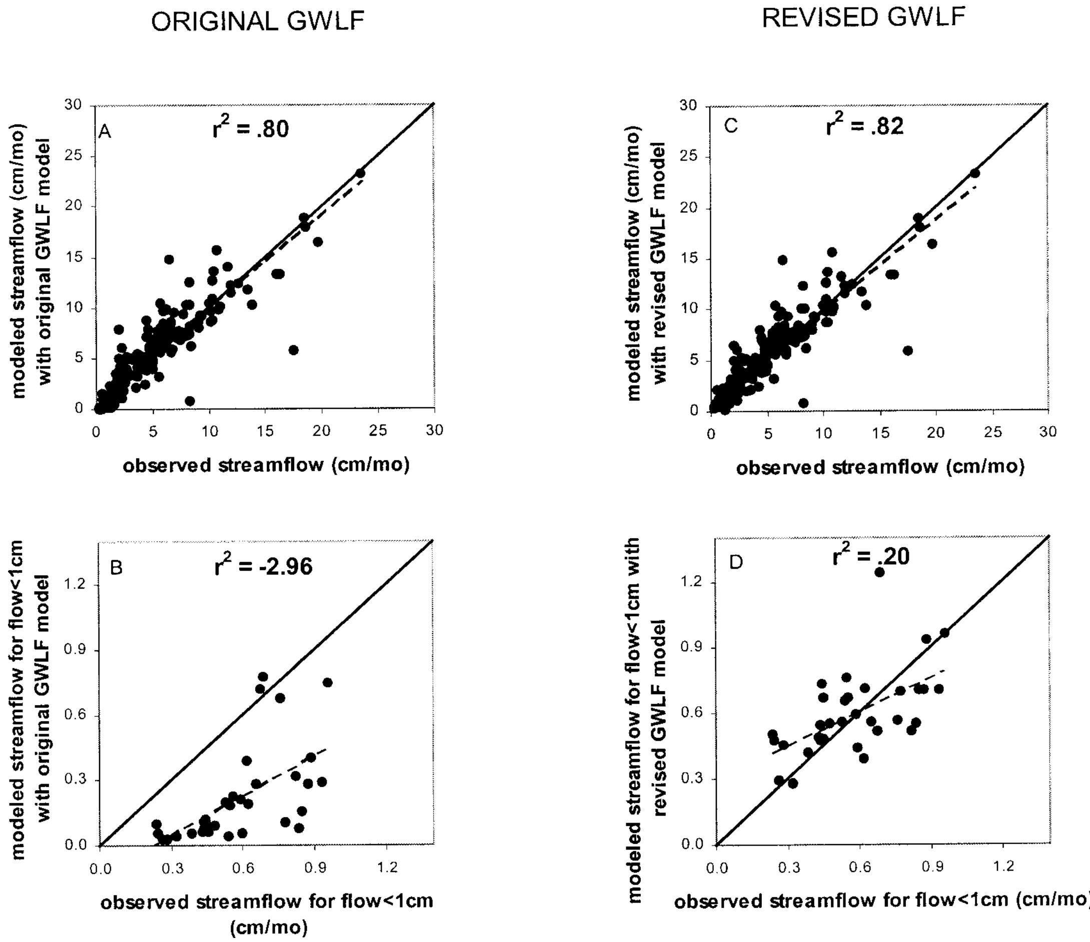


Figure 9. Correlations Between Observed and Modeled Monthly Streamflow During the Verification Period wy81-96 (solid is line of perfect fit; dashed is regression line).

was low. This is to be expected since urban areas are a minor land use component in Cannonsville. However, considerations of loading sources in more urbanized watersheds should be improved and made more realistic by the inclusion of this potentially significant source of dissolved nutrients. Adding an algorithm controlling the timing of point source particulate nutrient export from the watershed makes the transport of this source of particulate nutrients consistent with transport from other sources in the model. In watersheds where point sources are an important source of nutrients, this model revision may improve the model's utility.

Performance of the GWLF Model

Overall, the revised GWLF model performed well in simulating monthly streamflow, sediment yield, particulate P, and dissolved nutrients in the Cannonsville watershed during the verification periods. Streamflow predictions were excellent with r^2 greater than 0.80 (0.82) and cumulative error of 6 percent. Sediment yield, particulate P, and total P predictions were good with r^2 greater than 0.65 (0.75, 0.67, 0.72 for sediment, particulate, and total P, respectively) and cumulative errors of less than 15 percent (-12, 12, and 12 percent for sediment, particulate, and total P, respectively). Dissolved N and P predictions were acceptable with r^2 greater than 0.60 (0.62 for dissolved P and 0.71 for dissolved N) and cumulative errors less than 25 percent (less than 1 percent for dissolved P and 17 percent for dissolved N). These errors are comparable to those found in other applications of GWLF (Haith and Shoemaker, 1987; Lee *et al.,* 2000) and of the similar lumped parameter watershed models HSPF (Srinivasan *et al.,* 1998), and SWAT (Rosenthal *et al.,* 1995).

The model's weakest performance was in simulating nutrient fluxes for the extreme event during January 1996. Observed sediment yields and particulate P loads for this month (59,735 * 10^3 and 89,020 kg,

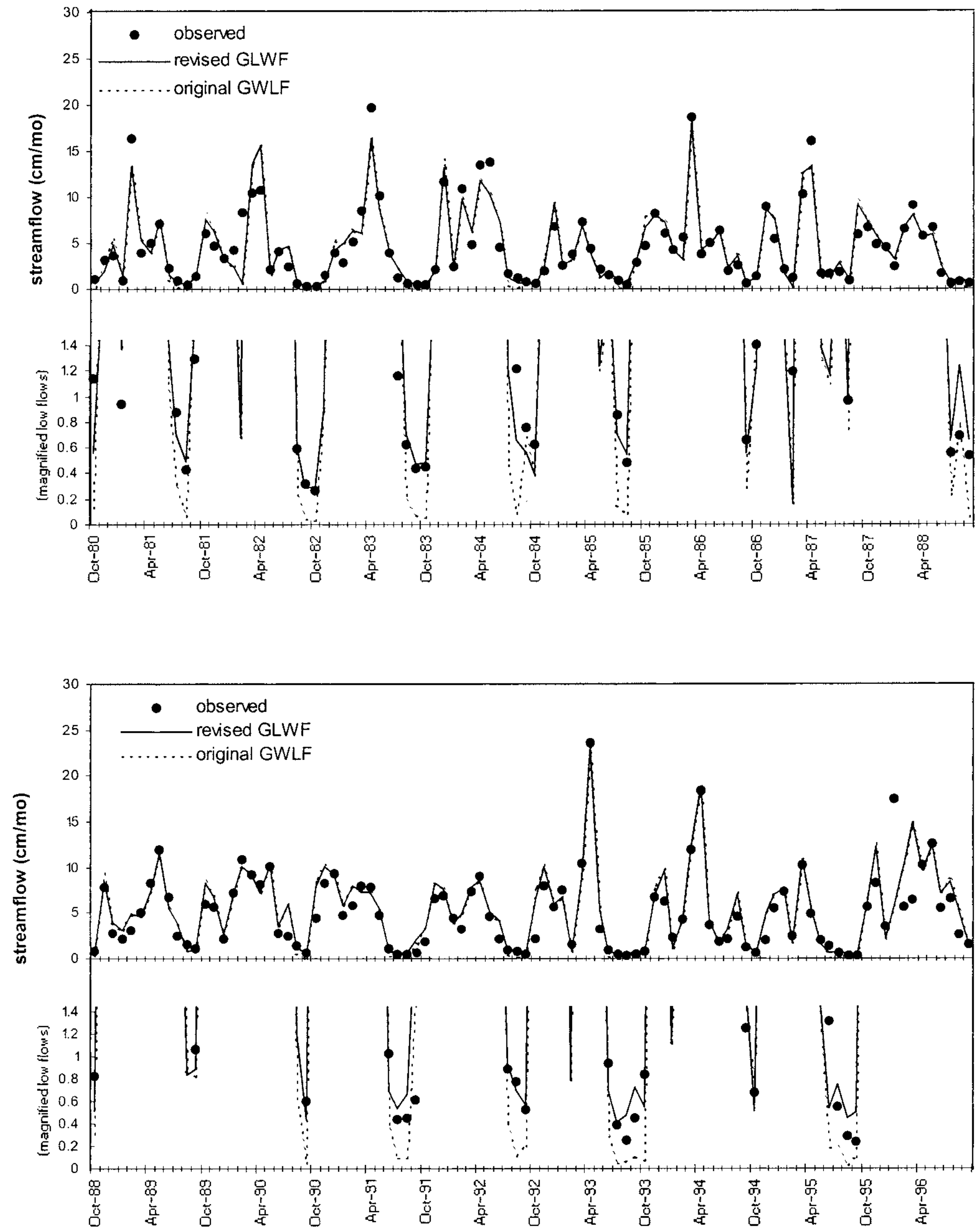


Figure 10. Time Series of Observed and Modeled Monthly Streamflow Using Original and Revised GWLF Model During the Verification Period wy81-96.

respectively) exceeded observed average annual loads, and they exceeded modeled loads by more than an order of magnitude. With this month excluded, the model performed well in simulating nutrient fluxes. The USEPA (1997) noted weak simulation of peak nutrient fluxes as a limitation of the original GWLF model. The revised GWLF model is better at simulating peak nutrient fluxes with its improved timing of sediment and particulate nutrient export, but it is still unsuited for simulating extreme events of the magnitude of January 1996. The weak performance of the model in simulating the January 1996 event was in part due to failure of the model to simulate the extensive snowmelt of the event. This had implications for model predictions for the following two months, during which the model faithfully melted a virtual snowpack that in reality had melted in January. When February and March 1996 are also excluded from the error analysis, model performance is improved ($r^2 = 0.75$), particularly for dissolved P.

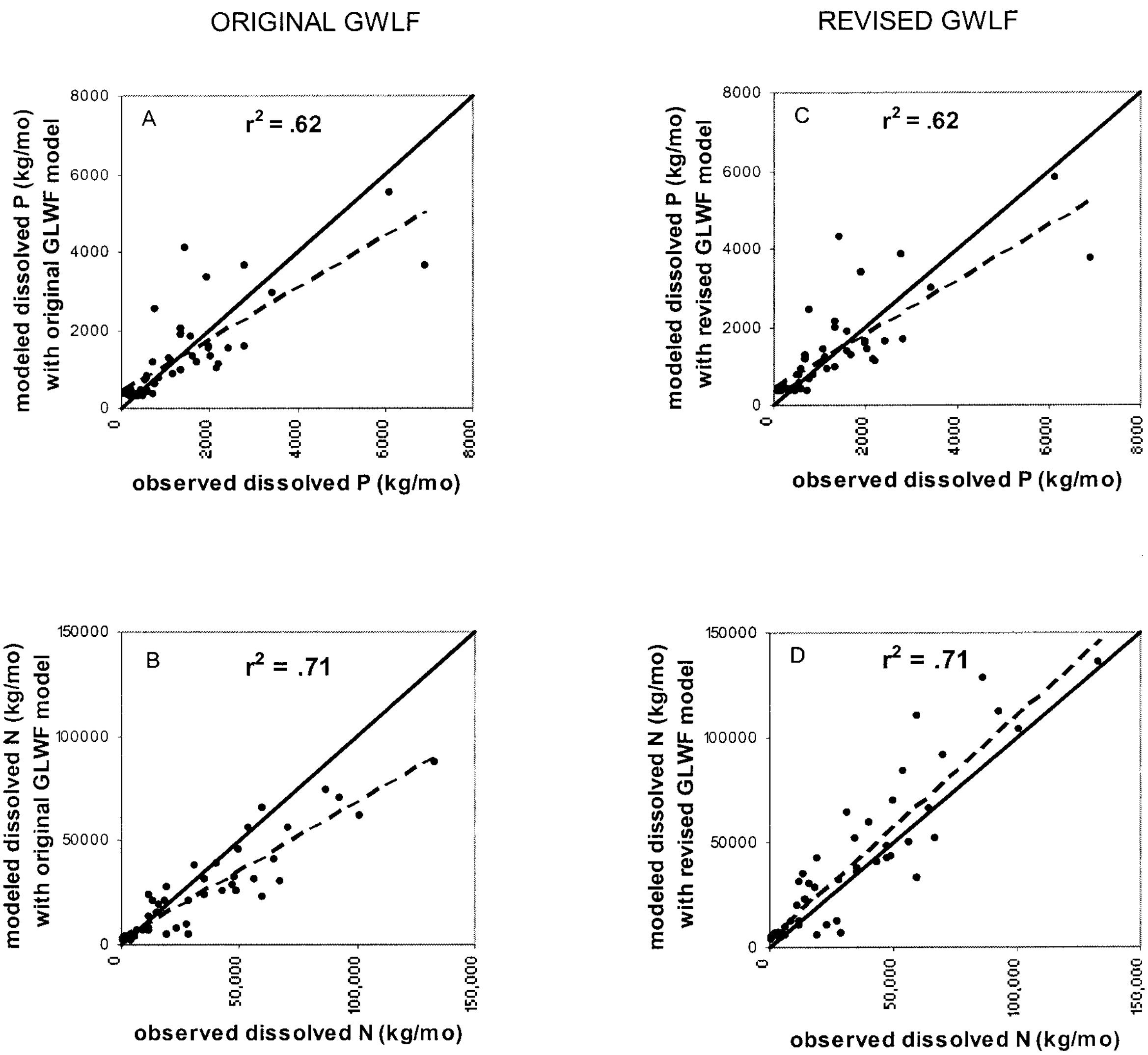


Figure 11. Correlations Between Observed and Modeled Monthly Dissolved Nutrients During the Verification Period wy 93-96 (excluding January 1996) (solid is line of perfect fit; dashed is regression line).

The revised GWLF model is true to the intent of the original GWLF model in requiring minimum calibration to effectively model monthly streamflow, sediment, and nutrient loads. For more accurate simulation of streamflow during low flow months, an unsaturated leakage coefficient that can be calibrated has been added to the model. However, the model can be considered to perform well simulating monthly stream flow without unsaturated leakage, as in the original model, if underestimation of streamflow during low flow months is not of concern. Model predictions of sediment yield and particulate P are sensitive to the three controlling parameters that were calibrated in our model application – the transport capacity power, sediment delivery ratio, and enrichment ratio. Of these, the sediment delivery ratio, and to a lesser extent the enrichment ratio, had calibrated values fairly close to the default values as given in Haith *et al.* (1992). Only the transport capacity power's calibrated value was significantly different from the default value; use of the default value would have introduced substantial error. This parameter is probably the most important one to calibrate to local conditions if using the model to simulate sediment yield and particulate and total P.

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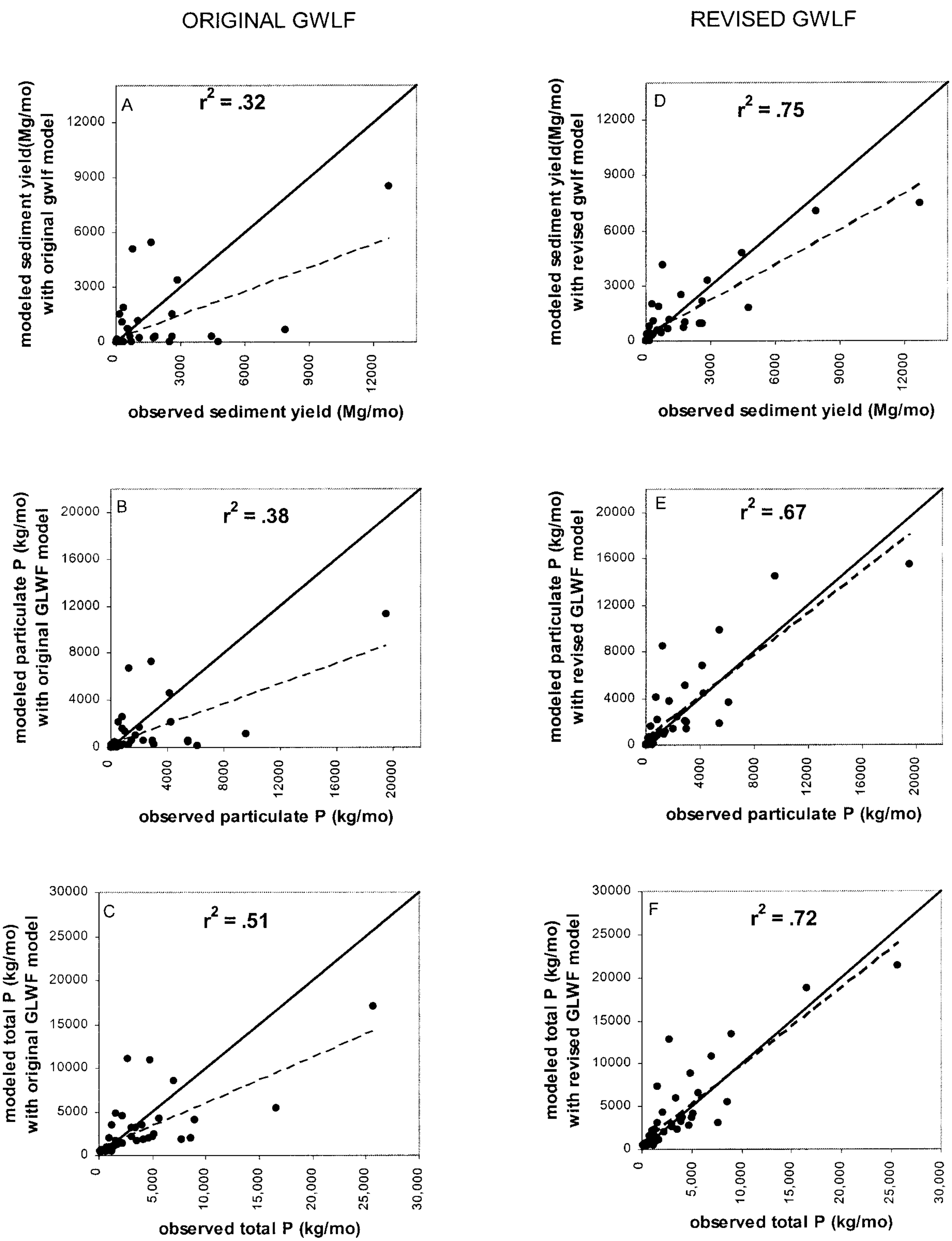

Figure 12. Correlations Between Observed and Modeled Monthly Sediment, Particulate P, and Total P During the Verification Period wy 93-96 (excluding January 1996) (solid is line of perfect fit; dashed is regression line).

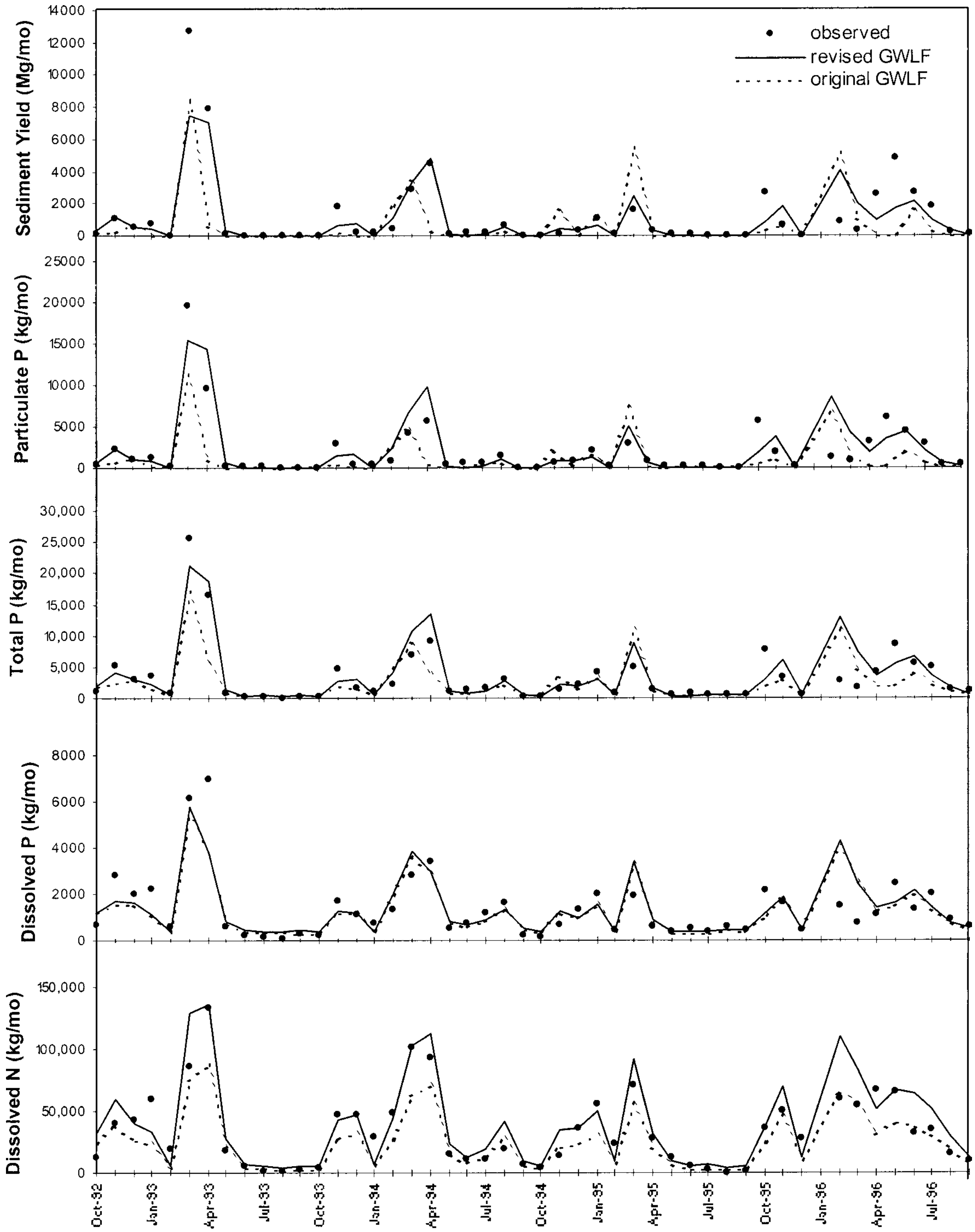

Figure 13. Time Series of Observed and Modeled Monthly Sediment and Nutrient Loads Using Original and Revised GWLF Model, During the Verification Period wy93-96 (excluding January 1996).

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