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Fox River Watershed Investigation: Stratton Dam to the Illinois River

Phase II
Hydrologic and Water Quality Simulation Models

Part 1
Methodology and Procedures for Development of HSPF Models

by
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Prepared for the
Fox River Study Group, Inc.

May 2007

Illinois State Water Survey
Watershed Science Section
Champaign, Illinois

A Division of the Illinois Department of Natural Resources

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Abstract

This report summarizes methods and procedures for calibration of watershed loading models. It describes data assimilation, model structure, and calibration and validation procedures carried out to prepare watershed models for the study area, Fox River watershed from Stratton Dam to the Illinois River. This report lays the foundation for model development in the study area. Calibration parameters for both hydrology and water quality components of the models are listed. Sources of uncertainty in models are discussed and a procedure for sensitivity analysis of models is established. Companion reports present the specific development of watershed loading models for two tributary watersheds (Blackberry and Poplar Creek) in the Fox River watershed and an assessment of hydrologic model parameters on five additional watersheds. Subsequent reports will present the development of models for the remainder of the study area.

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Any opinions, findings, conclusion, or recommendations expressed in this report are those of the authors and do not necessarily reflect those of the Fox River Study Group or the Illinois State Water Survey.

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Introduction

The Fox River watershed is located in Wisconsin and Illinois. The Illinois State Water Survey (ISWS) is participating in a study of the Fox River watershed within Illinois, below Stratton Dam to the confluence of the Fox River with the Illinois River. This report is one of a series of reports on the Fox River Watershed Investigation prepared by the ISWS. The model preparation is part of an ongoing investigation of water quality issues identified by the Illinois Environmental Protection Agency (IEPA). This work is being conducted for and in consultation with the Fox River Study Group, Inc. (FRSG).

Project Overview

The Fox River in northeastern Illinois is the focal point of many communities along the river, providing an aesthetically pleasing area and opportunities for fishing, canoeing, and boating. The Fox River is also a working river. Two major cities, Elgin and Aurora withdraw water for public water supply, and the river serves as a receptor for storm water and treated waste water. This highly valued river, however, has been showing increasing signs of impairment.

In response to local concerns about the Fox River water quality the FRSG organized in 2001. The FRSG is comprised of a diverse group of stakeholders representing municipalities, county government, water reclamation districts, and environmental and watershed groups from throughout the watershed. The goal of the FRSG is to address water quality issues in the Fox River watershed and assist with implementing activities to improve and maintain water quality. The FRSG has initiated activities to more accurately characterize the water quality of the Fox River: data collection and preparation of comprehensive water quality models.

The IEPA in their *Illinois Water Quality Report 2000* (IEPA, 2000) listed parts of the Fox River in McHenry and Kane Counties and part of Little Indian Creek as impaired. The 2002 IEPA report (IEPA, 2002) listed the entire length of the Fox River in Illinois as impaired, as well as Nippersink, Poplar, Blackberry, and Somonauk Creeks, and part of Little Indian Creek. The IEPA has included the Fox River and these tributaries on their list of impaired waters, commonly called the 303(d) list (IEPA, 2003). The latest report (IEPA, 2006) lists the entire length of the Fox River, Nippersink Creek, Tyler Creek, Crystal Lake outlet, Poplar Creek, Ferson Creek, and Blackberry Creek as impaired. The most prevailing potential sources for listing were hydromodification and flow regulation, urban runoff, and combined sewer overflows. The most prevailing potential causes for listing were flow alterations, habitat, sedimentation/siltation, dissolved oxygen, suspended solids, excess algal growth, fecal coliform bacteria, and PCBs. A suite of water quality models has been envisioned to characterize the various sources and causes of impairment.

Reporting Stucture

The Phase I report (McConkey et al., 2004) reviews the available literature and data for the study area and includes recommendations for development of a suite of models to simulate hydrology and water quality in the watershed targeted to key water quality issues identified in the watershed. The Hydrological Simulation Program FORTRAN version 12 (HSPF, Bicknell et al., 2001) model was selected to simulate watershed loading, and delivery and routing of nonpoint and point sources of pollution from the entire watershed. The QUAL2 model was selected to model dissolved oxygen diurnal processes during steady state low flow conditions along the mainstem Fox River. These models are referred to as watershed loading and receiving stream models respectively.

The report *Overview of Recommended Phase II Water Quality Monitoring, Fox River Watershed Investigation* (Bartosova et. al., 2005) outlines a plan for monitoring to collect data for improved model calibration.

This report (Part 1) describes the structure of the HSPF hydrology and water quality model and methods used in developing the watershed loading models, discusses sources of uncertainty in these models and data assimilation conducted in preparation of watershed loading models for the study area, and identifies statistical and graphical methods used in evaluating confidence in the model. It serves as a guide for model development, parameterization, calibration, and validation of the watershed loading models for all tributary watersheds and the Fox River mainstem.

Watershed models can provide insights about impacts of land use change, delivery of pollutants from nonpoint sources, and the hydrology of the watershed. These watershed models will be especially useful for tributary watersheds where benefits of preventative actions can be evaluated via reduction in pollutant loadings.

Two companion reports present the specific development of watershed loading models (HSPF). The Part 2 report (Bartosova et al., 2007a) focuses on two tributary watersheds (Blackberry and Poplar Creek) in the Fox River watershed. These pilot watersheds represent contrasting land use and different soil conditions. The HSPF models were calibrated to simulate daily streamflow and selected water quality constituents.

The Part 3 report (Bartosova et al., 2007b) describes the validation of hydrologic model parameters using flow observations from five tributary watersheds not used in the calibration process (Brewster Creek, Ferson Creek, Flint Creek, Mill Creek, and Tyler Creek watersheds).

The hydrologic model for the Fox River mainstem and remaining tributary watersheds currently is under development and will be addressed in a separate report. Development of water quality components of the HSPF model as well as development of the receiving water quality model (QUAL2) is planned to begin subsequently.

Background Information

A review of water quality data and previous studies (McConkey et al., 2004) led to the selection of the following constituents for detailed modeling: suspended solids, nitrogen (and its forms), phosphorus (and its forms), fecal coliform bacteria, dissolved oxygen (DO), and algae, including supporting parameters such as temperature, and organic matter (Biochemical Oxygen Demand or BOD). Table 1 provides an overview of water quality issues in the Fox River by identifying monitoring sites where measured values exceed water quality standards. Table 2 lists critical times and conditions when noncompliance with the IEPA standards typically occurs.

Table 1. Water Quality Issues Identified at Selected Locations (McConkey et al., 2004)

	Probabilistic noncompliance			*Presence of samples with substandard values*	
Location	*Ammonia nitrogen (Chronic quotient >1)*	*Fecal Coliform (>400/100 mL)*	*Phosphorus (>0.076 mg/L)*	*DO (<5 mg/L)*	*pH (>9)*
Johnsburg			X	X	
Route 176			X	X	
Algonquin	X	X	X	X	X
South Elgin		X	X	X	X
Geneva		X	X	X	
Montgomery		X	X		X
Oswego			X	X	X
Yorkville		X	X		X
Ottawa	X	X	X		X

Notes:
The phosphorus value is a guideline, not a water quality standard.
An “X” signifies water quality problems

Table 2. Critical Times and Conditions Identified for Selected Constituents in the Fox River Watershed (McConkey et al., 2004)

Constituent	*Critical time*	*Critical conditions*
DO	Summer (seasonal variation) Prior to sunrise (diurnal variation)	High temperature, low flow Impoundment, algae
Algae	Summer	Low flow, nutrient enrichment
Total nitrogen	Concentration fairly constant	Both high and low flows
Ammonia	Varies, typically summer (lower standard)	Low flow, high temperature, and high pH (effects standard)
Nitrate/nitrite	Spring	Precipitation events
Total phosphorus	Summer	Low flow (concentration) High flow (load)
Suspended solids	Summer (concentration) Spring to early summer (load)	High flow
pH	Varies	Low flow, algae
Fecal coliform	Summer (lower standard)	No clear pattern

Model Development

General Modeling Approach

The objective of the ISWS Fox River Watershed Investigation is to develop the structure of a suite of watershed loading and receiving water quality models of the Fox River watershed below Stratton Dam. Watershed loading model results can be used to evaluate future land use scenarios and their effect on delivery of water quality constituents, investigate and characterize pollution sources, and assess the flow/precipitation conditions when constituent loadings are critical. The receiving water quality model planned for later development will be used to assess the complex interactions and chemistry of the various constituents in the Fox River. The plan is to establish a model structure that retains options for more refined calibration as additional monitoring data become available. Model performance will be tested by comparison to observed values and through sensitivity analyses. Although not part of the current project plan, confidence limits could be further investigated, given additional data and specific numerical simulation tests.

The framework for the Fox River watershed model was created using the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), version 3.0, a multipurpose environmental analysis system developed by the U.S. Environmental Protection Agency (USEPA, 2001). The BASINS system enables users to prepare watershed scale hydrologic and water quality simulation models using a Geographic Information System (GIS), a vast inventory of watershed and meteorological data, and a set of modeling tools. The BASINS system includes:

- A nationally derived inventory of meteorological data, convenient access to GIS data layers required for the modeling analysis, including watershed boundaries, land use, soils, elevation, hydrography, and pollutant sources, etc.;
- Tools for model preparation, including watershed delineation, data management, and re-classification of a digital elevation model (DEM), land use, soils, and water quality data;
- Two watershed loading and transport models, HSPF and SWAT, a receiving water quality model QUAL2; and
- A data post-processor and several graphing/reporting formats for presenting results.

The 1400-square-mile (sq mi) study area was divided into 31 tributary watersheds and the mainstem watershed of the Fox River. Detailed information about soils, land use, topography, climate, and hydrology of the study area is provided in McConkey et al. (2004). Individual watershed loading models, prepared using the HSPF model for the 31 identified major tributaries, together with components to simulate loading from areas draining directly to the Fox River mainstem, when completed will provide information on the delivery of pollutants from the land surface. The HSPF model is a comprehensive, conceptual, long-term continuous simulation, distributed parameter watershed-scale modeling tool that simulates nonpoint source hydrology and water quality, and performs flow and water quality routing in the watershed reaches, including a contribution from point sources. The model requires spatial information about watershed topography, hydrography, land use, soils, and climate. Detailed information about data used in this study is provided in the "Data" section. The receiving water quality model (QUAL2) will be developed in the future part of the project.

The BASINS' Automatic Delineation Tool was used to subdivide each of the 31 tributary watersheds and the mainstem watershed into smaller, hydrologically connected subwatersheds and their stream reaches, and respective outlets. Land use in the models was divided into pervious and impervious areas. Agricultural, forest, and urban grassland areas were considered pervious, whereas urban areas were considered partly impervious. The Hydrologic Response Units (HRUs) created in these subwatersheds were based on various combinations of land use, hydrologic soil groups, and land surface slope. More information appears in the "HRU Definition" section. Calibration parameters were developed for unique HRU combinations in the pilot watersheds and can be transferred to corresponding HRUs in other tributary watersheds with data insufficient for calibration.

The study period, 1990-2003, was selected to provide a sufficiently long time series for model calibration and validation that represents contemporary watershed conditions. Study period data are separated into calibration and validation periods. Calibration data are used to establish parameter values in the models. The models are run using climate data from the validation period without adjustment to parameter values. The same statistical and graphic tests of fit are applied to both the final calibration and the validation results. Results of the test of fit ideally are similar for both calibration and validation datasets and acceptable. Data to calibrate individual models are not available for all 31 tributary watersheds. Thus, a stepwise approach to calibration was followed. Two tributary watersheds of the Fox River, Blackberry Creek and Poplar Creek watershed, were chosen as pilot watersheds for detailed model development and to provide guidance for parameterization of other tributary watersheds. These watersheds have the most abundant discharge and water quality datasets and also represent contrasting land uses. Blackberry Creek is a primarily rural watershed, and Poplar Creek is a primarily urban watershed. These models were calibrated to the extent possible with available data. Limited flow data are also available for these five tributary watersheds: Brewster Creek, Ferson Creek, Flint Creek, Mill Creek, and Tyler Creek. These watersheds were used to validate the hydrologic parameters developed during the calibration of the pilot watersheds in addition to validation in the pilot watersheds. Results of the calibration and validation appear in separate reports (Bartosova et al., 2007a, b).

Because the driving force in a watershed loading model is precipitation, which carries various constituents from the land surface to streams and rivers, the hydrologic component of the watershed model was developed first to characterize the relationship between precipitation and flow. After the hydrologic calibration step, water quality components of the HSPF models for the two pilot tributaries were calibrated with available data to simulate temperature (T), suspended sediment (SS), fecal coliform, nutrients (various forms of nitrogen, and total and dissolved phosphorus), dissolved oxygen (DO), and algae (as chlorophyll *a*). All available water quality data during the study period were used for calibrating the pilot watersheds. Full calibration and validation will be carried out after finalizing the hydrology model for the entire study area.

Ultimately, the HSPF models for the entire study area will be assembled, including the mainstem. Parameter values determined from the calibration of the hydrologic and water quality components of the HSPF model for these two pilot tributary watersheds can be applied to other similar (ungaged) tributary watersheds in the preparation of the HSPF model for the entire study area. Hydrologic and water quality simulation models of the Fox River mainstem will be developed, and output points chosen will correspond to the water quality stations and U.S. Geological Survey (USGS) streamflow gages on the mainstem. A time series of the simulated streamflows and concentrations from the tributary watersheds will be input to the Fox River model at the points of confluence with the mainstem. The hydrologic and water quality simulation models of the mainstem will be calibrated and validated using the streamflow and water quality data available throughout the Fox River mainstem and its tributaries, respectively.

Sources of Uncertainty in Modeling

Uncertainty in the model parameters and the output is unavoidable in any hydrologic and water quality modeling study. The extent of this uncertainty or the accuracy of a watershed model depends primarily on: 1) amount, accuracy, and resolution of the physical data available as model input; 2) amount, accuracy, and resolution of the physical data available to calibrate the model; 3) model structure (segmentation of reaches and/or subdivision of watersheds), and types of equations and assumptions the model uses to simulate hydrologic, chemical, and biological processes within the watershed and receiving waters; and 4) appropriateness of and uncertainty in parameter values that can be fitted (calibrated), measured, or empirically derived. These factors also are depicted in Figure 1.

Any measurement or representation of physical data always has limited accuracy. Various sources contribute to inaccuracy of measurements even when all errors, human or instrumental, are avoided. For example, direct discharge measurements are considered very good if they are within 5% of the flow. Accuracy of discharges computed from stage records at typical gaging stations is a function of the accuracy of instrumentation and the accuracy of the relationship between stage and discharge that has been established at the site. Properly calibrated instrumentation can measure precipitation with ±1% accuracy, but that accuracy is valid only at the single point of collection for the measured time interval. The measured value must be extrapolated or disaggregated to obtain precipitation in other locations or at other time intervals, respectively. Water quality data also have inherent limits of measurement accuracy as well as issues related to representativeness of samples both in space and in time. Uncertainty introduced with geospatial datasets is even more complex due to the spatial dimension added to data. Geospatial datasets usually do not display actual measurements but rather show generalized categories determined from point measurements or raster images. For example, when an aerial photograph is analyzed for land use data, a decision is made on categories that will be generated (lump all agricultural land into one category or divide by crop type), data format (create raster or polygon dataset), spatial resolution and scale of data (how to display small changes and irregularities), etc., with each decision affecting the model output. Given the amount of model-required data, complex data interactions, and inherent errors, accuracy of model output values cannot be quantified easily as a function of input error.

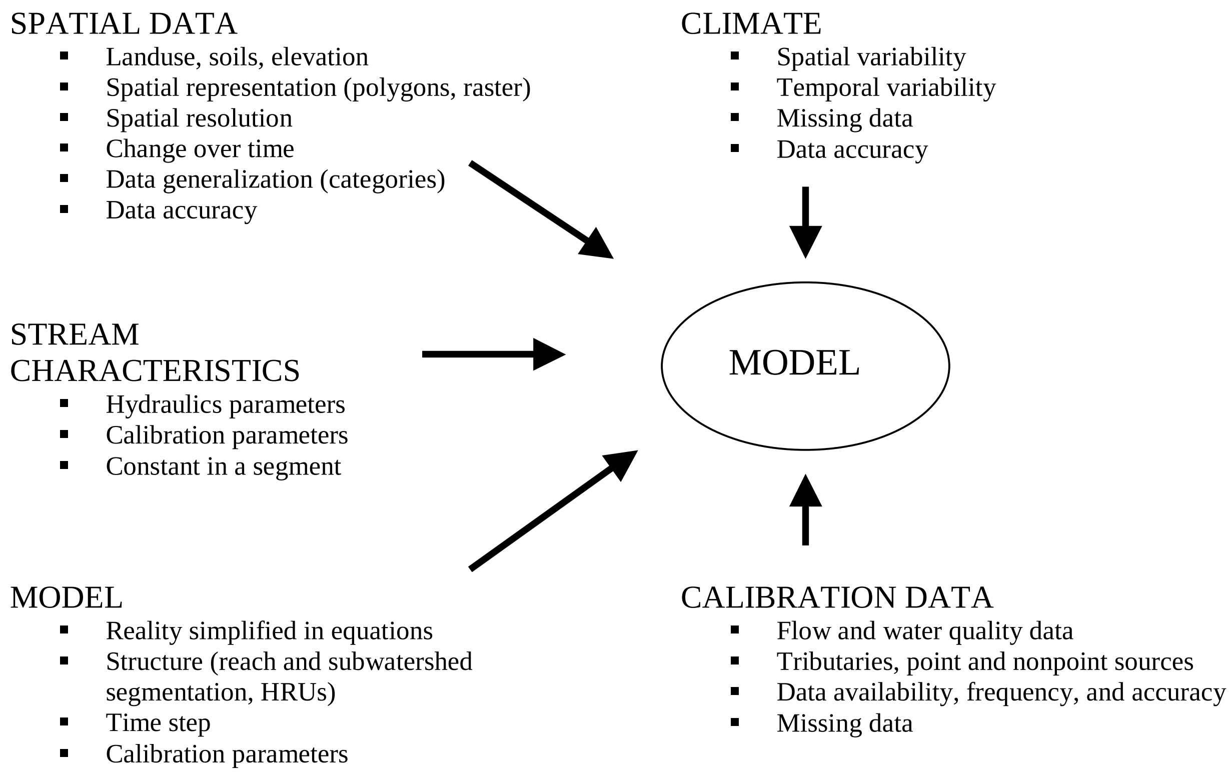

Figure 1. Various factors related to model structure, data, and parameters that affect model uncertainty.

Because the knowledge of basic but complex physical processes occurring in nature still is limited, even the most sophisticated watershed models are simplified representations of real-world physical processes that determine streamflow quantity and quality. Each watershed or a stream is represented in the HSPF model by individual subwatersheds, HRUs, and reach segments that are connected. Each HRU or reach segment is assumed to have homogenous characteristics. The model does not allow spatial variation within the HRU or reach segment; all parameters defined for each one are constant.

Most hydrologic and water quality simulation models conceptualize and aggregate complex interactions driven by a number of spatially distributed and highly interrelated water, energy, human, and vegetation processes. Compared to most watershed models, the HSPF model mathematically represents many physical processes that occur in a watershed, which allows the modeler to fine-tune the model to the unique characteristics of a given watershed. Even with the complexities of the HSPF model, however, complex processes and interactions are simulated using only relatively simple mathematical equations. Model parameters often do not correspond directly to measurable entities, and their values must be estimated in the calibration process by comparing model output to observed watershed and stream characteristics. During model calibration, these parameters are adjusted such that model behavior approximates the observed response of the system within specified calibration criteria over a selected time period. Models often are calibrated manually to match model output with historical data. Due to model complexity, nonlinearity, parameter correlation, and long model run times in case of long-term continuous watershed simulation models such as the HSPF, this subjective manual calibration process rarely results in finding a unique set of model parameters. Thus, variability or errors in the model structure, inputs (forcing), and output data may result in considerable uncertainty of the model predictions.

Calibration, Validation, and Confidence

During the calibration process, model parameter values are determined. Simplistically, the values are adjusted to achieve the closest possible agreement between simulated and observed values of flow and water quality constituents. A time period is selected for calibration, and model parameter values systematically are chosen to achieve the best possible agreement to observations during this period. Statistical and graphic measures of fit (agreement) are used as criteria to evaluate the calibration. Validation of the models is conducted by using data from a time period outside the calibration period and comparing simulated and observed values. Parameter values set during calibration are not modified. The same statistical and graphical measures of agreement used for calibration are applied to compare validation results. Validation is considered successful if simulated results have the same or similar measure of agreement as achieved during calibration.

Specific calibration and validation criteria for flow and water quality constituents are discussed later in this report. Application of these criteria and the results are presented in companion reports that describe specific models developed.

There are additional tools to assess the correctness of the parameterization of the model. Numerical experiments can be run to determine if the combination of parameter values are an unbiased set that uniquely characterize the system. Sensitivity analyses can be performed to test each parameter to determine relative impact of its value on simulated output values. This provides insight on critical parameters and can be used to develop recommendations for additional data collection. However, determining confidence in the model output values requires field observations. Rarely are there sufficient data of sufficient accuracy to define statistical confidence limits over a broad range of constituents and conditions.

Establishing parameter values and predicting uncertainty are paramount concerns for scientists as well as policy makers. A study by Melching (1995) explains in great detail the types and sources of model uncertainties, and reliability analysis methods. Researchers have developed techniques not only to parameterize the models using nonsubjective methods that globally determine optimum or unique parameters, but also to quantify the reliability of such parameters and resulting model predictions. Vrught et al. (2003) have developed the Shuffled Complex Evolution Metropolis algorithm (SCEM-UA), which is based on a variant of Markov Chain Monte Carlo methods. The SCEM-UA algorithm can be used to determine optimal model parameters automatically and to assign parameter and prediction uncertainties. Parameter Estimation or PEST (Doherty and Johnston, 2003) uses a modified Gauss-Marquardt-Levenberg method for parameter optimization and a nonlinear predictive analysis technique for parameter and prediction uncertainty analyses.

Due to time and resource constraints of this project, only a simple sensitivity analysis of selected HSPF parameters will be conducted for the models developed to determine the relative effect of those parameters on the simulation (model prediction). This process helps identify those model parameters that, when changed, cause the greatest change in model outputs. The sensitivity analysis will be conducted after the models are calibrated for the pilot watersheds and described in the report on each model as it is developed. Model output for the calibration period will be used for this analysis. Only one model parameter will be evaluated per sensitivity run corresponding to -60%, -20%, +20%, and +60% changes in the value of a calibrated parameter. Values for all 12 months will be changed by a fixed percentage for parameters with varying monthly values. The average of the model-simulated daily value for the given calibration period will be computed after each model run and compared with the average daily value simulated from the calibrated model to determine the percentage change of the parameter on modeled streamflow. After six runs with each parameter, the parameter will be reset to its former (or calibrated) value, and the sensitivity analysis will continue with the next parameter. The sensitivity analysis provides guidance to identify the most critical parameters for the particular watershed. Resources then can focus on gathering information to best establish the value of critical parameters. Success of the calibration process and the ability of the model to simulate realistic values depend on the availability and accuracy of observations. Once a model is calibrated and validated to simulate observed conditions adequately, it then can be used reliably to assess the impacts of change.

Results from calibration and validation model runs establish confidence in the model application and a typical variation of model outputs from measured values. Using a variety of conditions in model calibration is crucial for evaluating different management options or land use scenarios. The stepwise calibration process used in this project is designed to develop and test calibration parameters under different conditions. The pilot watersheds represent contrasting land uses and different soil conditions, five additional watersheds are used to evaluate performance of calibration parameters outside the pilot watersheds, and, finally, the parameters will be fine-tuned on the Fox River mainstem. This approach tests the underlying assumption of homogeneous HRUs. Future scenarios can be simulated by substituting HRUs representing existing land use conditions with HRUs representing alternate conditions, such as urban areas replacing agriculture.

Model components are calibrated to achieve the closest match possible between simulated values and observations. Once this is achieved, the models can be used to fill in data gaps and simulate possible future events. Given the limits of knowledge of natural processes, ability to compose formulas expressing physical conditions, and data accuracy; perfect agreement is not expected. However, the comparison of simulated to values to observations provides insights about model strengths and weaknesses. Calibration adjustments are made to most closely simulate periods of interest, times when water quality conditions are most critical in this project.

Data

Climate

Climate and hydraulic data are required for hydrologic model development, calibration, and validation. Time series of the climate data provide the input necessary for the HSPF model to simulate the continuous hydrologic and water quality response of the watershed. Appropriate representation of precipitation, temperature, wind speed, potential evapotranspiration (ET), potential surface evaporation, solar radiation, dew point temperature, and cloud cover are required to develop a valid model. As a group, these time series allow the HSPF model to represent changing weather conditions in the study watershed for the simulation. Using data from multiple climate stations located in or near the study area ensures spatial variability in rainfall will be incorporated into the model. The climate data must be compiled from various stations for the period of interest, stored in the WDM format, and resolved in an hourly time step to accommodate the algorithm in the HSPF model.

Climate data are available from several sources. Most stations record observations daily. The most comprehensive network of climate stations reporting daily data is the Cooperative Observer Network (Coop network) operated by the National Weather Service (NWS). The Coop stations collect only basic weather data, such as daily maximum and minimum temperatures, 24-hour precipitation totals, snowfall, and snow cover. Hourly weather observations are available only from a limited number of stations typically operated at major airports by the NWS or the Federal Aviation Administration. Observations from the airport network provide detailed information on climate, including temperature, precipitation, winds, atmospheric humidity, barometric pressure, and cloud cover (NOAA, 2004).

The National Climatic Data Center (NCDC) is the official Federal repository of all climatic data, including historical datasets, extremes, and other statistics. Published data are certified official data that have undergone quality control procedures. Data are stored in various datasets. The following datasets contain information on climate stations within the Fox River watershed (number of stations included in individual datasets varies):

- TD3200/TD3210, Coop: daily
- TD3240, Airport: hourly (precipitation only)
- TD3280, Airport: hourly (no precipitation)
- Integrated Surface Hourly (ISH), Airport: hourly (no precipitation)
- Unedited Local Climatological Data (ULCD), Airport: hourly

The Illinois Climate Network (ICN) is a 19-station network of automated weather sites scattered across Illinois and operated by the ISWS. The network records hourly weather observations on atmospheric pressure, air temperature, relative humidity, wind speed and direction, solar radiation, precipitation, and soil temperatures at several depths (ISWS, 2004). Two ICN stations are located in or near the Fox River watershed at St. Charles and DeKalb.

Table 3 shows availability of data for stations located within or in close proximity (10 mi or less) to the Fox River watershed. Information from all available sources was combined to obtain the most complete dataset. Representative climate stations were assigned to each subwatershed within a tributary or mainstem watershed based on the Thiessen polygon method.

Climate data for stations within or near the Fox River watershed were downloaded from the NCDC Web site (NOAA, 2004) or obtained from the ICN (ISWS, 2004). Some NCDC datasets are not available online and must be purchased as data CDs. Those datasets were obtained from the Midwestern Regional Climate Center, housed at the ISWS, which already had purchased the CDs.

Significant amounts of some constituents (e.g., nitrogen) can reach the land surface through wet and/or dry atmospheric deposition. The National Atmospheric Deposition Program (NADP) has two stations near the study area, NAPD monitoring site IL18 (Shabbona, DeKalb County) and IL19 (Argonne, DuPage County). Data collected at these sites include wet deposition of ammonium (NH_4), nitrate (NO_3), and inorganic nitrogen. Dry deposition data were downloaded from the USEPA Clean Air Status and Trends Network, or CASTNET (USEPA, 2005) for three stations in Illinois surrounding the study area. Data include fluxes of nitric acid (HNO_3^-), NH_4, and NO_3. Data for Argonne National Laboratory (ANL146), DuPage County, primarily were used. Missing data were supplemented by data from Stockton (STK138), Jo

Table 3. List of Stations and Hourly/Daily Data Imported into WDM Format

Station Name	*Precipitation*	*Tempera-ture*	*Wind speed*	*Solar radiation*	*Dew point*	*Potential evapo-transpiration*	*Evaporation*	*Cloud cover*
Antioch	D	D						
Aurora, IL (ICN)	H*	H*/D	H*/D	D	H*/D	D		
Aurora (Coop)	D	D						
Barrington 3 SW	D	D						
Chicago O'Hare	H		H/D	D	H/D	D		H
DeKalb	H/D	H/D	H	H	H	H	D	
DuPage	H*/D	H*/D	H*/D	D	H*/D			
Elgin	D	D						
Gurnee Public Works	D	D						
Harvard	D	D						
Lake Villa 2 NE	D	D						
Marengo	D	D						
Marseilles Lock	D	D*	D	D	D	D		
McHenry Stratton L&D	H/D	D*						
Morris 1 NW	H*/D	D						
Paw Paw 2 NW	D	D						
St. Charles	H	H	H	H	H	H		
Ottawa 5 SW	D	D						
Rockford	H		H/D	D	H/D	D		H
Utica Starved Rock Dam	D	D*						
Wheaton 3 SE	D	D						

Note: * Period of record does not cover the full calibration/validation period (1990-2003).

Daviess County, which were nearly identical to the ANL146 data. When both ANL146 and STK138 data were missing, data from Bondville (BVL130), Champaign County, were applied through linear regression.

The WDM Utility, software developed for creating and managing time series in WDM format, includes several scripts for the most common data formats. These scripts were used to import the TD3200/TD3210 data and TD3240 data. Other datasets required prior manipulation, reformatting in Excel software, and development of dataset-specific scripts for import into the WDM format.

Additional data manipulation was necessary to fill in missing information, including disaggregating daily data into hourly data or calculating missing time series from available data. Missing data were replaced with data from the nearest station. Time series are finalized progressively as necessary for individual tributary watershed models.

A request was sent to the FRSG and various other agencies to obtain additional climate data for the study area. Hourly precipitation data (January 2001-August 2004) for seven more stations located in Aurora, Geneva, Oswego, and Sugar Grove were obtained (Ryan D. Cramer, Walter E. Deuchler Associates Inc., Personal Communication, June 2005). Daily precipitation data (June 1999-December 2003) also were provided (Tim Morral, Fox Metro Water Reclamation District, Personal Communication, June 2005). The USGS operates 15 daily precipitation gages in Kane, DuPage, Cook, McHenry, Lake, and Will Counties. These gages are either in the Fox River watershed or very close to its boundary. Data were available primarily from October 1998 to August 2004. The Stormwater Management Commission of Lake County operates several hourly precipitation stations. Data (August 2001-present) for four stations located in the study area also were obtained (Perry W. Danler, Stormwater Management Commission, Personal Communication, June 2005).

Land Use

Land use (land cover) provides information on the permeability of the land surface that affects the volume of runoff from precipitation events, and the type and amount of constituents that may be washed off from the surface. The Illinois Interagency Landscape Classification Project (IILCP) has prepared an inventory of land cover for Illinois from satellite imagery acquired during the spring, summer, and fall seasons of 1999 and 2000. Through this effort, various data products are available, including a GIS dataset, *Land Cover of Illinois 1999-2000 Classification*, and tabular data available in electronic format, *Land Cover of Illinois 1999-2000 On-Line Statistical Summary* (IDOA, 2003). The *Land Cover of Illinois 1999-2000* GIS dataset was used for land use analysis in this study as it represents recent conditions, which is important when evaluating management options, and it is available in a consistent format for the entire study area. Applicability of this dataset over the study period was tested on Blackberry Creek watershed by having two validation series, one at the beginning and one at the end of the study period.

Soils

Soils are characterized by their porosity (ability to hold moisture) and transmissibility (ease with which water can move through the soil). For example, soils that can hold water and allow it to move through them will delay delivery of precipitation to a stream network, generally resulting in a strong contribution to base flow.

The State Soil Geographic Database STATSGO is available for the entire Fox River watershed at a scale of 1:250,000. The Soil Survey Geographic Database SSURGO has a higher resolution, with mapping scales from 1:12,000 to 1:63,360. The SSURGO data are only available for selected counties in the Fox River watershed: Kane, McHenry, DuPage, DeKalb, and Will Counties. Both databases have similar data structure and attributes but different levels of accuracy. Both datasets are based on county soil surveys. However, original soil survey data are more generalized in STATSGO than in SSURGO (NRCS, 2003a, b). Each map unit (polygon) on a STATSGO soil map contains up to 21 components for which there are attribute data with the corresponding percent area within the map unit, but there is no visible distinction of the location of these components in the polygon. Each map unit in a SSURGO soil map represents up to three soil components.

Alternate sources for soils data can be used in some areas when SSURGO data are not available, although their geographic scope can be limited. The soil type for each HRU was determined spatially from GIS data, but parameters corresponding to the soil type were entered manually during development of the HSPF model. Thus, alternate soil coverages could be used. The ISWS digitized soil survey data for Kendall County (County Soil Association Maps) as part of the Illinois Streamflow Assessment Model (ILSAM) project development, and each map unit represents up to five soil components. The resolution of this dataset is not as high as resolution of SSURGO but significantly higher than resolution of STATSGO. Cook County soil survey data were digitized for the Illinois Department of Transportation. This dataset was created on a single component level with a resolution comparable to SSURGO data, although the accuracy of the line work was lower.

Soils in tributary watersheds were classified based on hydrologic soil groups (A, B, C, or D) as specified in available digital soil coverages with the most detail. Soils of hydrologic soil group A are highly permeable (e.g., sand) while soils of hydrologic soil group D have a very low infiltration rate (e.g., clay). The SSURGO data or data with a similar level of detail were preferred. The STATSGO data were used when more detailed information was not available.

Digital Elevation Models (DEMs)

The outcome of automatic delineation and its accuracy greatly depends on accuracy and resolution of elevation data used in the process. Because a large portion of the watershed has a very low slope, both vertical and horizontal accuracy and resolution are crucial in determining subwatershed boundaries. Three statewide datasets describing elevation are available. In Illinois, the Illinois State Geological Survey (ISGS) and the USGS shared costs to update a number of the

DEMs from Level 1 (low quality) elevation data to Level 2 (best quality) to make this the highest-resolution, statewide DEM coverage at the time (Luman et al., 2002). The USGS National Elevation Dataset (NED) was produced by merging the highest-resolution, best-quality elevation data available across the United States (USGS, 2005b). The NED is available for download in 30-meter or m (1 arc second) or 10-m (1/3 arc second) seamless raster format. The higher resolution NED was made available to the public in 2005.

Additional datasets are available but only for some counties. For example, Cook County, Illinois, recently acquired Light Detection and Ranging (LiDAR) data. Filtered LiDAR point data provided by Cook County were converted into 10-m DEM with 0.01 foot (ft) vertical resolution, the same as reported in the original LiDAR data. However, the BASINS system could not process the coverage, possibly due to incompatible formatting or the large amount of data.

Watershed boundaries of the pilot watersheds were generated using various available datasets, and the results were compared to Hydrologic Unit Code 12 (HUC-12) watershed (NRCS, 2003c) boundaries. The Illinois 30-m DEM was used to delineate watershed boundaries for the two pilot watersheds, Blackberry Creek and Poplar Creek. The watershed boundary delineated from the 30-m DEM varied significantly from the HUC-12 boundary, particularly in areas characterized by very flat terrain. Pre-processing the DEM grid by enforcing (burning in) HUC-12 watershed boundaries eliminated most of the significant differences in the pilot watersheds. However, the relevance of internal subdelineation remained in question. When the 10-m NED was available for download, all three datasets (30-m DEM, 30-m NED, and 10-m NED) were tested using the automatic delineation procedure. After comparing results of automatic delineation across individual datasets and with information on storm sewers, the 10-m NED most closely represented the actual drainage situation and was used in delineating watershed and subwatershed boundaries in this study. Resulting boundaries conformed to the established HUC-12 boundaries significantly better than the 30-m DEM.

Although the NED resolution is relatively high, it does not necessarily reflect the present situation. Figure 2 shows the dates of the sources used to derive the NED. Most quadrangles (43 of 51 displayed) reflect topography before 1985, more than 20 years ago. The NED for the Upper and Lower Fox River watersheds was derived from sources created typically in the 1960s and 1970s, respectively. The 10-m NED was derived from the same source as the 30-m NED, but for a smaller grid size.

Streams and Related Water Features

Spatial Representation. Geospatial representation of streams for watershed delineation or display was taken from the high-resolution National Hydrography Dataset (NHD), as it became available throughout the project (USGS, 2004). The medium-resolution NHD was modified early in the project to help display locations of other features that may be specified as a river mileage such as gages or measured cross sections. Using detailed information available from the ILSAM, reaches defined in the NHD further were attributed with upstream and downstream river mile, and ILSAM code. Unlike a stream name, the ILSAM code uniquely identifies a stream in Illinois. The ILSAM contains 95 data points on the Fox River mainstem, of which 81 are in the study area. The ILSAM river miles correspond to those developed by the

USGS from 1:24,000 scale topographic maps, except for a few points updated by ILSAM developers. The ILSAM data points were used to calibrate the linear referencing of the NHD. The shapefile created from the NHD and the ILSAM has river miles encoded directly into spatial representation of streams.

Channel Geometry. Flood Insurance Studies (FIS) issued by the Federal Emergency Management Agency (FEMA) contain data on channel cross sections, including bottom elevations necessary to evaluate channel slope. Current models used in the FIS for the Fox River are in HEC-2 format, a hydraulic program developed by the Hydraulic Engineering Center of U.S. Army Corps of Engineers, (USACE, 2003). Data files were converted to a format compatible with the Hydrologic Engineering Center's River Analysis System or HEC-RAS (USACE, 2002) that was used to analyze the data. Table 4 shows FIS data along the Fox River used in this study.

Exact locations of cross sections were verified, and river miles in data files were adjusted to match those encoded in the medium-resolution NHD. (**Note:** The ILSAM information was used to attribute the NHD with river miles.)

A total of 573 individual cross sections were extracted from FIS models. The distance between available cross sections was less than 0.5 mi (92%) and less than a mile (98%). The median distance between cross sections was 0.068 mi (359 ft).

Dams and Impoundments. The ISWS created a shapefile of dams on the Fox River mainstem (McConkey et al., 2004). Latitude and longitude information for the dams initially was gathered from Chicago Area Paddling Guide Web site (2003). Dam locations were verified using digital orthoquadrangles (DOQs) at 1:13,000 scale. The attribute information was gathered from Santucci and Gephard (2003), including the extent of impoundment. Information on smaller dams was extracted from National Inventory of Dams or NID (USACE, 2005), FIS profiles, or visually from topographic maps at 1:24,000 scale or DOQs.

Intakes for Public Water Supply. Information on public water-supply intakes was taken from the ISWS Arc/INFO geographic database Public Water Supply Surface Water Intakes. Intake locations are maintained as part of the ISWS Illinois Water Inventory Program (IWIP) database (http://www.sws.uiuc.edu/gws/iwip). The annually updated IWIP database contains extensive information on location (river miles), ownership, and historical annual average pumpage.

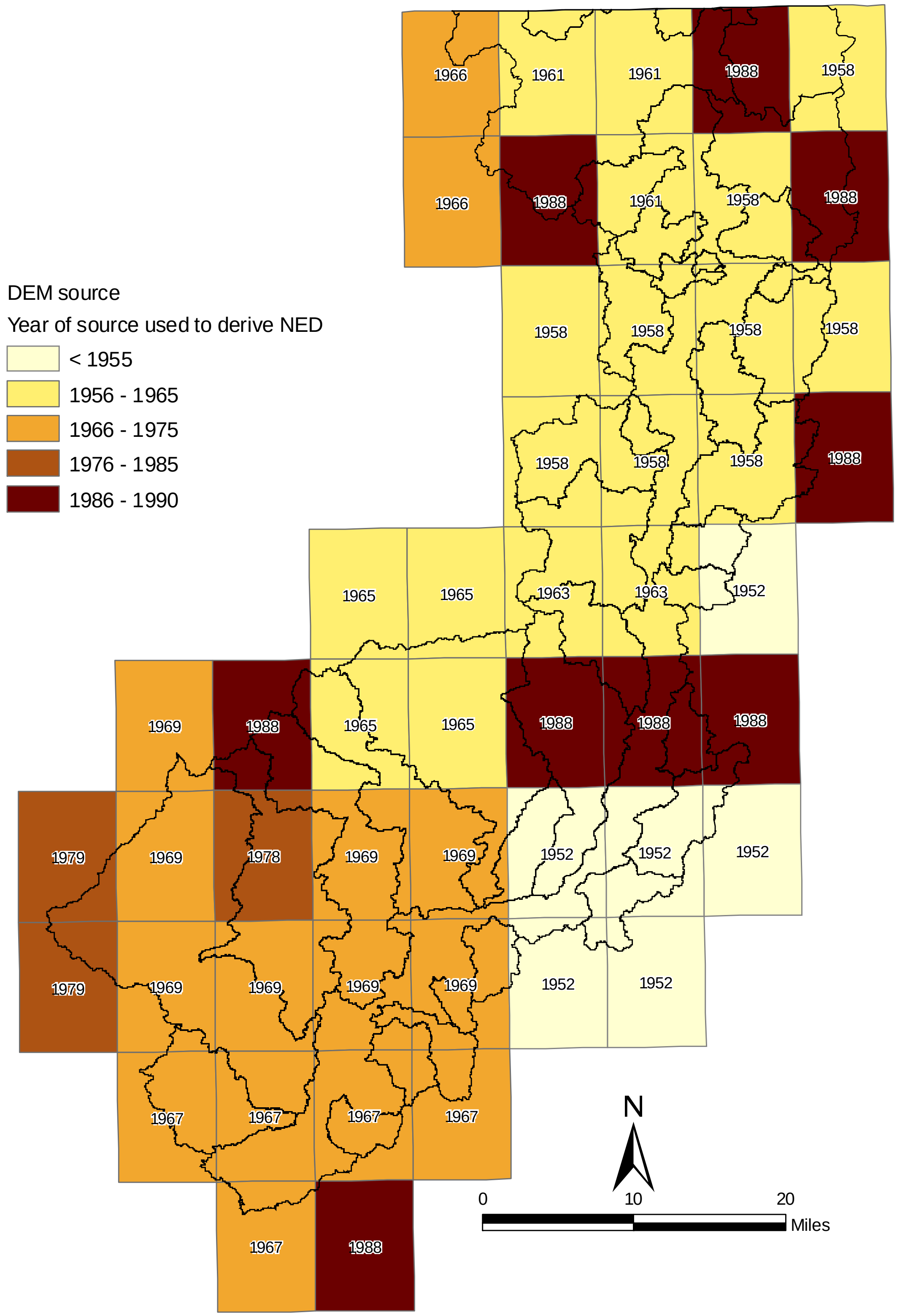

Figure 2. Year of original photography of the source data used to derive the NED in the Fox River watershed.

Table 4. Flood Insurance Studies Available for the Fox River

	FIS Extent		
	Location name		*River mile*
Source	*Downstream*	*Upstream*	
LMMP 1998-LaSalle FIS 2001	Mouth at Ottawa	LaSalle-Kendall Co line	0.0 - 25.2
Kendall FIS 1982-2002	LaSalle-Kendall Co line	Kendall-Kane Co line	25.2 - 45.4
Montgomery FIS 1979-Kane 2002	Kendall-Kane Co line	Montgomery Dam	45.4 - 46.3
Aurora FIS 1979-1997	Montgomery dam	½ mi S I-88, Aurora	46.3 - 50.7
Kane FIS 1981-2002	½ mi S I-88, Aurora	South Elgin Dam	50.7 - 67.3
Elgin FIS 1981-Kane 2002	South Elgin Dam	Elgin Dam	67.3 - 71.0
Kane FIS 1981-2002	Elgin Dam	Carpentersville Dam	71.0 - 77.2
Kane FIS 1981-2002, Algonquin FIS 1980	Carpentersville Dam	Algonquin Dam	77.2 - 81.6
Post-FIS model	Algonquin Dam	McHenry Dam	81.6 - 97.7

Note: LMMP is Limited Map Maintenance Program

Streamflow Gages. A previously prepared shapefile of USGS gages was used (McConkey et al., 2004). Gage locations were displayed by latitude and longitude published on the USGS Web site (USGS, 2003) using ArcMap software.

National Pollution Discharge Elimination System (NPDES) Permitted Discharges. A shapefile created by the ISWS (McConkey et al., 2004) used information from the USEPA EnviroFacts database available online (USEPA, 2003). Location in that database is specified by latitude and longitude. Geographical coordinates provided on permit applications by applicants are not verified by the USEPA. Permit locations displayed using ArcMap software were adjusted where necessary to match descriptions or locations of permits active in 2002 as provided by the IEPA. Updated locations then were submitted to the FRSG for review and correction. The description included in the database is not always specific; thus, local knowledge of stakeholders is invaluable in identifying proper location of NPDES facilities.

Combined Sewer Overflows (CSOs). CSOs can be found in Elgin and Aurora. Geographic coordinates provided on the NPDES permit applications were displayed with DOQs using ArcMap software, and a printed map was submitted to CSO operators for review and verification.

Water Quality Monitoring. A relational database, FoxDB, was developed during Phase I of the project. The FoxDB contains all water and sediment quality data collected in the Illinois part of the Fox River watershed. Database structure and content are described fully (McConkey et al., 2004). Monitoring site locations are encoded in the database by latitude and longitude.

Agriculture Activities

Corn and Soybean Production. These data provide information on nutrient uptake by corn and soybeans. Although the nutrient cycle on the land surface was not simulated directly in the HSPF model, production data were used to guide the estimation of inputs. Production statistics were compiled with USDA NASS (2004) data for the eight counties in the Fox River watershed. Yields of corn (Table 5) and soybeans (Table 6) are very similar in different counties, but most production of these crops is in LaSalle, DeKalb, McHenry, Kane, and Kendall Counties. Data on planting and harvesting dates and tillage practices will be based on the *Illinois Agronomy Handbook* (UIUC, 2004).

Table 5. Corn Production Statistics for Different Counties (Average of 1990-2003)

County	*Average area planted (acre)*	*Average yield (bu/acre)*
Cook	9,314	114
DeKalb	201,971	145
DuPage	7,000	124
Kane	99,993	140
Kendall	86,236	132
LaSalle	288,621	140
Lake	16,607	101
McHenry	111,093	127

Table 6. Soybean Production Statistics for Different Counties (Average of 1990-2003)

County	*Average area planted (acre)*	*Average yield (bu/acre)*
Cook	10,586	34
DeKalb	129,236	46
DuPage	5,100	38
Kane	68,564	43
Kendall	66,550	42
LaSalle	254,471	44
Lake	18,336	30
McHenry	67,557	39

Livestock Population. Facilities located in the watershed that house different types of livestock should be considered in the water quality model as these activities contribute loadings of water quality constituents to the watershed, such as fecal coliform. A systematic inventory of such facilities is not available from the Illinois Department of Natural Resources (IDNR), IEPA, nor the Illinois Department of Agriculture (IDOA). Thus, it was difficult to obtain detailed (or sometimes any) information about such facilities in different parts of the Fox River watershed. A list of livestock facilities the IEPA inspected between 1977 and 2004 was provided (Tim Kluge, IEPA, Personal Communication, February 2005). That list does not include all facilities in the area, only those visited by IEPA officials, but does provide some detailed information about facility locations. These facilities are displayed in Figure 3.

Based on USDA NASS (2004) data, populations in eight different counties were compiled for cattle and calves (Table 7) and hogs and pigs (Table 8). These statistics helped identify counties with the greatest population of different types of livestock. Based on the USDA NASS data (2004), insignificant populations of poultry and sheep and lambs were found in those counties.

Based on feedback from the Poplar Creek watershed group in October 2004, there were no significant livestock facilities in that watershed. Given the lack of detailed data, similar feedback from other watershed groups would help to identify or confirm the existence of such facilities elsewhere in the Fox River watershed.

Chemical Fertilizer Application Data. Nitrogen and phosphorus-based fertilizers are used extensively in agriculture. These fertilizers also are used for landscaping and lawn maintenance in urban areas. Based on communication with the IDOA and various Soil and Water Conservation Districts, none of these agencies had information about the type of fertilizers used, rate of application, time of application, or methods of application in the Fox River watershed. Therefore, information on recommended fertilizer application was taken from the *Illinois Agronomy Handbook* (UIUC, 2004).

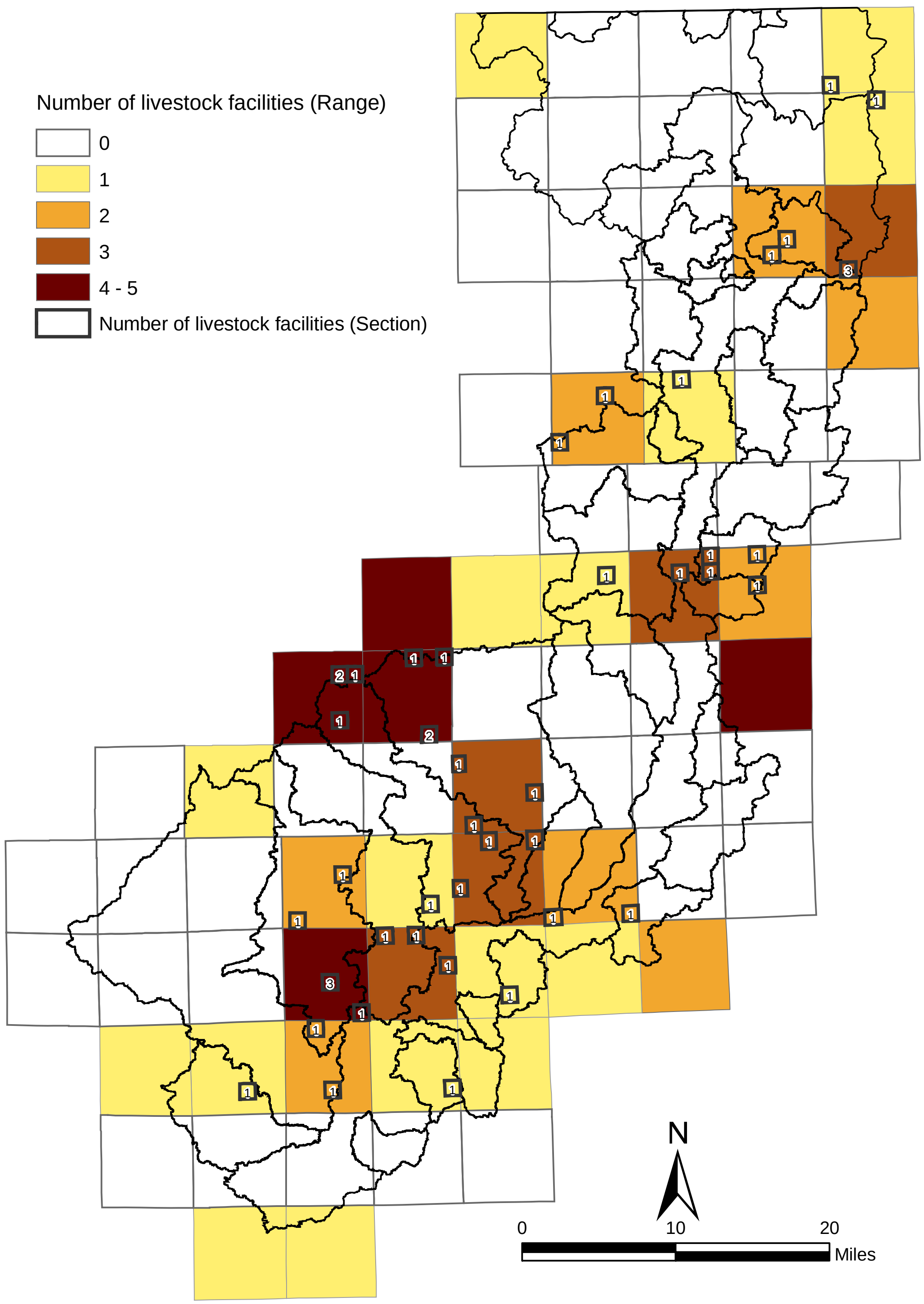

Figure 3. Number of livestock facilities by Range and Section.

Table 7. County-based Statistics of Cattle and Calves, 1997 and 2002

County	Number of farms with 200-499 head		Number of farms with 500+head		Total head count	
	1997	2002	1997	2002	1997	2002
Cook	0	0	0	0	438	75
DeKalb	29	19	12	21	28,046	31,151
DuPage	0	0	0	0	194	66
Kane	10	6	6	5	11,742	9,539
Kendall	2	1	2	1	4,845	3,439
Lake	0	0	1	1	1,792	1,394
LaSalle	12	10	5	6	16,913	14,753
McHenry	11	14	12	6	26,432	18,497

Table 8. County-based Statistics of Hogs and Pigs, 1997 and 2002

County	Number of farms with 500-999 head		Number of farms with 100+ head		Total head count	
	1997	2002	1997	2002	1997	2002
Cook	0	0	0	0	4	1
DeKalb	25	9	39	47	155,141	201,681
DuPage	0	0	0	0	3	1
Kane	2	4	11	6	38,803	28,047
Kendall	7	1	4	5	22,525	29,905
Lake	0	0	0	0	11	3
LaSalle	7	9	12	4	32,561	16,205
McHenry	6	4	8	4	33,014	21,634

Populations of Wild Animals/Birds. When present in significant numbers in proximity to surface water bodies, wild animals/birds may add considerably to fecal coliform loads. It is therefore imperative to identify any such occurrences in the watershed. Officials at the IDNR regional and Springfield offices, Illinois Natural History Survey, U.S. Fish and Wildlife Service, and the county wildlife biologists were contacted for population statistics. Unfortunately, no single database contains the necessary data. A list of threatened and endangered species and their numbers of occurrence in the eight counties was obtained (Tara Kieninger, IDNR, Personal Communication, 2004). No information about the total population of these species or other common mammals was available. Only limited information about the populations of common watershed mammals, such as deer, raccoon, otters etc., is available (Bob Bluette, IDNR, Personal Communication, 2004), but fecal coliform loads from Canada geese far surpass those of mammals. Similar feedback also was received from the Poplar Creek watershed group. The populations of various species were estimated with the Bacteria Tool. Details are described in the section “Fecal Coliform Bacteria.”

Subwatershed Definition and Delineation

The process of delineating the subwatersheds is very important as it defines the internal structure of the model and location of possible calculation or outlet points for which model output can be exported and reviewed. The BASINS Automatic Delineation Tool was used to subdivide each tributary watershed into smaller, hydrologically connected subwatersheds. Reaches and outlets were defined for each tributary watershed based on selected criteria. Subwatersheds were delineated by enforcing existing streams using the high-resolution NHD (USGS, 2004). In selected cases, the NED grid was pre-processed to enforce (burn in) HUC-12 watershed boundaries by artificially increasing the elevation at HUC-12 boundary cells by up to 7 feet to resolve major discrepancies.

The BASINS delineation algorithm also delineates streams based on the stream threshold number. Those numbers were assigned accordingly to match the network of perennial streams in the high-resolution NHD and to prevent delineation of intermittent streams or artificial streams not in the NHD or on the DOQ (USGS, 2005a).

Stream Reach Definitions and Outlet Specifications

Delineation of the reachwise segmentation of a stream is fundamental to the data input to any hydrologic or water quality model, including the HSPF model. Stream reaches represent physical segments along the river for the model. Reaches must be selected carefully because the model assumes constant hydraulic characteristics and rate coefficients within each reach. Physical geometry specifications define relationships between water depth, flow, surface area, and volume in a reach. Mixing of constituents and travel time along the stream are influenced by channel slope, cross-sectional area, velocity, channel roughness, and other physical characteristics or structures, such as dams. Those parameters play an important role in the fate and transport of modeled water quality constituents.

The following criteria were used to identify reaches and their respective outlet points:

- Junctions of perennial tributaries
- USGS flow gages
- Water quality sampling stations (FoxDB) and River Watch sites
- Change in physical characteristics of the stream (slope, impoundment, etc.)
- Significant change in land use or soil conditions
- Availability of climate data

High-resolution NHD (1:24,000 scale) linework was used to identify perennial tributaries. The HSPF model generates channel geometry from available data; for very small streams, typically there is insufficient data to define the channel adequately. During very low flows this often leads to instability of the water quality modules within the HSPF model. Therefore, intermittent tributaries (small streams) were not modeled explicitly as streams but rather were assumed to contribute to perennial streams through surface runoff.

The USGS gages, River Watch sites, or water quality monitoring stations do not mark a change in physical channel conditions, but rather provide data for calibration and verification of simulated watershed hydrology and water quality. The HSPF model provides results only at outlets along the river explicitly selected before the model run (i.e., computational points). These stations identify those outlets that are specified as computational points in the model.

The channel slope was determined from FIS profiles when available. Surface elevation profiles were generated for streams for which no FIS data exist. Figure 4 shows both land surface elevation along the NHD flowline and channel bottom elevation as specified in an FIS model for individual cross sections. Although the absolute values of elevation and even slope somehow differ, the points of a major change in slope, as indicated by black arrows in the figure, do correspond across both methods.

A dam creates a significant discontinuity in a river flow regime, with different sediment and water quality conditions upstream and downstream. The extent of the impoundment (area of reduced velocity and increased depth created by the dam structure) will vary depending upon the flow conditions. Endpoints of the impoundment on the Fox River were defined based on the length of impoundment given by Santucci and Gephard (2003), FIS profiles, topographic maps or DOQs.

Preliminary criteria for reach segmentation and outlet specification were presented to the FRSG on June 8, 2004. Their recommendations on outlet locations were incorporated into the model design. Model outlet (calculation) points identified through this process represent points

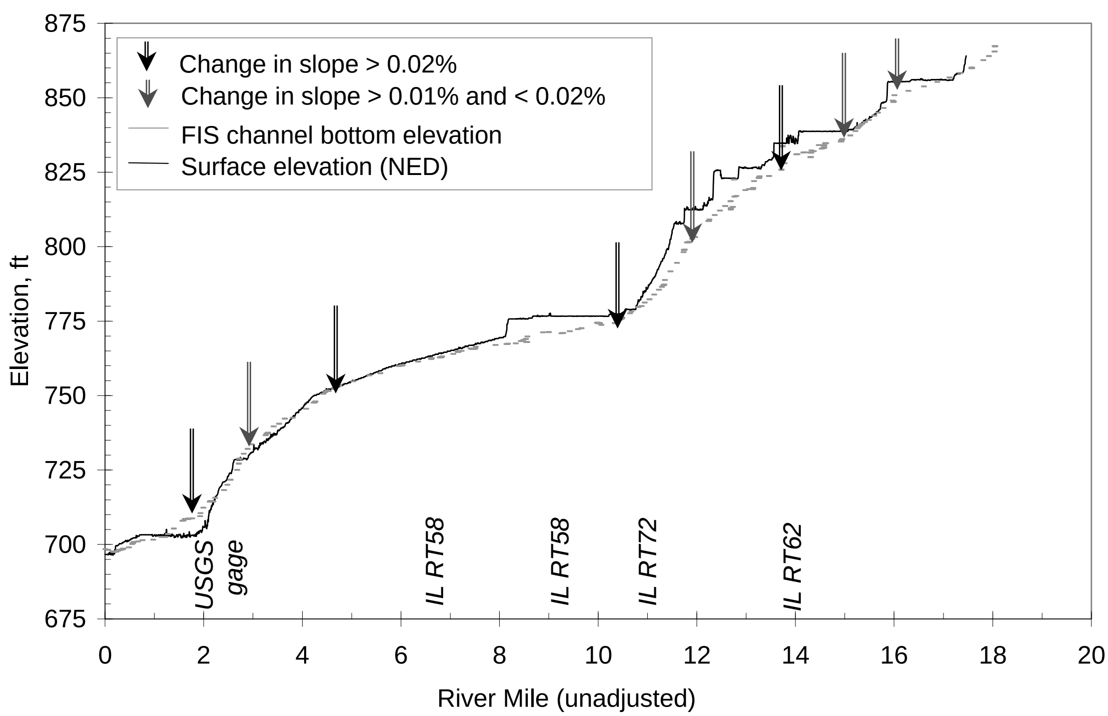

Figure 4. Comparison of elevation profiles from FIS (channel bottom elevation) and NED (land surface elevation) data, Poplar Creek.

for which flow and water quality results can be output and inspected. It is important to understand that the accuracy and reliability of the simulated values at any given outlet depend upon whether or not monitoring data are available for calibration at that point.

Boundary Issues

The HUC-12 watershed boundaries, the product of an interagency effort, are recognized for use within the State of Illinois. The watershed boundary generated from automatic delineation should follow the HUC-12 boundary as closely as possible, giving consideration to small discrepancies due to data resolution and scale, calculation procedure, and uncertainty in HUC-12 boundaries. Delineated watershed areas were compared to the HUC-12 areas. Where the difference between these areas exceeded 5%, the area was examined closely using the NED, digital topography maps (1:24000 scale), and DOQs, and findings were documented. Due to the file sizes, these documents are provided to the FRSG only in the electronic form and are available from the ISWS upon request. The decision on which boundary represents the reality was made for each case separately.

Urban stormwater systems must be considered when developing watershed boundaries. Municipalities in the Poplar Creek watershed were contacted directly for digital or paper copies of their storm sewer systems. Remaining problematic areas were resolved individually by contacting respective municipalities.

The inconsistencies typically occur in extensive flat areas, marshland, recently developed urban areas, and near elevated road or rail structures. The most common problems encountered during delineation are described below:

Flat Areas and Marshland. In flat areas, BASINS algorithms often have difficulty finding flow patterns. The NED was examined very closely in areas with discrepancies, including creating an elevation profile along the discrepancy lines. In some cases, local city or village authorities were contacted regarding drainage of a specific discrepancy area. Problems in flat areas were resolved on a case-by-case basis, selecting a delineation line that most closely represented detailed findings.

Urban Residential Areas. The BASINS boundary algorithm strictly follows a path defined by NED. Problems occur especially in urban areas developed since the NED source date (Figure 2). For example, storm sewers can reroute natural drainage patterns, and landscaping modifies the elevation. When new detention ponds are constructed in a new development (Figure 5), the BASINS-delineated boundary may cross through the detention pond. The residential area in question does not appear on the topographic map or the NED. Due to increased residential development, existing ponds were combined and extended. Figure 5 shows the area before and after development. In this case, the HUC-12 boundary was followed as it did not cross the water features in question.

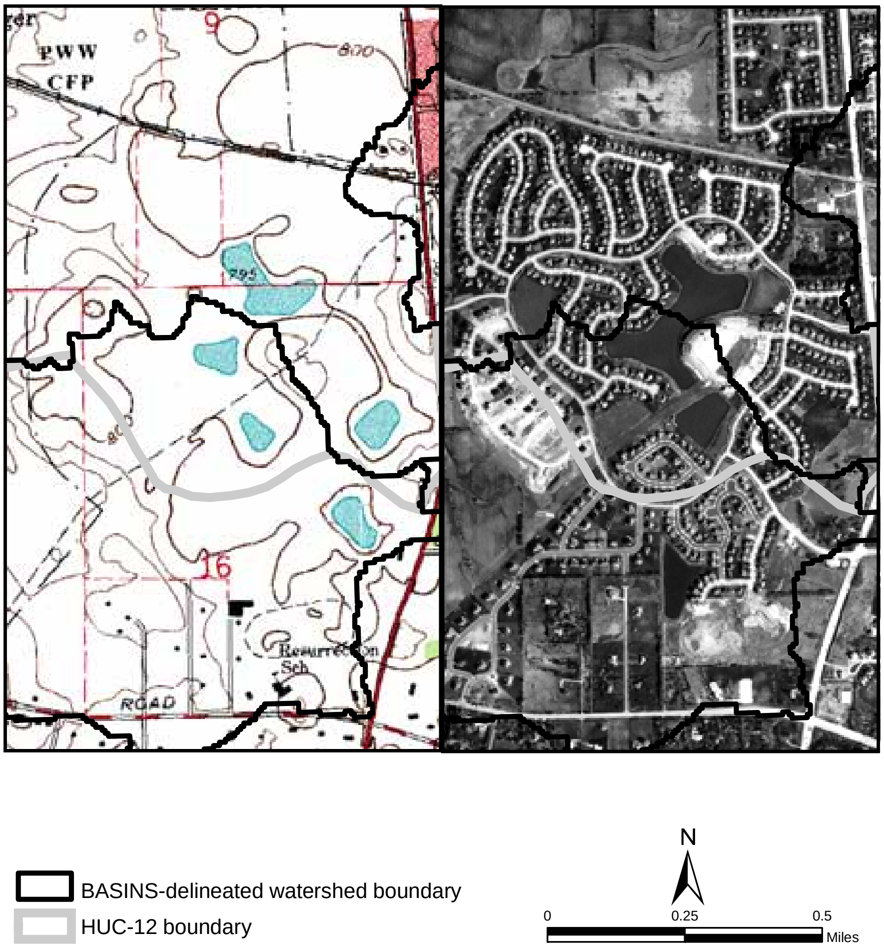

Figure 5. An example of a discrepancy in the watershed boundary due to residential development, Brewster Creek watershed.

Road as Barrier. Quite often roads and railroads complicate the delineation. When elevated structures, such as overpasses or railroads, appear in the NED, they create an obstruction and cause the delineation algorithm to reroute flow in a different direction. Figure 6 illustrates how BASINS-delineated boundary changes direction when it encounters an elevated road. Because natural drainage patterns typically are preserved by constructing culverts that allow surface runoff to pass underneath such structures, HUC boundaries were enforced in most cases.

Multiple Outfalls from a Single Structure. Fermi National Accelerator Laboratory (Fermilab) has three NPDES outfalls that discharge into three different watersheds. Only one outfall, the Indian Creek watershed, discharges into the Fox River watershed. Based on outfall locations and a previous study by Knapp (1998), it was decided to follow the BASINS boundary that excluded the Fermilab area from the Fox River watershed and use data for the relevant NPDES outfall to specify the surface runoff contribution from the structure. Outfall locations and watershed boundaries are illustrated (Figure 7).

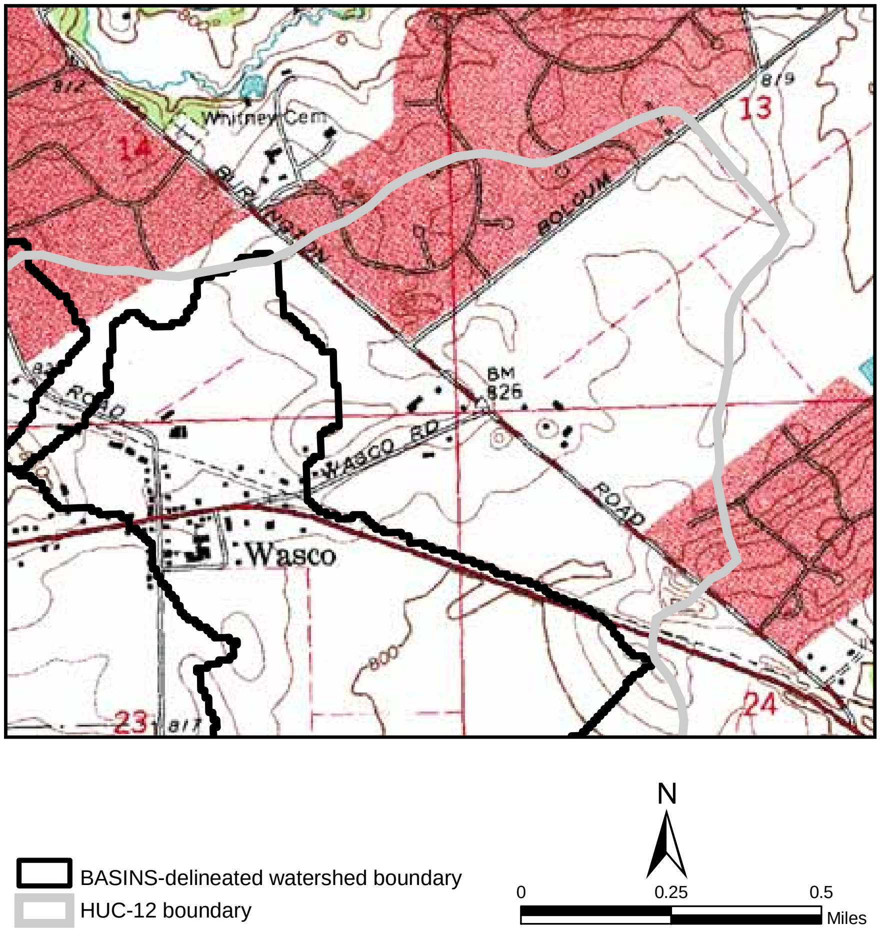

Figure 6. An example of a discrepancy in the watershed boundary due to elevated road structure, Mill Creek watershed.

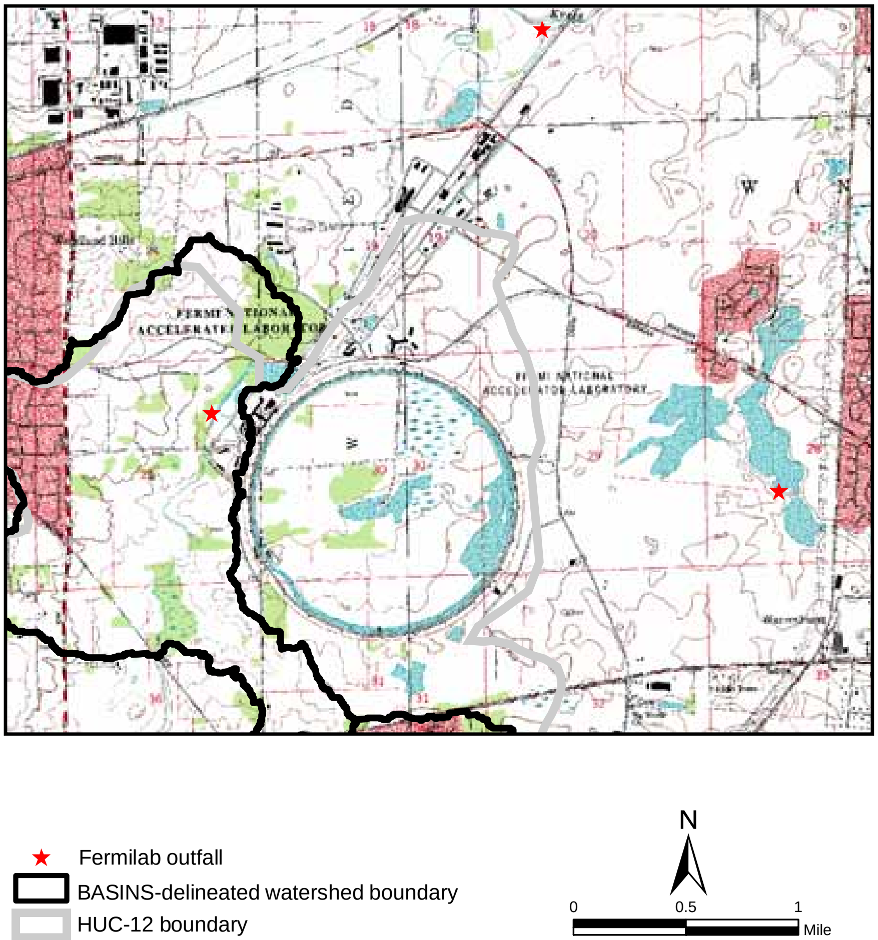

Figure 7. An example of a discrepancy in the watershed boundary due to a single structure with multiple outfalls, Indian Creek watershed.

Segmentation of the Fox River

A detailed reach segment scheme of the mainstem of the Fox River from Stratton Dam to the confluence with the Illinois River was determined. Tributary inflows, NPDES discharge locations, public water-supply withdrawal sites, and channel geometry were evaluated to design the reach segmentation scheme for the river. Table 9 summarizes criteria used in defining a reach segment scheme for the Fox River. Although criteria are general and must be considered when developing any watershed loading and/or water quality model, numerical values specifically were selected for this study.

Channel slope was calculated from channel bottom elevation and location along the river. The longitudinal profile of the Fox River is displayed (Figure 8). Arrows identify significant change in slope. Figure 9 shows changes in the Manning's *n* roughness coefficient used in the HEC-2 models for the Fox River. The Manning's roughness plays an important role in calculating channel hydraulics. It affects the relationship between channel cross-sectional area and flow. Again, a division is suggested to designate homogeneous segments of the river.

Table 9. Criteria Considered in Fox River Segmentation

Criterion	*Watershed hydrology*	*Water quality*
Channel characteristics:		
Change in slope > 0.02%	*	*
Change in channel Manning's roughness > 0.01	*	*
Structures:		
Dams	*	*
USGS gages	*	
Others:		
Flow condition (free flowing or impounded)	*	*
Significant tributary	*	
Water quality monitoring		*

Note: * Signifies an important criterion for the respective model.

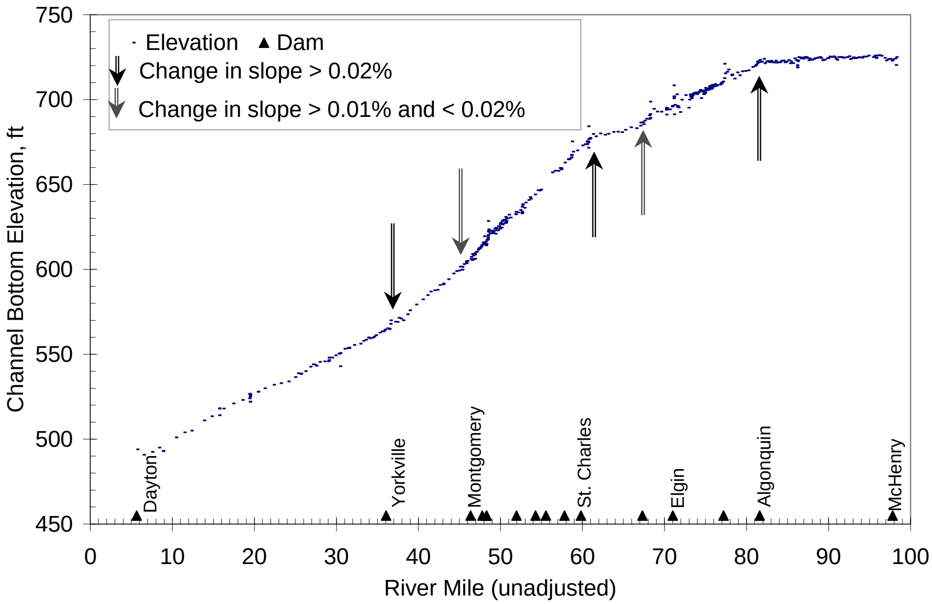

Figure 8. Longitudinal profile of the Fox River from Dayton to Stratton Dam.

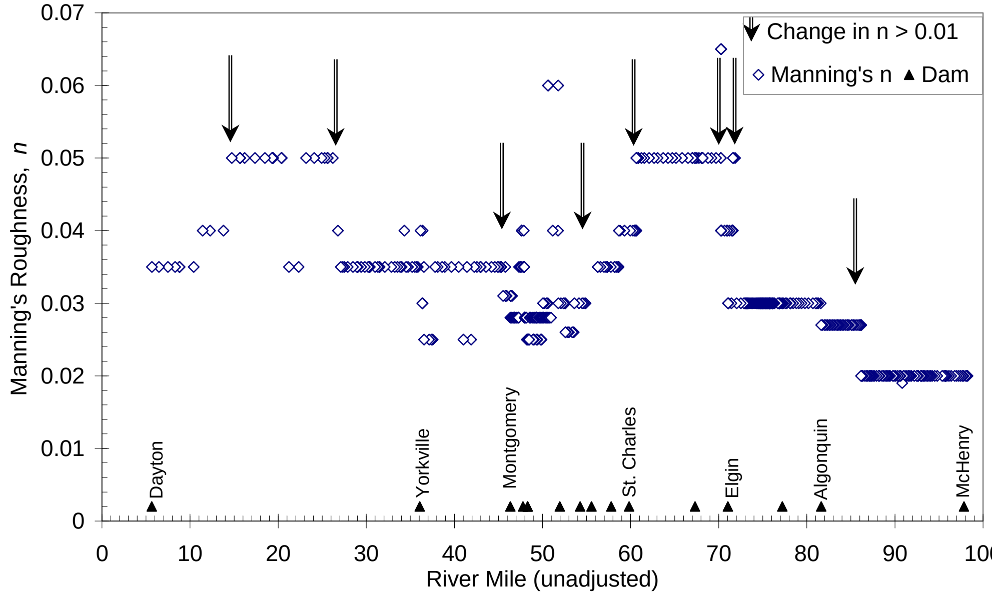

Figure 9. Profile of Manning's roughness in the Fox River from Dayton to Stratton Dam.

The list of major tributary watersheds represented as individual watersheds in the HSPF model of the Fox River below Stratton Dam was submitted and reviewed by the FRSG on 25 February 2004. Figure 10 shows the approved tributary watersheds.

The reach segment scheme is presented in map format showing reach limits, tributaries, stream gages, dams, and impoundments (Figure 11). The reach segment scheme also is presented in tabular format referenced to river miles (Table 10). The segmentation recommended in this study represents minimum requirements for watershed hydrology and water quality models of the entire study area (Fox River below Stratton Dam) due to physical characteristics. Special requirements of stakeholders in a particular area may necessitate further subdivision, especially for HSPF models with outputs available only at computational points (downstream end of segments).

Stream (NHD 24K)

Watershed boundary

Watershed number on map	Miles above mouth at Ottawa	Stream name	Drainage area (sq. mi.)
1	8.5	Buck Creek	42.4
2	9.4	Indian Creek	177.5
3		Little Indian Creek	88.8
4	12.8	Brumbach Creek	11.9
5	15.8	Mission Creek	15.5
6	20.1	Somonauk Creek	81.4
7	21.0	Roods Creek	16.2
8	25.4	Clear Creek	6.6
9	29.5	Hollenback Creek	13.8
10		Little Rock Creek	75.1
11	31.0	Big Rock Creek	118.7
12	31.3	Rob Roy Creek	20.8
13	35.6	Blackberry Creek*	74.6
14	37.8	Morgan Creek	19.7
15	42.7	Waubonsie Creek	30.0
16	49.0	Indian Creek	13.8
17	53.0	Mill Creek*	31.2
18	60.9	Ferson Creek*	54.0
19	62.4	Norton Creek	11.7
20	65.9	Brewster Creek*	16.2
21	68.8	Poplar Creek*	43.4
22	72.2	Tyler Creek*	40.5
23	74.6	Jelkes Creek	6.8
24	81.6	Crystal Lake Outlet	25.9
25	85.3	Spring Creek	26.5
26	89.4	Flint Creek*	36.3
27	89.6	Tower Lake Outlet	5.8
28	92.6	Silver Lake Outlet	1.9
29	92.3	Unnamed Tributary	6.6
30	96.9	Sleepy Hollow Creek	15.5
31	94.3	Cotton Creek	20.5

Notes:
* Continuous gaging station discharge data available.

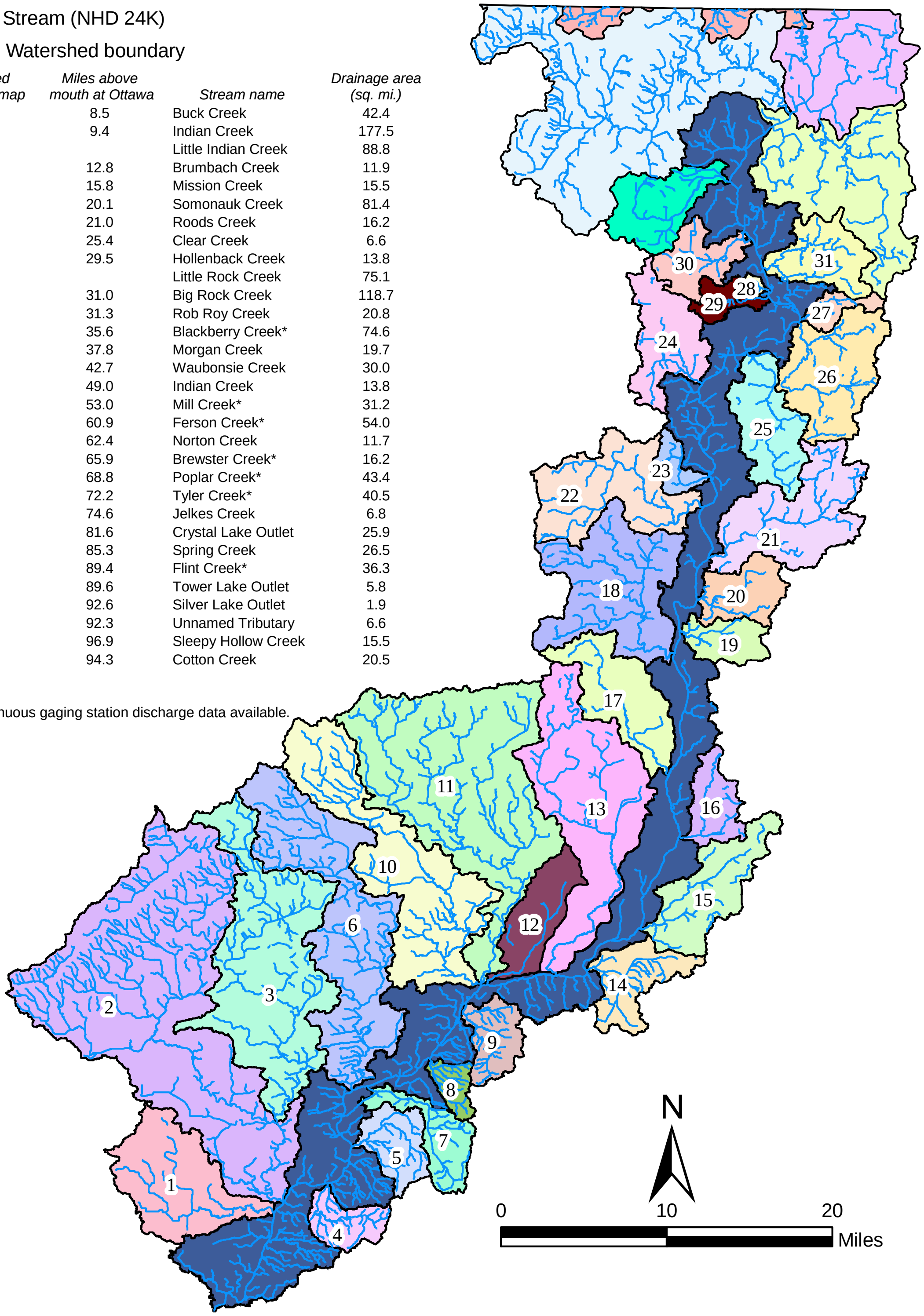

Figure 10. Major tributary watersheds considered as separate HSPF models.

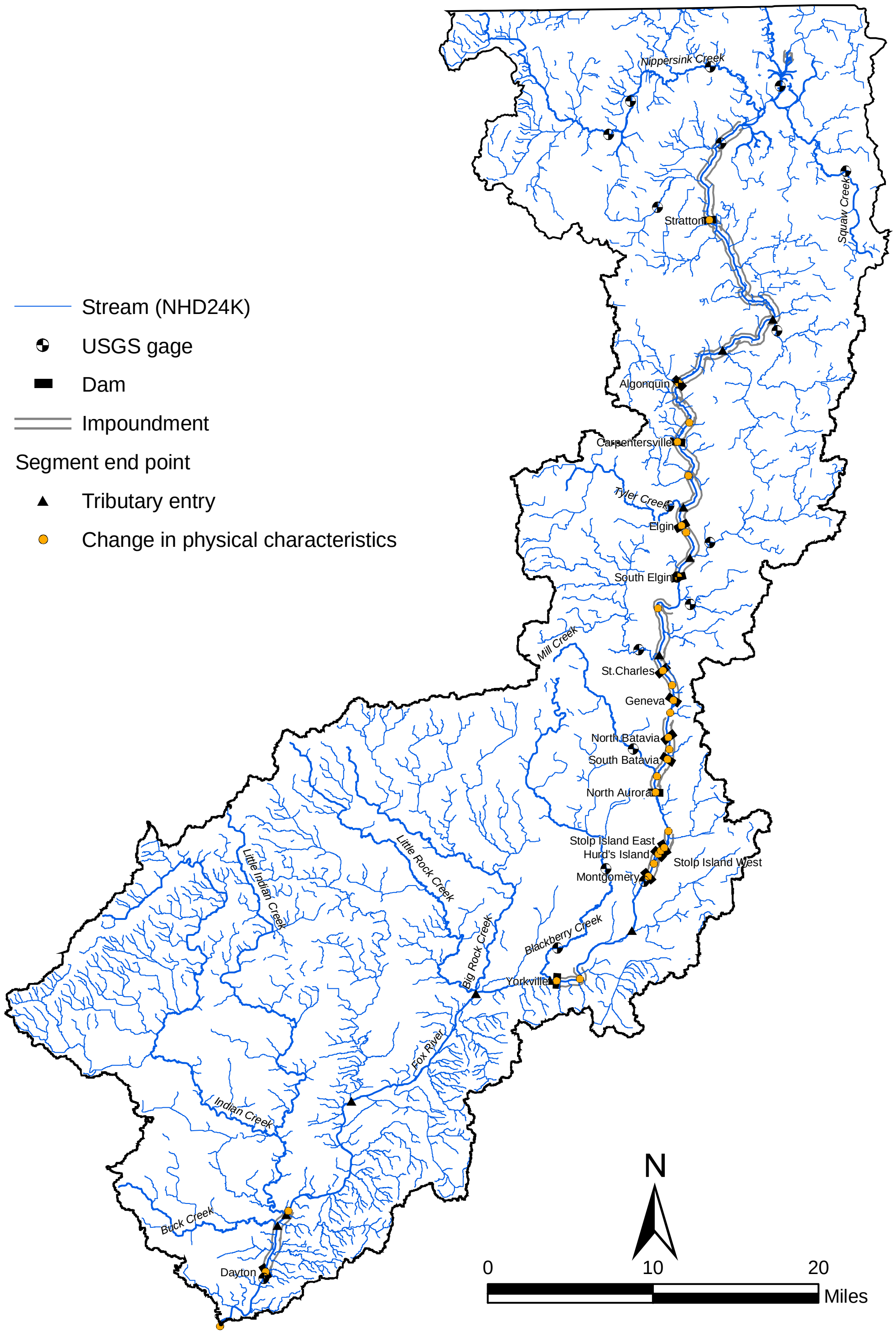

Figure 11. Reach segment scheme for the Fox River mainstem.

Table 10. Proposed Reach Segment Scheme

River Mile	*Slope*	*Dam*	*Flow[(1)] condition*	*Gage*	*Tributary*	*n[(2)]*	*Location*	*Length (miles)*
97.83		*	*	*			Stratton Dam	0.93
96.90					*		Creek below Stratton Dam	2.60
94.30					*		Cotton Creek	1.70
92.60					*		Silver Lake Outlet	0.26
92.34					*		Creek below Silver Lake Outlet	2.74
89.60					*		Creek above Flint Creek	0.19
89.41					*		Flint Creek	3.26
86.15						*		0.85
85.30					*		Spring Creek	3.68
81.62	*	*		*			Algonquin Dam	0.03
81.59					*		Crystal Lake outlet	2.98
78.61			*					1.40
77.21		*					Carpentersville Dam	2.64
74.57			*		*		Jelkes Creek	2.37
72.20					*		Tyler Creek	1.17
71.03		*				*	Elgin Dam	0.52
70.51			*			*		1.71
68.80					*		Poplar Creek	1.49
67.31		*		*			South Elgin Dam	1.41
65.90					*		Brewster Creek	2.17
63.73			*					1.33
62.40					*		Norton Creek	1.50
60.90					*	*	Ferson Creek	1.07
59.83	*	*					St. Charles Dam	1.12
58.71			*					0.90
57.81		*					Geneva Dam	0.76
57.05			*					1.50
55.55		*				*	North Batavia Dam	0.67
54.88			*					0.60
54.28		*					South Batavia Dam	1.28
53.00			*		*		Mill Creek	1.04
51.96		*					North Aurora Dam	2.54
49.42			*					0.42
49.00					*			0.68
48.32		*					Stolp Island East Dam	0.32
48.00			*					0.20
47.80		*					Hurd's Island Dam	0.65
47.15			*					0.80
46.35	*	*		*		*	Montgomery Dam	3.65
42.70					*		Waubonsie Creek	4.90
37.80					*		Morgan Creek	0.24

Table 10. Proposed Reach Segment Scheme (concluded)

River Mile	*Slope*	*Dam*	*Flow[1] condition*	*Gage*	*Tributary*	*n[2]*	*Location*	*Length (miles)*
37.56			*					1.50
36.06	*	*					Yorkville Dam	0.46
35.60					*		Blackberry Creek	4.30
31.30					*		Rob Roy Creek	0.31
30.99					*		Rock Creek	1.49
29.50					*		Hollenback Creek	3.30
26.20						*		0.80
25.40					*		Clear Creek	4.40
21.00					*		Roods Creek	0.91
20.09					*		Somonauk Creek	4.29
15.80					*		Mission Creek	1.60
14.20						*		1.40
12.80					*		Brumbach Creek	3.15
9.65			*					0.25
9.40					*		Indian Creek	0.90
8.50					*		Buck Creek	2.85
5.65		*		*			Dayton	5.65
0.00							Confluence with Illinois River	0.00

Notes:
*Signifies criteria that define the specific segment endpoint.
[1] Change from free flowing to impounded river reach.
[2] Manning's roughness.

Hydrologic Response Units (HRUs)

Subwatersheds can be characterized by further subdivision into homogeneous areas represented by HRUs. An HRU is an area within a watershed that is expected to have a similar hydrologic response to inputs of precipitation and evapotranspiration. A watershed may be partitioned into different HRUs to account for the spatial variability in land use, soil, and physiographic features. The number of unique HRUs is a product of the number of categories used: land use/land cover, soil types, and land slope. Within the Fox River watershed nine pervious and four impervious land use categories, four soil groups, and three land slope categories were identified: 124 possible unique combinations based on these physical features. Because the BASINS-HSPF model interface does not create these unique HRUs automatically, they were created by spatial overlay of land use, soil, and surface slope categories outside the interface, and then relevant model parameters were specified in the model's User Control Input (UCI) file. Each physiographically unique HRU can be assigned a set of parameter values determined through the model calibration process to define runoff characteristics, as well as loading of various constituents from the HRU.

Land use categories from the original dataset were combined to achieve a manageable number of homogeneous units. Land use categories throughout the Fox River watershed study area were identified and land uses representing less than 5% of the Fox River watershed area were combined into a similar category representing more than 5% of the land area (e.g., winter wheat and other small grains were combined with soybeans). There were two exceptions to the 5-percent rule. The division between high and low/medium density was retained as their impacts on hydrology or water quality differ significantly. Surface water was considered a separate category. Land use categories from the IILCP data, categories used in the model, and the percentage of each type in the Fox River watershed are provided (Table 11 and Table 12).

The urban high density (UHD) or low/medium density (ULM) areas were divided into pervious and impervious fractions. A range of 70-80% imperviousness for the UHD areas and 30-40% imperviousness for the ULM areas was assumed. The exact value later was determined through hydrologic model calibration. The urban impervious areas were subdivided further into effective impervious area (EIA) and non-effective impervious area (NEIA). The EIA is the portion of the mapped impervious area that connects directly to the drainage system (e.g., storm drains, streams, rivers, and lakes), including rooftops that drain directly to driveways or storm drains. The NEIA is the portion that drains to the surrounding pervious areas. Again, a range of 70-80% EIA for UHD areas and 45-55% EIA for ULM areas was assumed. The percentage was calibrated.

Hydrologic soil groups and the estimated percentage area they represent in the Illinois portion of the Fox River watershed were determined using the uniformly available STATSGO data (Table 13). Area is divided into STATSGO map units, and soil components in one map unit are not necessarily in the same hydrologic soil group. Because the exact location of an individual soil component within a map unit is not specified and map units had to be adjusted (clipped) to watershed boundaries, percentages of various soil types were estimated assuming uniform representation of soil components in a given map unit. Given the composition of the STATSGO data, the only option was to assume a constant ratio of individual soil components throughout a map unit. Hydrologic soil groups covering less than 5% of the Fox River watershed area were combined with the prevalent group for the component's map unit. Hydrologic soil groups B, B/D, and C are the primary groups in the Fox River watershed.

The BASINs Automatic Delineation Tool calculates the average slope of each subwatershed during the delineation. Subwatersheds were categorized based on the following criteria: slope less than 2%, slope more than 2% but less than 4%, and slope more than 4%. Figure 12 shows the distribution of watershed slopes in the Fox River, Blackberry Creek, and Poplar Creek watersheds derived directly from the 10-m NED raster dataset. The Poplar Creek watershed includes relatively more area with steeper slope. For example, while 50% of the Poplar Creek watershed has a slope higher than 2%, the same slope category is found in only 38% of the Fox River watershed and 32% of the Blackberry Creek watershed.

Table 11. Reclassification of Land Use

IILCP classification	*Model classification*	*IILCP general category*	*Fox River watershed % area**
Corn	Corn	Agricultural Land	26.5
Soybeans	Soybeans	Agricultural Land	23.4
Winter Wheat	Soybeans	Agricultural Land	<0.1
Other Small Grains/Hay	Soybeans	Agricultural Land	1.0
Other Agriculture	Soybeans	Agricultural Land	0.1
Rural Grassland	Rural Grassland	Agricultural Land	13.1
Upland	Forest	Forested Land	7.0
Partial Canopy/Savannah Upland	Forest	Forested Land	3.4
Coniferous	Forest	Forested Land	<0.1
Shallow Marsh/Wet Meadow	Wetland	Wetland	0.9
Deep Marsh	Wetland	Wetland	0.4
Seasonally/Temporally Flooded	Wetland	Wetland	0.1
Floodplain Forest	Wetland	Wetland	0.8
Shallow Water	Wetland	Wetland	<0.1
High Density	Urban High Density	Urban/Built-up Land	2.0
Low/Medium Density	Urban Low/Medium Density	Urban/Built-up Land	8.8
Urban Open Space	Open Space	Urban/Built-up Land	9.7
Barren/Exposed Land	Open Space	Other	0.3
Surface Water	Water	Other	2.4

Note: *Illinois portion of watershed only.

Table 12. Representation of Land Use Categories in the Study Area

Model classification	*Watershed, % area*		
	*Fox River**	*Poplar Creek*	*Blackberry Creek*
Corn	26.5	3.7	28.6
Soybeans	24.5	2.2	25.4
Rural Grassland	13.1	0.0	18.7
Forest	10.4	13.6	7.8
Urban High Density	2.0	6.8	1.5
Urban Low/Medium Density	8.8	30.2	7.6
Open Space	10.0	37.6	8.6
Wetland	2.3	2.7	1.3
Water	2.4	2.9	0.6

Note: *Illinois portion of watershed only.

Table 13. Representation of Hydrologic Soil Groups in the Study Area

		Watershed, % area	
Hydrologic soil group	*Fox River**	*Poplar Creek*	*Blackberry Creek*
A	1.6	0.9	2.9
A/D	2.5	4.4	0.0
B	59.1	17.9	79.9
B/D	20.9	20.4	4.0
C	13.6	43.4	6.4
C/D	0.3	0.2	0.0
D	1.3	0.7	0.5
Not specified (urban)	0.7	12.1	6.3

Note: *Estimated from STATSGO data.

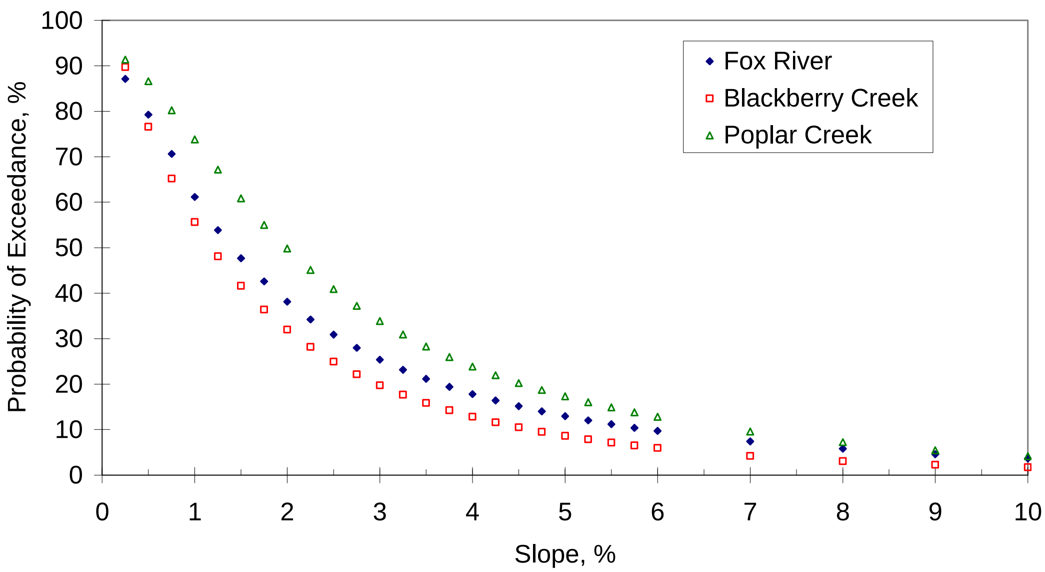

Figure 12. Distribution of land slope in the Fox River, Blackberry Creek, and Poplar Creek watersheds, and percentage of watershed area with slope equal to or exceeding values shown.

Each unique combination of land use, soil, and slope was assigned an HRU code in the model (followed by a two-digit subwatershed code) to facilitate model parameter assignment during calibration. The HRU code for pervious land use is composed of a three-letter code identifying land use and a four-digit number in which the first digit indicates the hydrologic soil group, the second digit indicates land-surface slope category, and the last two digits indicate the subwatershed number. The subwatershed number is included in the HRU code to facilitate identification of the subwatershed of a particular HRU during calibration. The impervious HRU code is composed similarly, except the first digit indicating a soil group is replaced by a letter code indicating whether the area is or is not effective. For example, UHIe209 represents the effective impervious portion of urban high-density land use (code = UHIe) with 2-4% slope (code = 2) in a subwatershed 9 (code = 09). The HRU code COR2109 represents corn (code =

COR) grown on soil of hydrologic soil group B (code = 2) with an average surface slope less than or equal to 2% (code = 1) in the same subwatershed 9 (code = 09).

Hydraulic Function Tables (FTABLEs)

In order for the flow in the channel to be routed adequately downstream, input files must specify the hydraulic characteristics (or the volume-discharge relationships) of all the reaches in the model network. Hydraulic characteristics are stored in hydraulic function tables (FTABLEs) in the HSPF input sequence and describe a river reach or reservoir segment by defining the functional relationship between water depth, surface area, water volume, and outflow in the segment. The BASINS model can derive FTABLEs automatically, but the procedure uses simplified assumptions on river geometry and does not consider effects of impoundments. The modeler can create or modify each FTABLE to specify more representative properties of the reaches in the model network. FTABLEs have columns for water depth, surface area, and volume, plus up to five columns for volume-dependent outflows. Each row contains values corresponding to a specified water surface elevation.

Each FTABLE defines average depth, water surface area, and volume stored in the river segment as a function of outflow from the segment. The required variables were calculated using the HEC-RAS program with data from the FIS model. Originally, the FIS models of the Fox River were developed for flood insurance purposes and were calibrated for flood flows. The following recurrence intervals were used: 1, 2, 5, 10, 20, 50, 100, and 500 years. Model outputs were analyzed to derive functional relationship for the FTABLEs.

Available channel cross-section data were assembled from FIS models in both electronic and paper format and then transferred into an electronic data table in a consistent format. Figure 13 shows locations of cross sections on the Fox River. An Excel spreadsheet was created to speed the analyses of the HEC-RAS output and derivation of values for FTABLEs. The spreadsheet was set up to perform calculations automatically and will be used to derive FTABLEs for relevant tributaries in later parts of the Phase II investigation.

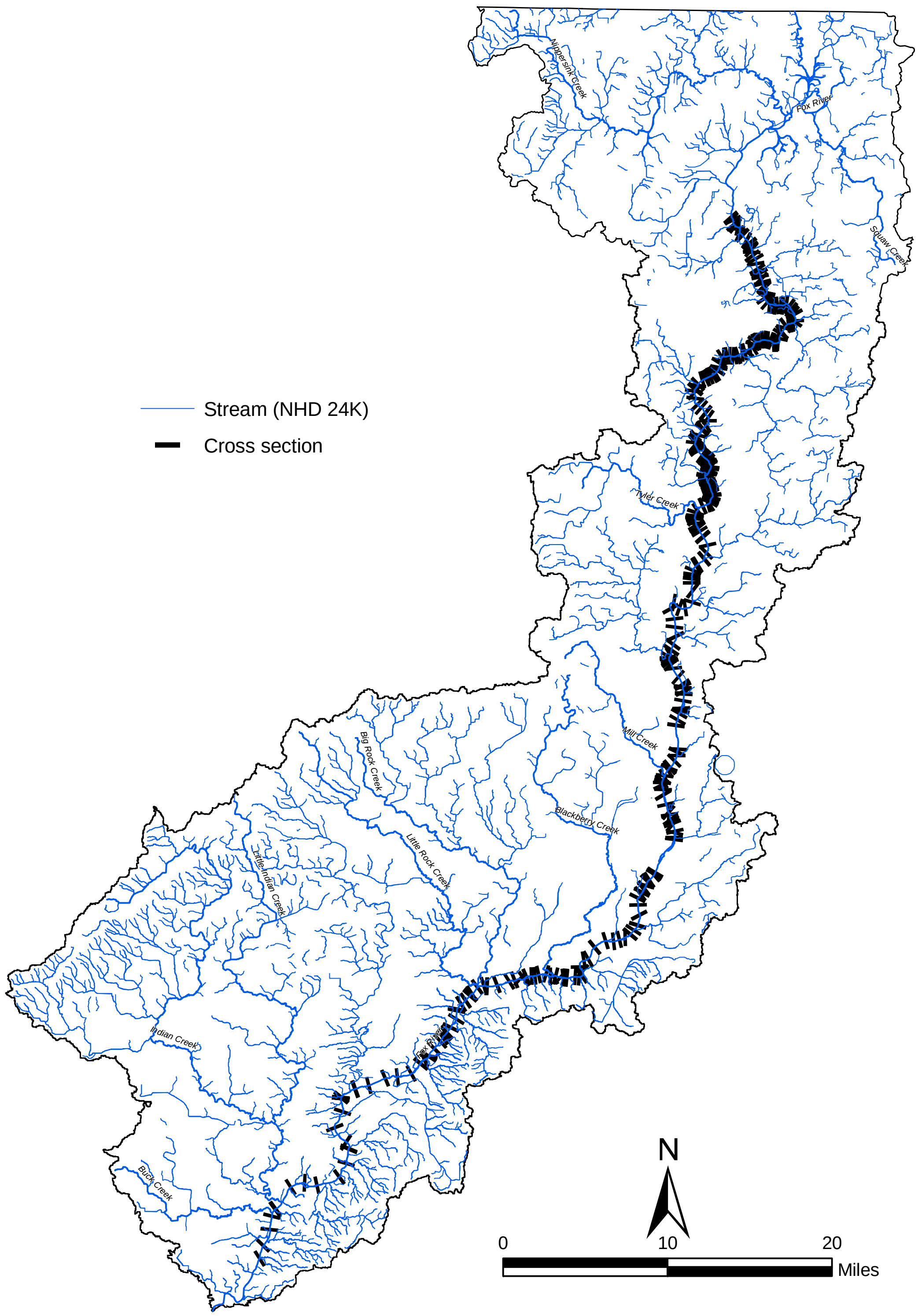

Figure 13. Location of cross sections with available geometry data.

Hydrologic Modeling

The driving force in the watershed loading model is precipitation, which carries various constituents from the land surface to streams and rivers. The HSPF model simulates the land-surface portion of the hydrologic cycle as shown in Figure 14 by a series of interconnected storages—an upper zone, a lower zone, and a groundwater zone. Model parameters control the fluxes of water between these storages and to the stream or atmosphere. The first, fundamental step in hydrologic modeling is to calibrate the model to simulate hydrology, the relationship between precipitation and flow in the tributaries and in the Fox River. Model parameters often do not correspond directly to measurable entities, and their values must be estimated in the calibration process by comparing model output to observed watershed and stream characteristics.

The HSPF model has three main modules that simulate pervious land segments, impervious land segments, and free-flow reaches/mixed reservoirs (PERLND, IMPLND, and RCHRES), respectively. The land segment modules (PERLND and IMPLND) determine a portion of runoff that contributes to streamflow through modeling individual processes on the land surface, such as infiltration, evapotranspiration, surface runoff, groundwater discharge, etc. Actual evapotranspiration (ET) is a function of the potential ET (user input) demand and the amount of water available in the soil and on the land surface for ET. The model also simulates accumulation and melting of snow and ice based on the meteorological data for the study area. The SNOW sub-module simulates sublimation, freezing, and melting of the snowpack. Both rainfall and water from snowmelt are considered for surface detention, infiltration, or runoff. Infiltration in the model varies with space and time based on soil moisture. Infiltrated moisture accumulates in the upper soil zone, lower soil zone, and in active and inactive groundwater storages. Upper zone storage represents the shallow root zone, which is affected mainly by ET, interflow, and percolation. Water percolates from the upper zone to the deeper root zone or lower zone from which it can be removed through ET and percolation to the groundwater storage. While HSPF parameters can be adjusted to indirectly account for faster subsurface flow associated with tile drains, the HSPF model has no specific tile drainage component. Water from active groundwater storage leaves as baseflow or percolates to the inactive groundwater storage.

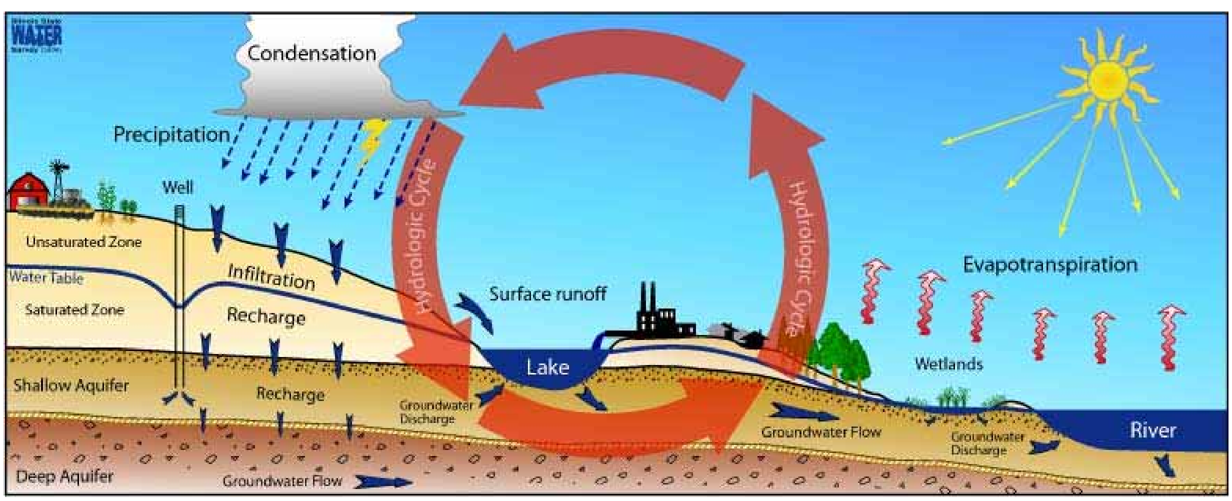

Figure 14. Various components of the hydrologic cycle modeled in the HSPF.

The RCHRES module simulates in-stream flow processes and channel hydraulics. The module uses a storage routing technique to route water from one reach to the next during stream processes. Parameters in the FTABLES that represent volume-discharge relations for reaches define hydraulic characteristics of model reaches. The FTABLES can be modified based on measured hydraulic data.

Calibration and Validation Procedures

Each class of land cover in the HSPF model can be assigned a wide range of physical attributes to represent various land cover conditions. The HSPF model recognizes two broad classes of land cover, pervious and impervious. In this study, each type of land cover was classified further based on land use, soil type, and slope category to form different HRUs. The purpose of model calibration is to assign the best possible parameter values to each HRU and stream reach so that simulated fluxes of water between upper, lower, and groundwater storages, and to the stream or atmosphere approximate the observed values. Net output of these flows is the streamflow reaching the designated watershed or subwatershed outlet.

Calibration of the HSPF model is a trial-and-error procedure consisting of several iterations. A stepwise approach was used for model calibration to obtain an acceptable match between simulated and observed values within specified criteria. The goodness of fit is determined using statistical and graphical comparisons. These calibration criteria are discussed in the next section. The first step is to calibrate the model for annual and monthly streamflow values. Model parameters are then adjusted further to attempt agreement that satisfies the calibration criteria between daily observed and simulated streamflow hydrographs and flow-duration curves. This approach was supported by the hierarchical structure in the HSPF model in which annual streamflow values are affected by one set of parameters (e.g., LZETP, DEEPFR, LZSN, and INFILT parameters), monthly flows by another set (e.g., UZSN, BASETP, KVARY, AGWRC, and CEPSC), and storm flows by a third set (e.g., INFILT, INTFW, and IRC). Snowmelt and freezing phenomena in the watershed (e.g., SNOWCF, TSNOW, and CCFACT) were simulated by the snow simulation component of the HSPF model. The INFILT parameter affects the infiltration into the ground, whereas the UZSN and LZSN parameters define the capacity of upper and lower zones, respectively. The INTFW and IRC parameters affect interflow, and the LZETP and BASETP parameters affect ET from the lower and groundwater zones.

The HSPF model uses simple storage routing in the stream reaches. Because HSPF model-simulated streamflows are compared with observed streamflows (which reflect routing and attenuation in the stream system), timing and magnitude of peak flows as well as shape of the storm event hydrograph cannot be evaluated as part of hydrologic calibration. Different values of model parameters were specified for different HRUs based on their physical characteristics. Some parameters were assigned monthly values. Detailed documentation of parameter values assigned to various parts of the watershed is stored in the model’s UCI file. Definition and values/ranges of model parameters used in this study are given in Table 14.

Table 14. Model Calibration Parameters for the HSPF Hydrology Module

Parameter	*Description*	*Units*	*HSPF range*	*HSPF default*
For Pervious HRUs:				
AGWETP	Active groundwater evapotranspiration		0 - 0.2	0
AGWRC	Basic ground water recession rate	day^{-1}	0.92 - 0.99	0.98
BASETP	Baseflow evapotranspiration		0 - 0.2	0.02
CCFACT	Condensation/convection melt factor		1 - 8	1.0
CEPSC	Interception storage capacity	in	0.03 - 0.4	0.1
DEEPFR	Fraction of inactive groundwater		0 - 0.5	0.1
INFILT	Index to soil infiltration capacity	in/hr	0.01 - 0.5	0.16
INTFW	Interflow inflow parameter		1 - 10	0.75
IRC	Interflow recession constant		0.5 - 0.85	0.5
KVARY	Variable groundwater recession flow	in^{-1}	0 - 5	0
LZETP	Lower zone evapotranspiration	in	0.2 - 0.9	0.1
LZSN	Lower zone nominal storage	in	3 - 15	6.5
NSUR	Manning's *n* for overland flow		0.15 - 0.5	0.2
SNOWCF	Snow gage catch correction factor		1.1 - 2	1.2
TSNOW	Temperature at which precipitation is snow	°F	31 - 40	32
UZSN	Upper zone nominal storage	in	0.1 - 2	1.128
For Impervious HRUs:				
NSUR	Manning's *n* for overland flow		0.03 - 0.15	0.05
RETN	Retention storage capacity	in	0.03 - 0.3	0.1

During calibration, values of different parameters were adjusted within reasonable limits until an optimal fit between simulated and observed streamflow was obtained based on calibration criteria. Calibrated model was then modified to accept climate data from validation period and the model was executed without any change in the model parameters. The results of this validation run were compared to observed data from the validation period using the same criteria as for calibration.

Calibration and Validation Criteria

The hydrologic component of the HSPF model is calibrated to simulate the observed streamflow recorded by the USGS streamflow gages at the watershed outlets. Both graphical and statistical tools were used to evaluate the quality of fit between simulated (S) and observed (O) streamflows for the calibration period and then for the validation period. Both graphs and statistics are used because graphs can depict trends and biases in a simple way, whereas statistics provide an objective measure of fit. For the overall and annual comparisons, only percentage errors in streamflow volumes (Dv, %) were considered. This error also was calculated for monthly flows. Donigian et al. (1984) state that the annual and monthly fit in HSPF simulations is very good when the absolute Dv is less than 10%, good between 10% and 15%, and fair between 15% and 25%. Monthly and daily flows also were compared statistically by calculating the coefficient of correlation (r) and model efficiency (Nash-Sutcliffe Efficiency or NSE of model fit) between observed and simulated flows. The NSE indicates how well the plot of observed versus simulated data fit the 1:1 line. Both NSE and r values equal to one indicate perfect fit.

Monthly data also were compared graphically using three different plots. First, a scatter plot of observed and simulated mean monthly flows was used to identify any bias in terms of consistent overestimation or underestimation of flows. Higher scatter around the S = O line would result in a lower r value. In the second plot, mean monthly S/O ratios were plotted against the month of the year to determine any seasonal bias. In the third plot, S/O ratios were plotted against the mean monthly observed flow for that month to determine the presence of any systematic flow or wetness-dependent errors or errors related to the magnitude of the observed monthly flows. The fit between daily observed and simulated streamflows also was checked graphically by plotting a scatter plot and the flow-duration curves. General agreement between observed and simulated flow-duration curves indicates adequate calibration over the range of the flow conditions simulated. Percentage error in the highest 10% and smallest 50% flows also was determined.

Water Quality Modeling

Water quality modeling components of the HSPF model simulate (1) generation of pollutant yields on the land surface and (2) transport and transformation of individual constituents through the stream system. On pervious and impervious land segments loading of different constituents (e.g., sediment, nitrate, ammonium, orthophosphorus, and fecal coliform) is modeled as a simple buildup-and-washoff process. In-stream water quality modeling includes simulation of concentrations and loads of suspended sediment, nitrogen (e.g., nitrate, nitrite, ammonium, and organic nitrogen), phosphorus (e.g., orthophosphorus and organic phosphorus), bacteria (i.e., fecal coliform), and DO. Algae, simulated as phytoplankton, zooplankton, and benthic algae biomass and output as chlorophyll *a* concentration, affects DO concentration and nutrient cycling in the water.

The HSPF model simulates these water quality constituents for the pervious and impervious land areas and for stream reaches by the specialized sub-modules of the PERLND, IMPLND, and RCHRES modules, respectively. Calculation of the water quality constituent loading is based on the premise that dust, dirt, and pollutants accumulate on the land surface during dry periods (buildup). During periods of rainfall, a portion or the entire accumulated load is carried away with the overland flow (washoff). This cycle repeats itself in the model throughout the year for both pervious and impervious areas. The function that simulates the buildup process in the HSPF model is linear, with parameters for the maximum buildup quantity (SQOLIM) and accumulation rate (ACQOP) to be specified by the user as part of the input data. Washoff is simulated by an exponential decay function, which computes the washoff rate as a function of surface runoff during the simulation interval, pollutant storage on the land surface at the beginning of the interval, and a user-defined parameter representing the depth of surface runoff that results in 90% washoff in one hour (WSQOP). Subsurface flow, in the form of interflow and groundwater concentrations in milligrams per liter (mg/L), is the third contributor of pollutant loadings to receiving waters. The HSPF model does not calculate concentration for subsurface flow components; concentrations are specified as a constant for each HRU using groundwater or baseflow concentration, either one constant throughout the study period or 12 constants, one for each month of the year. The three components are combined in the RCHRES module for in-stream transport.

Because water temperature in the stream affects DO concentration and transformation of other constituents, it is simulated first. Suspended sediment is modeled next because the sediment results are necessary to model sediment-related constituents (e.g., phosphorus). Then fecal coliform bacteria are modeled, including inputs from human, livestock, and wildlife populations. Nitrogen concentrations and loads modeled next require specification of fertilizer application rates and timing and other sources of nitrogen, such as point sources, septic systems, and atmospheric deposition. Phosphorus concentrations and loads are modeled next. Model components for simulating the complex DO cycle are prepared last, including effects of water temperature, reaeration, BOD, SOD, nutrients, and phytoplankton on DO. Individual processes considered by the HSPF model are discussed in sections below for each constituent separately.

Importance of Water Quality Constituents

Dissolved oxygen (DO) is necessary to sustain aquatic life and is an important indicator of water quality. Oxygen can enter the water by gas exchange (reaeration) through the water surface or from aquatic plants by means of photosynthesis. Water can lose available oxygen through respiration and chemical or biochemical reactions such as nitrification or decomposition, both in the water column and in the sediment layer. Dams increase the depth and decrease the velocity of water, thus decreasing reaeration, increasing travel time, and generally decreasing DO. Sediment accumulating behind dam structures can cause higher sediment oxygen demand (SOD) in the impoundment as opposed to free-flowing sections. All DO concentrations are reported in milligrams per liter (mg/L) or as percent saturation. Saturation oxygen concentration depends on water temperature. The warmer the water, the less oxygen can be dissolved in it. Temperature also influences chemical and biochemical reaction rates.

The nutrients (e.g., nitrogen and phosphorus) influence stream productivity. They can be present in many forms, in both the water column and sediment. They are naturally present in soils and organic matter in dissolved or solid form. Most phosphorus typically is bound. Phosphorus has a high affinity for fine soil particles and often is associated with sediment. It also forms precipitates with iron, aluminum, or calcium that are largely insoluble under aerobic conditions.

Nitrogen gas present in the atmosphere can be dissolved directly in water and fixed by certain plants. Nitrogen in organic matter decomposes into ammonium. Ammonium (NH_4^+) and ammonia (NH_3) exist in equilibrium, depending on the pH and temperature of water: at a pH of 7 or below, most ammonia will be ionized (ammonium); at higher pH, proportions of non-ionized ammonia increase. Ammonia is toxic to aquatic life while ammonium is not. Ammonium is converted to nitrate by a process called nitrification. Nitrite, a product of the first step in the nitrification process, is typically present in very small concentrations due to its instability under most conditions.

Nitrogen and phosphorus transformations affect the DO cycle, either directly through transformation processes that consume oxygen (e.g., nitrification) or indirectly by influencing stream productivity. An increase in nutrients typically stimulates higher production of algae or aquatic plant biomass. Excess nutrients can lead to eutrophication of water bodies, and DO can vary drastically over 24 hours, with excess oxygen produced during the day and then consumed by respiration at night with only low levels remaining.

The term suspended solids refers to matter suspended in water that does not pass through a filter with a pore size of 0.45 microns. Suspended solids include various organic and inorganic materials, e.g., sand, soil particles, plant or animal remains, industrial waste, or municipal sewage. Concentration of suspended solids is related to turbidity: the higher the suspended solids concentration, the more turbid the water. The HSPF model simulates suspended sediment, the inorganic portion of suspended solids.

As rain falls on a surface, soil and other material can disintegrate, and any particles picked up by surface runoff are carried to surface waters. Fast-running water can carry larger, heavier particles, erode streambanks, and disturb bottom sediments. Particles settle when water slows down, filling up impoundments and covering aquatic habitat. Other constituents such as phosphorus or various priority pollutants also are associated with suspended solids.

High concentrations of suspended solids decrease the amount of light penetrating beneath the water surface, thus reducing photosynthesis, which leads to lower production of oxygen. Significant reduction of light completely can suppress photosynthetic oxygen production, kill aquatic plants, and further decrease DO through plant decomposition. The process becomes even more complex as suspended solids affect water temperature. Finer particles also can reduce the ability of fish to see and to find food, clog fish gills, cover breeding habitats, etc.

Direct measurement of pathogenic bacteria is not practical due to a large number of different pathogens. Thus, indicator groups such as fecal coliform bacteria, total coliform bacteria, *E. coli*, fecal streptococcus, or enterococcus are used as surrogates. The most common surrogate used in Illinois (including the data available for the Fox River watershed) is fecal coliform. Fecal coliform bacteria are present in large numbers in human intestines and feces as well as those of many warm-blooded animals. Their presence in surface waters in large numbers may indicate the presence of pathogenic bacteria that would make water unsafe for human use. Exposure to pathogens may occur through primary or secondary contact or through consumption.

Calibration Criteria

The HSPF model components are calibrated to available water quality observations. Data at various stations on the Fox River and its tributaries are available in the FoxDB, a database of water quality data in the Fox River watershed (McConkey et al., 2004). Model parameters must be adjusted carefully during calibration. The preliminary set of parameters is developed based on information from other studies reported in the literature. Table 15 shows numerical targets for calibration of HSPF modeled variables. The following sections explain how the HSPF model simulates different water quality constituents and what model parameters are calibrated.

The HSPF model will be run on an hourly basis, with hourly and/or daily model output compared with the corresponding observations. Observed and model-simulated values will be compared graphically in a scatter plot. Where observation time-stamps are not available, observed data points will be compared only graphically with the 24 hourly model-simulated values to see if an observed value lies within the range of 24 simulated values for that day.

Table 15. General Calibration/Validation Targets or Tolerances for HSPF Applications (after Donigian et al., 1984)

	Simulated and Recorded Values, % Difference		
Modeled variable	*Very Good*	*Good*	*Fair*
Hydrology/Flow	< 10	10 - 15	15 - 25
Sediment	< 20	20 - 30	30 - 45
Water temperature	< 7	8 - 12	13 - 18
Water quality/Nutrients	< 15	15 - 25	25 - 35
Pesticides/Toxics	< 20	20 - 30	30 - 40

Suspended Sediment

To simulate the sediment generated by soil erosion and washed off by rainstorms on the pervious HRUs, the SEDMNT sub-module of PERLND models sediment detachment, reattachment, and removal. Sediment produced on pervious land surfaces by kinetic energy from rain falling on the soil is added to the detached sediment storage (DETS). Detached particles are then available for transport by overland flow or reattachment to the soil matrix on dry days. If the overland flow has sufficient energy, it results in scouring of the soil matrix. Rainfall intensity, soil management practices, and the fraction of land surface area under vegetative and snow cover affect the quantity of detached sediment. All relevant HPSF model parameters are defined in Table 16. The detachment coefficient KRER and exponent JRER are dependent on soil properties. Coefficient KRER is the primary calibration factor for the sediment detachment process. To simulate processes such as compaction of soil by agricultural or other off-road practices, the HSPF model allows reattachment of detached sediment to the soil matrix. This process is expressed by the parameter AFFIX, the fraction by which detached sediment storage decreases each dry day as a result of soil compaction. Parameters that affect soil detachment due to rainfall impact (i.e., COVER, SMPF, AFFIX, KRER, and JRER) were adjusted based on the land use characteristics of each HRU. Forest and grassland were assigned the highest cover value, whereas, monthly values were used for cropland to represent seasonal variation in vegetative cover (Table 16).

Table 16. The HSPF Parameters for Suspended Sediment Simulation

Parameter	*Description*	*Units*	*HSPF defaults*	*HSPF range*
AFFIX	Fraction by which detached sediment storage decreases each day due to soil compaction	day^{-1}	0.03	0.01 - 0.5
SMPF	Support management practice factor		1	0 - 1
COVER**	Fraction of land area shielded from erosion by direct rainfall impact		0.88	0 - 0.98
KRER	Coefficient in the soil detachment equation	*	0.14	0.05 - 0.75
JRER	Exponent in the soil detachment equation	*	2	1.0 - 3
KSER	Coefficient in the detached sediment washoff equation	*	0.1	0.1 - 10
JSER	Exponent in the detached sediment washoff equation	*	2	1 - 3
KGER	Coefficient in the matrix soil scour equation	*	0.01	0 - 10
JGER	Exponent in the matrix soil scour equation	*	1	1 - 5
ACCSDP	Sediment accumulation rate on the land surface	lb/ac-day	0.0044	0 - 30
REMSDP	Fraction of sediment removed per day	day^{-1}	0.03	0.01 - 1
JEIM	Exponent in the sediment washoff equation		2	1 - 3
KEIM	Coefficient in the sediment washoff equation	*	0.1	0.1 - 10
KSAND	Coefficient in the sandload power function	*	0.1	0.001 - 10
EXPSND	Exponent in the sandload power function	*	3.92	1 - 6
W	Fall velocity in still water	in/s	0.1	0.1 - 10
M	Erodibility coefficient of the sediment	$lb/ft^2 \cdot day$	0.9	0.001 - 5
TAUCD	Critical bed shear stress for deposition	lb/ft^2	0.1	0.001 - 1
TAUCS	Critical bed shear stress for scour	lb/ft^2	0.3	0.01 - 3

Notes: *Complex.
**Monthly values.

The amount of detached sediment washed off from the pervious HRUs is determined by the transport capacity of the resulting overland flow. To determine how much sediment is washed off, the HSPF model compares the amount of detached sediment with the transport capacity of the overland flow during every time step. If transport capacity is inadequate to carry all detached sediment in storage, only a fraction of the detached sediment is carried with the overland flow. In such cases, the sediment load is transport limited. On the other hand, if the transport capacity exceeds the amount of detached sediment, the load is sediment limited. The parameter KSER, the coefficient in the transport equation and a major calibration parameter, encompasses the effects of several factors, including slope, overland flow length, soil particle size, and roughness. Parameters KGER and JGER represent gully erosion in the soil matrix scour process. The total amount of sediment that leaves a PERLND segment is the sum of sediment that washes off the surface and the sediment that scours from the soil matrix.

The SOLIDS sub-module of the IMPLND model simulates the accumulation, removal, and washoff of sediment on the impervious HRUs using simple buildup and washoff processes explained earlier. There is no detachment and reattachment of sediment to the soil matrix in this case, so the source and sink of sediment on impervious land are the atmosphere and street cleaning, respectively. The ACCSDP parameter represents the accumulation rate of sediment storage and is a major calibration parameter for sediment production. The parameter REMSDP represents the fraction of sediment removed each day by the wind, street cleaning, etc. Washoff of stored sediment depends on the transport capacity of the overland flow, which is affected by exponent JEIM and coefficient KEIM in the sediment transport equation. The parameter JEIM approximates the relationship between runoff intensity and sediment transport capacity. The parameter KEIM represents the combined effects of slope, overland flow length, particle size, and surface roughness in a single calibration parameter.

The sand, silt, and clay fractions in the sediment load estimated from the pervious and impervious HRUs needs to be specified in the model. The transport of these three fractions within stream reaches in the HSPF model then is simulated by the SEDTRN sub-module of the RCHRES module. Scour and deposition of cohesive sediments (silt and clay) are modeled differently than noncohesive sediments (sand). The model performs a separate mass balance calculation for sand, silt, and clay fractions in each reach. The power function method selected to model sand flux allows scour of sand if the sand-carrying capacity of a reach exceeds the actual sand load in suspension, and sand deposition if the reverse is true. Besides user-supplied values of coefficient KSAND and exponent EXPSAND in the potential sand load equation, the sand-carrying capacity for a reach also depends on AVVELE, the average velocity of water determined by the hydraulics component of the HSPF model. Other model inputs include density, effective diameter, and fall velocity in still water of sand particles. These three inputs also are required for cohesive sediments, in addition to the erodibility coefficient (M), shear stress for deposition (TAUCD), and the shear stress for scour (TAUCS). Over time, the model calculates bed shear stresses (TAU) for each reach as a function of the slope and hydraulic radius. Scour occurs in a reach when shear stress exceeds TAUCS, and deposition occurs when it is less than TAUCD, each at model-calculated rates. The values of TAUCS and TAUCD are calibrated using a percentage of exceedance from simulated values.

Observed SS data from stations on the Fox River and its tributaries will be used for model development. These data, generally one sample every two to six weeks, indicate SS concentration as milligrams per liter of the grab sample collected at a single point in time and space on a given day. The observation at a single fixed point in time may or may not be representative of the actual average constituent concentration for the entire day. Generally, HSPF model output is the mean daily value of the constituent concentration based on 24 hourly values. Therefore, the HSPF SS-model component will be run on an hourly basis, and hourly model output used to evaluate model performance. Observed and model-simulated values will be plotted graphically against observed daily streamflow. In cases when observed data do not have a time-stamp, observed data points will be plotted with the 24 hourly model-simulated values to see if an observed value lies within the range of 24 simulated values for that day. Model performance will be considered acceptable during the calibration process if simulated values fall within the same range as observations during the calibration period, and simulated values generally indicate similar long-term and monthly trends as those indicated by observations.

Water Temperature

Several HSPF sub-modules model temperature of inflows from the watershed and in-stream water temperature. The meteorological time series used by the model in this process includes solar radiation, cloud cover, dew point, air temperature, and wind speed. The temperature of inflows, namely, surface runoff, interflow, and baseflow, are determined in sub-modules PSTEMP, PWTGAS, and IWTGAS. The PSTEMP sub-module uses the regression equation method or the smoothing factor method to correlate temperature of the soil layers with measured air temperature. Because measured soil profile data for pervious areas are not available, the PSTEMP sub-module will be used to estimate the temperatures of the surface, upper, and lower soil layers. Monthly values of the slope and intercept for these regression equations must be specified as calibration parameters. The PWTGAS sub-module sets the surface runoff, interflow, and baseflow temperatures equal to surface, upper, and lower layer temperatures, respectively, but keeping it above freezing. The IWTGAS sub-module correlates the temperature of the outflow from impervious areas to the air temperature using a simple regression equation with the slope and intercept specified as constants or changing monthly.

Using standard heat exchange equations between the water body, atmosphere, and sediment, the one-dimensional HTRCH sub-module of the HSPF model determines water temperature in each reach. It uses energy budget accounting methods to determine net heat exchange by estimating up to six separate types of heat exchange processes: shortwave solar radiation, longwave radiation, conduction-convection, evaporative heat loss, heat content of precipitation, and bed heat conduction. This net heat exchange is multiplied by water surface area to determine net change in heat content, which the model converts to temperature change for a known volume of water. Thus, any input of water to the reach must be assigned a heat content (temperature and volume) to prevent dilution of heat in the reach and artificial lowering of water temperature. The heat content per volume of water is transported downstream by the ADCALC sub-module.

Values of parameters affecting the temperature of surface runoff, interflow, and baseflow can be specified monthly to model seasonally variable heat input from pervious and impervious land segments. For pervious land segments, the surface layer temperature is simulated with the help of a regression equation that relates measured air temperature to the surface temperature. Monthly values of parameters ASLT and BSLT are specified as the intercept and slope of this regression equation, respectively. To estimate upper and lower layer temperatures, monthly values of intercept parameters ULTP1 and LGTP1, and slope parameters ULTP2 and LGTP2 for upper and lower layers, respectively, initially will be determined by correlating the measured 4-inch and 8-inch soil temperature data from the ICN station at St. Charles (ISWS, 2004).

For impervious land segments, monthly values of intercept and slope parameters (AWTF and BWTF, respectively) are specified to estimate surface temperature based on observed air temperature. The HTRCH sub-module simulates water temperature using several heat balance parameters (Table 17), such as the correction factor for solar radiation or shade (CFSAEX), the atmospheric longwave radiation coefficient (KATRAD), the conductive-convective heat transport coefficient (KCOND), and the evaporation coefficient (KEVAP). The overall heat budget is affected by the CFSAEX and KATRAD parameters due to their effect on incoming shortwave radiation and the exchange of longwave radiation.

Seasonal variations in shading due to topography and riparian vegetation affect the solar radiation reaching the stream surface, and therefore the water temperature. By default, the HSPF model permits only one input value of the CFSAEX parameter for the entire year. To account for seasonal changes in shading throughout the year, the SPECIAL-ACTION block of the HSPF model must be invoked. Three different values of CFSAEX are specified, one for spring, summer and early fall, and late fall and winter. The parameter KCOND, which affects conductive-convective heat transport between water and air, is used to specify the amplitude of the diurnal temperature cycle. The parameter KEVAP affects evaporative heat loss from the water column.

The observed data of water temperature in the Fox River watershed, generally one sample every two to six weeks, indicate stream temperature at a single point in time and space. Therefore, the HSPF temperature-simulation model component will be run on an hourly basis, and hourly model output compared with the corresponding observations. Observed and model-simulated values will be compared graphically in a scatter plot and the NSE also will be computed. Where observation time-stamps are not available, observed data points will be compared only graphically with the 24 hourly model-simulated values to see if an observed value lies within the range of 24 simulated values for that day.

During initial trials of the temperature modeling for the pilot watersheds, the model resulted in very high stream temperatures (150-180°F) in some stream reaches, which led to erroneous DO simulation. This problem was investigated with help from the HSPF model developers at the USEPA. It was found that due to an error in the original model UCI file created by the BASINS system, the lateral inflow of heat from pervious and impervious land areas to the respective stream reaches was added twice, thereby resulting in erroneously high water temperature. The UCI file was modified to fix this problem. The FTABLES for some reaches also were modified based on recommendations from the HSPF model developers.

Table 17. Heat Transfer Parameters for Computing Water Temperature

Parameter	*Description*	*Units*	*HSPF defaults*	*HSPF range*
CFSAEX	Correction factor for solar radiation		1.00	0.001 - 2
KATRAD	Atmospheric longwave radiation coefficient	K^{-2}	9.37	1.0 - 20
KCOND	Conductive-convective heat transport coefficient	*	6.12	1.0 - 10
KEVAP	Evaporation coefficient	*	2.24	1.0 - 10

Note: *Complex.

Fecal Coliform Bacteria

Sewage can transmit many water-borne diseases. Fecal coliform (FC) bacteria, in general, indicate presence of human sewage in surface water. Contamination is reported as a number of colony-forming units (cfu) per 100 mL. The HSPF model simulates FC bacteria loading associated with overland flow using a simple buildup/washoff relationship for pervious and impervious regions. The user specifies the accumulation rate and storage limits of bacteria on these HRUs considering all sources of bacteria. The FC bacteria loadings also can be associated with interflow and groundwater flow from pervious areas of the watershed. Model parameters that can be modified during the calibration process are shown in Table 18.

Precipitation-related contributions from the land surface include washoff of accumulated FC bacteria from animal waste, organic fertilizer, etc. The HSPF model specifies FC loading from pervious and impervious areas using parameters that represent surface accumulation (ACQOP), maximum daily buildup (SQOLIM), and runoff rate that will remove 90% of buildup (WSQOP). The ratio between SQOLIM and ACQOP values indirectly indicates first-order bacteria dieoff on the land surface. Monthly distribution of the ACQOP values can be determined using the Bacteria Tool. The Bacteria Tool (USEPA, 2005), a spreadsheet-based tool, converts the number of animals into their FC contribution and summarizes inputs for each land use. Different values of these parameters will be used for summer and winter months to account for seasonality and effects of temperature. In addition, the interflow and groundwater concentrations of FC will be specified in the model as constants using parameters IOQC and AOQC, respectively.

Lateral inputs of FC bacteria to stream reaches are specified through a constant interflow concentration ((IOQC). Contributions from point sources of bacteria (e.g., wastewater treatment plants) are specified directly as a time series for relevant stream reaches. The GQUAL sub-module of the RCHRES module simulates the in-stream concentration of bacteria using a temperature-corrected, first-order decay function. In-stream FC modeling involves first-order exponential decay, which simulates FC die off in the water column using the decay coefficient (FSTDEC), and the temperature correction coefficient (THFST).

Table 18. The HSPF Parameters for Fecal Coliform Bacteria Simulation

Parameter	*Description*	*Units*	*HSPF defaults*	*HSPF range*
Pervious land segment				
ACQOP	Daily accumulation rate of bacteria	cfu/ac-day	0	Minimum 0
SQOLIM	Maximum amount of bacteria	cfu/ac	1×10^{-6}	Minimum 1×10^{-6}
WSQOP	Runoff depth required to remove 90% bacteria in one hour	in/hr	2×10^{-6}	Minimum 2×10^{-6}
IOQC	Interflow concentration	cfu/L	0	Minimum 0
AOQC	Groundwater concentration	cfu/L	0	Minimum 0
Impervious land segment				
ACQOP	Daily accumulation rate of bacteria	cfu/ac-day	0	Minimum 0
SQOLIM	Maximum amount of bacteria	cfu/ac	1×10^{-6}	Minimum 1×10^{-6}
WSQOP	Runoff depth required to remove 90% bacteria in one hour	in/hr	2×10^{-6}	Minimum 2×10^{-6}
Reaches				
FSTDEC	Bacteria decay rate	day^{-1}	0	Minimum 9.99×10^{-6}
THFST	Temperature correction parameter		1.07	1 - 2

Direct sources of FC include point sources, failing septic systems, illegal sewer connections, and waste from animals. Data on point-source loads was acquired from the IEPA's Permit Compliance System (PCS) database. Information on the number of septic systems in each subwatershed was gathered from 1990 Census data (U.S. Census Bureau, 2005) on a census track basis. Percentage of total FC load from septic systems reaching the stream is included as a calibration parameter. A failure rate of 25% was assumed for all septic systems in the watershed. It also was assumed that 20% of FC daily load from these failing septic systems would reach the stream. The type and number of animals also must be specified for each land use based on data in the "Agriculture Data" section and literature values. The Bacteria Tool was modified to include a preferred goose habitat (open spaces in a 100-m buffer along water banks). It is assumed that 5% of FC bacteria produced by geese in the preferred habitat entered the stream directly, and the remaining 95% is used to augment FC accumulation rate on the land surface. Daily input data time-series will be prepared for inclusion in the HSPF model's WDM input file.

Observed data from various water quality stations generally have one sample every two to six weeks. The HSPF FC-model component will be run on an hourly basis, and hourly model output compared with the corresponding observations. Observed and model-simulated values will be compared to check for any trends with respect to time, flow, etc. Where an observation time-stamp is not available, the observed data point will be compared graphically only with the 24 hourly model-simulated values to see if an observed value lies within the range of 24 simulated values for that day.

Nutrients

The PERLND sub-module simulates nutrients as attached to sediment, dissolved in overland flow, and associated with the interflow and groundwater. Sediment-attached fractions are simulated through user-specified potency factors, expressed in pounds of the specific nutrient per ton of sediment. For each nutrient, two potency factors can be supplied: one simulates the sediment-attached nutrients transported by overland flow (POTFW), and the other handles nutrients attached to scoured sediments (POTS). The HSPF model simulates nutrient loading associated with overland flow using a simple buildup/washoff relationship for pervious and impervious regions. Model parameters are shown in Table 19.

The HSPF model simulates nutrient loading associated with overland flow using a simple buildup/washoff relationship for pervious and impervious regions. The HSPF model determines nutrient loading from pervious and impervious areas using parameters that represent surface accumulation (ACQOP), maximum daily buildup (SQOLIM), and runoff rate that will remove 90% of buildup (WSQOP). These parameters then define surface loading from all sources combined, natural or anthropogenic, except for wet and dry deposition for nitrogen specified directly in input time series. Atmospheric deposition of phosphorus was included in the estimate of surface accumulation rate. The first estimate of the ACQOP is based on land use and adjusted for known sources of nutrients (e.g., fertilizer application). Values then are calibrated to match the observed water quality data. The surface washoff parameter (WSQOP) is included in the calibration along with the nutrient concentration in the interflow (IOQC) and baseflow (AOQC). Those three components of flow are combined in the RCHRES module of the HSPF model for in-stream transport.

Nutrient loads from the watershed undergo further transformation in stream reaches where phytoplankton and benthic algae become an additional source and/or sink of some nutrients. The RCHRES module can simulate a variety of decay processes that may affect dissolved nutrients. These processes mainly are simulated using first-order decay. The sediment-attached fraction of the nutrients is in dynamic equilibrium with the water column. Thus, sediment-attached nutrients can be released from the sediment and become part of the dissolved fraction in the water column and vice-versa. Because this process is relatively slow in comparison with the transport times in the watershed, the exchange of the sediment-attached nutrients with the water column will not be simulated.

Table 19. The HSPF Parameters for Simulation of Nutrients

Parameter	*Description*	*Units*	*HSPF default*	*HSPF range*
Pervious Land Segment:				
ACQOP	Daily accumulation rate on the surface	lb/ac-day	0	Minimum 0
SQOLIM	Maximum amount of nitrogen in the storage	lb/ac	$1x10^{-6}$	Minimum $1x10^{-6}$
WSQOP	Runoff depth required to remove 90% of storage in one hour	in/hr	$2x10^{-6}$	Minimum $2x10^{-6}$
IOQC	Interflow concentration	mg/L	0	Minimum 0
AOQC	Groundwater concentration	mg/L	0	Minimum 0
Impervious Land Segment:				
ACQOP	Daily accumulation rate of nitrogen	lb/ac-day	0	Minimum 0
SQOLIM	Maximum amount of nitrogen in the storage	lb/ac	$1x10^{-6}$	Minimum $1x10^{-6}$
WSQOP	Runoff depth required to remove 90% of storage in one hour	in/hr	$2x10^{-6}$	Minimum $2x10^{-6}$
Reaches:				
KTAM20	Oxidation rate of total ammonia	hr^{-1}	None	Minimum 0.001
KNO220	Oxidation rate of nitrite	hr^{-1}	None	Minimum 0.001
KNO320	Oxidation rate of nitrate	hr^{-1}	None	Minimum 0.001

Dissolved Oxygen (DO)

For simulating the DO concentration, the HSPF model considers kinetic processes, such as decomposition of organic matter represented as biochemical oxygen demand (BOD), sediment oxygen demand (SOD), benthic releases of settled decomposable materials, photosynthesis from algae and water plants, and reaeration. Chlorophyll *a* concentration affects DO concentration and nutrient cycling in the water. The HSPF model simulates the biomass of algae and converts it to an approximate chlorophyll *a* concentration internally. The OXRX submodule of the RCHRES module simulates effects of atmospheric reaeration, BOD, and SOD on the DO. The OXRX sub-module considers processes such as longitudinal advection of DO and BOD, sinking of BOD material, SOD, benthic release of BOD, reaeration through air-water interface, and oxygen depletion from decay of organic material. Separately, the NUTRX sub-module simulates concentrations of nutrients in the reaches because they affect both BOD and SOD. The PLANK sub-module simulates algae biomass and its influence on DO and nutrients through growth, respiration, death, sinking, and predation processes. Phosphate, nitrate, and total ammonia serve as a source of nutrients for algae growth and are considered bioavailable in the HSPF model. Model parameters that can be modified during the calibration process are shown in Table 20.

Three different methods are available in the HSPF model to determine the reaeration coefficient in free-flowing reaches. The HSPF model does not directly simulate dam reaeration. Parameters in the user-specified power functions of hydraulic depth and velocity can be specified to force a particular reach to have a higher reaeration constant, however.

Table 20. The HSPF Parameters for Simulation of DO Regime

Parameter	*Description*	*Units*	*HSPF default*	*HSPF range*
Pervious Land Segment:				
ACQOP	Daily accumulation rate on the surface	lb/ac-day	0	Minimum 0
SQOLIM	Maximum amount of BOD in the storage	lb/ac	$1x10^{-6}$	Minimum $1x10^{-6}$
WSQOP	Runoff depth required to remove 90% of storage in one hour	in/hr	$2x10^{-6}$	Minimum $2x10^{-6}$
IOQC	Interflow concentration	mg/L	0	Minimum 0
AOQC	Groundwater concentration	mg/L	0	Minimum 0
Impervious Land Segment:				
ACQOP	Daily accumulation rate of bacteria	lb/ac-day	0	Minimum 0
SQOLIM	Maximum amount of BOD in the storage	lb/ac	$1x10^{-6}$	Minimum $1x10^{-6}$
WSQOP	Runoff depth required to remove 90% of storage in one hour	in/hr	$2x10^{-6}$	Minimum $2x10^{-6}$
Reaches:				
KBOD20	Unit BOD decay rate at 20 degrees C	hr^{-1}	None	Minimum $1x10^{-30}$
KODSET	Rate of BOD settling	ft/hr	0	Minimum 0
BENOD	Benthal oxygen demand at 20 degrees C	mg/m^2-hr	0	Minimum 0
REAK	Empirical constant for equation used to calculate the reaeration coefficient	hr^{-1}	None	Minimum $1x10^{-30}$

Summary

Methods and procedures described in this report represent an essential part of the modeling effort for the Fox River watershed. Decisions on model structure, number of reaches and subwatersheds, delineation procedures, selection of HRUs, or selection of HSPF modules for simulation influence the uncertainty in model results, as well as time and labor required. Hydrology and water quality modules of the HSPF model are very complex with a number of model coefficients for which a numerical value must be estimated. A structure has been put in place to develop model coefficients through calibration and validation of the HSPF models for two pilot watersheds, Poplar and Blackberry Creek watersheds, representing urban and agricultural uses, respectively. Representativeness of the hydrology model coefficients will be evaluated further at five additional tributary watersheds (Brewster Creek, Ferson Creek, Flint Creek, Mill Creek, and Tyler Creek) for which streamflow data are available. Results of hydrology and water quality simulations will be discussed in the Part 2 and Part 3 reports.

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