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Fox River and Green Bay
PCB Fate and Transport
Model Evaluation

Technical Memorandum 2a

Simulation of historical and projected total suspended solids loads and flows to the Lower Fox River, N.E. Wisconsin, with the Soil and Water Assessment Tool (SWAT)

August 19, 1998

Fox-Wolf Basin 2000

Acknowledgments

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Fox-Wolf Basin 2000 is a broadly based, not-for-profit organization dedicated to ensuring cost-effective public policy and private action to achieve and maintain high-quality surface waters in Wisconsin's Fox-Wolf River Basin. The objective of this project was to estimate TSS loads and flows from Lower Fox River tributaries which were to be used as inputs to the Fox River PCB Fate and Transport Model. In addition, the TSS loads generated from this project, in conjunction with anticipated future modeling of TSS and phosphorus loads by Fox-Wolf Basin 2000, may expedite the development of Total Maximum Daily Loads (TMDLs) within the Fox-Wolf Basin, under Section 303(d) of the Clean Water Act.

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I. Introduction

The basin scale model SWAT (Soil and Water Assessment Tool) was applied to the 1,580 km^2 Lower Fox River Basin (Figure 1) to simulate historical (January 1, 1954 to December 31, 1996) and projected (January 1, 1996 to December 31, 2020) daily stream flows and total suspended solid loads at watershed outlets. This information was required to supply the Lower Fox River and Green Bay PCB Fate and Transport Model with estimated total suspended solids (TSS) loadings and flows to model water column segments within the Lower Fox River.

II. SWAT Model Overview

SWAT is a distributed parameter, daily time step model that was developed by the United States Department of Agriculture, Agricultural Research Service (ARS) to assess non-point source pollution on watersheds and large river basins (Arnold et al. 1996). SWAT simulates hydrologic and related processes to predict the impact of management on water, sediment, nutrient and pesticide yields in rural basins. Large river basins can be sub-divided into hundreds of subwatersheds for modeling purposes.

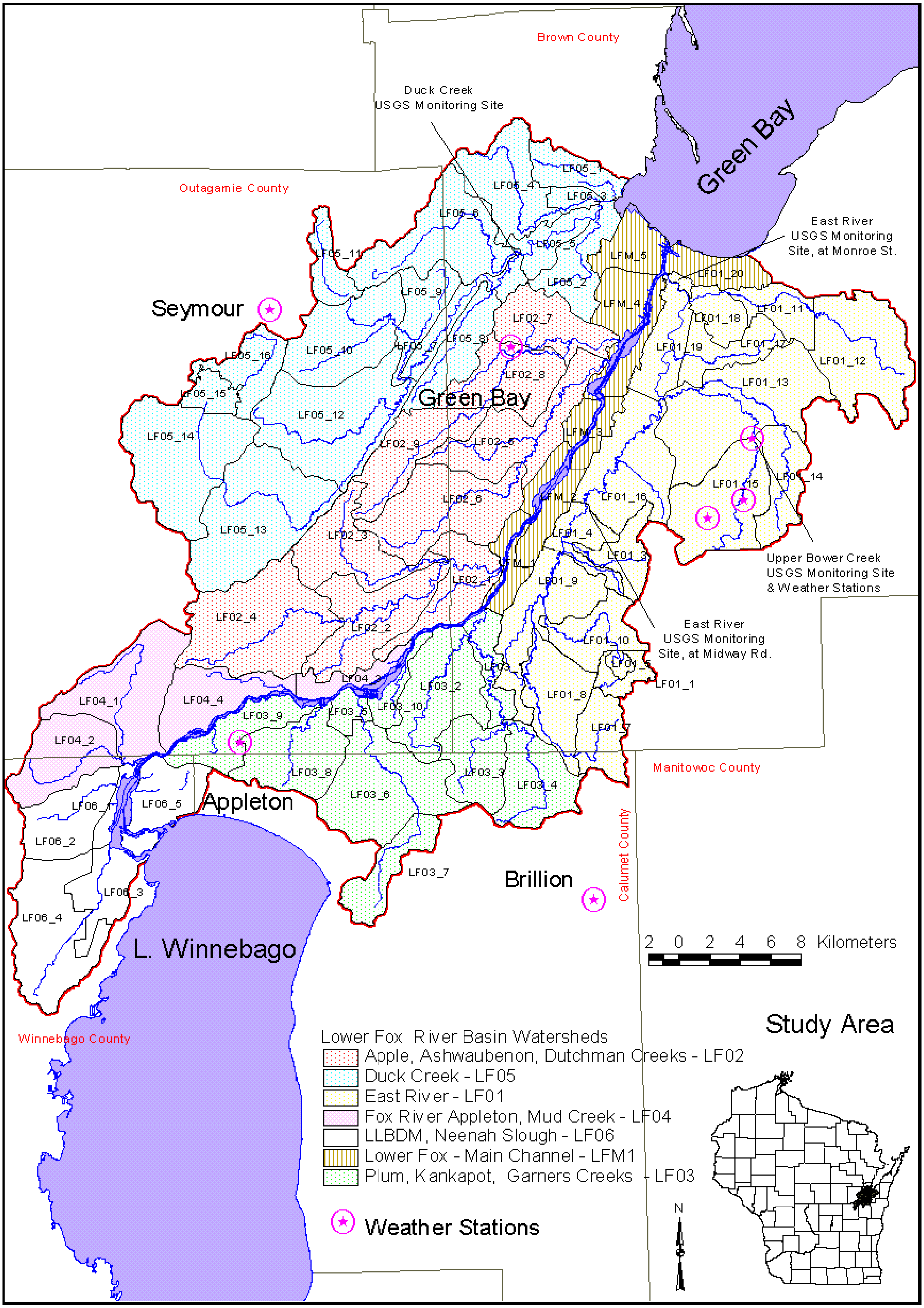
Major processes simulated within the SWAT model include: surface and groundwater hydrology, weather, soil percolation, crop growth, evapotranspiration, agricultural management, sedimentation, nutrient cycling and fate, pesticide fate, and water and constituent routing. SWAT utilizes a separate input file for each subwatershed and routing reach. A number of other separate files are also utilized by SWAT including: soils, weather, groundwater, basin, tillage, management, crop, chemical, pesticide, automatic fertilizer and irrigation, reservoir, lake water quality, wetland, pond and routing configuration files. Control of these files is managed through a single "control-input-output" file which allows for much flexibility. SWAT is currently in the development stage, so enhancements and refinements are continually being made.

III. Model Inputs and Methods

Basin Configuration: As illustrated in Figure 1, the Lower Fox River Basin was sub-divided into seven major hydrologic units (watersheds): (1) LF01 - East River; (2) LF02 - Dutchman, Ashwaubenon, and Apple Creeks; (3) LF03 - Plum, Kankapot and Garners Creeks; (4) LF04 - Appleton Watershed, which includes Mud Creek; (5) LF05 - Duck Creek; (6) LF06 - Little Lake Buttes des Morts Watershed, which includes the Neenah Slough Creek; and (7) LFM1 - Lower Fox River Main Channel. These watersheds were further delineated into a total of 67 subwatersheds according to surface hydrology, landuse and the placement of monitoring stations. In most cases, the subwatersheds shown in Figure 1 were delineated such that their size was similar to that of the primary calibration site: the Upper Bower Creek subwatershed (35 km^2). The methods used for delineating the Lower Fox River Basin and providing inputs to the model are described below. In this document, the Lower Fox River Basin shall simply be referred to as the "Basin".

Application of Geographical Information System: PC ARC/INFO (vector-based GIS), ARCVIEW, and ARCVIEW Spatial Analyst (grid-based GIS) were used to construct, process and

Figure 1. Lower Fox River Basin, N.E. Wisconsin - Swat-Modeled Watersheds



analyze a variety of GIS coverages to supply inputs to the SWAT model. These coverages were then utilized in this project to construct maps and provide SWAT model inputs such as channel lengths and watershed areas.

III-A. Watershed Delineation, Hydrology and Climate

Watershed Delineation: Several different information sources were used to create a preliminary watershed boundary GIS coverage for the Basin. The 1:24,000 statewide watershed boundary GIS layer (wsdnt024) that was provided by the Wisconsin Department of Natural Resources (WDNR) was supplemented with other GIS layers including: (1) "Small Project Layer" from the WDNR, which contained delineations of some subwatersheds within the Duck, Apple and Ashwaubenon Priority Watershed Project; (2) subwatershed boundaries for the lower portion of the East River, as produced by the U.S. Geological Survey, Madison, Wisconsin (applied in McIntosh 1994); and (3) delineation of the upper portion of the East River was extracted from an East River watershed coverage that was produced by the Bay Lakes Regional Planning Commission, Green Bay, Wisconsin. These layers were combined to produce a preliminary watershed boundary coverage for the Basin.

The preliminary watershed boundary layer was then converted into an ARCVIEW shape file for further editing within ARCVIEW. Digital Raster Graphic versions of 1:24,000 U.S. Geological Survey (USGS) topographic maps (DRG's) were used as background coverages within ARCVIEW to assist in adding additional subwatershed boundaries to the shape file. The DRG's were obtained from the WDNR on two CD ROM's. With the exception of two of the DRG's (Kaukauna and Green Bay East), the DRG's in the Basin were based on 1992 imagery. Standard versions of USGS 1:24,000 7.5 Minute Quadrangles topographic maps were also obtained from USGS, Reston, Virginia; all of these maps were based on 1992 imagery. Watershed boundary delineation was primarily based on surface hydrology and topography, but land cover/use was also utilized for delineations in urban areas. The final version of the basin watershed delineation was then used to create numerous subwatershed-specific model inputs by overlaying this boundary layer with other GIS layers.

Hydrology: Six 1:24,000 hydrologic layers which encompassed the entire lower Fox River Basin were provided by the WDNR. These hydrologic coverages were provisional, so they contained no annotation or hydrological attributes. The hydrologic layers were "intersected" with the basin watershed boundary coverage to provide stream segments that coincided with watershed boundaries. These layers were then used to assign main and routing channels to the individual subwatersheds along with the corresponding stream lengths and channel slopes, which served as model inputs. Figure 1 shows the main and routing channels. Elevation changes, as determined with the DRG topographic maps, were combined with main and routing reach channel lengths to compute the corresponding channel slopes required by SWAT.

Climatological Data. The locations of the weather stations that were used in this project to provide measured daily precipitation and temperature data are shown in Figure 1. Simulated temperature and precipitation data were not used. The Green Bay airport site was the only NOAA National Weather Service (NWS) Station that was utilized in this project. Three weather stations located in the Upper Bower Creek watershed were maintained and operated by the USGS. The remaining stations were official NWS cooperative observers. With the exception of the USGS site at Bower Creek, all of the other data was supplied in ASCII format by the Geological and Natural History Survey State

Climatology Office in Madison, Wisconsin. Table 1 summarizes the nature of each of the weather stations, data availability, and the weather years that were used in this project.

Reports of trace precipitation amounts were assumed to be zero. Data from the closest available site was substituted whenever a daily value was missing for a particular site. Thus, missing daily values were replaced with values from nearby stations as follows: (1) missing precipitation values from the Brillion data set were replaced with data from Appleton, and also from the Green Bay data set whenever Appleton data was also missing; (2) missing values from the Appleton data set were replaced with values from the Green Bay site; and (3) missing precipitation values from the Upper Bower Creek data set were replaced with data from Green Bay. The Green Bay NWS site contained the most complete data set. The Seymour site was not utilized because it had a limited data set (1983-present), and there were obvious phase differences between this station and the others.[1]

Minimum and maximum temperature data were converted from Fahrenheit to Celsius and rounded to tenths of a degree. Precipitation data was converted to millimeters (mm) and rounded to one-tenth mm. Data from all weather stations was then processed into an ASCII format that was compatible with SWAT. A separate precipitation or temperature file was utilized for each weather station and model simulation period. Measured precipitation and temperature data from Appleton, Brillion, Bower Creek and Green Bay stations were processed to produce daily weather data sets which were later used for five model simulation periods: 1953-1956, 1956-76, 1976-96, 1962-83, and 1983-87 (all periods were inclusive - Jan. 1 to Dec. 31). The latter two periods were utilized for the 1996-2020 forecast simulation because they corresponded to the 1963-87 hydrograph selected for future projections. The first year of each model simulation period was used only to initialize the model. That is, the model was run an extra year at the beginning of each period, without producing any output for that year, so that the model variables could be given sufficient time to stabilize and better reflect actual conditions.

The weather database furnished with the SWAT model was used to supply the SWAT weather generator with statistical weather information for the Green Bay NWS site. This information was required by the SWAT model to generate simulated miscellaneous climatological data, such as rainfall intensity. Monthly average dew point temperatures from New London were added to this data set. Dew point temperatures for the New London site were furnished with the Erosion Productivity Impact Calculator (EPIC) model (Sharpley and Williams 1990). Monthly average wind speed data for the Green Bay NWS site (1948-90) were also added (UWEX-WGNHS 1996). Snowfall was simulated by SWAT according to the measured precipitation amount and the average measured air temperature.

Subwatershed Climatological Assignment: Initially, an attempt was made to provide subwatershed-specific daily precipitation estimates from several nearby weather stations based on a distance formula that was previously employed by Marcus (1993). Weather station locations were

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[1] For example, one of the reported rainfall events appears to have been recorded two days after it actually occurred. On Saturday, April 20 1996, Fox-Wolf Basin 2000 conducted preliminary sampling during a major runoff event to determine the best sites for a proposed paired watershed study. While Green Bay rainfall for that day was 18 mm, the Seymour site didn't record any rain for that day even though substantial rain and runoff was observed to occur by Fox-Wolf Basin 2000 no more than 3 miles east of the Seymour station. However, 17 mm was reported to occur on Monday, April 22 1996 at Seymour, while none was recorded at the Green Bay site between April 21-23, 1996. In all likelihood, the rainfall in Seymour actually coincided with that which occurred in Green Bay on April 20, 1996, and not the reported date.

provided by the Wisconsin State Climatological Office. An ARC/INFO coverage containing these coordinates was created. The distance between each of the stations and each of the subwatershed centroids was computed with the ARC/INFO "pointdist" command. These distances were then used with the aforementioned point distance precipitation formula to produce subwatershed-specific daily precipitation data sets. While this approach seemed to work well at first, it was later discarded because of problems caused by time lags between actual events at different locations, and/or between the date that the precipitation was reported to have occurred at different locations.

Cooperative observers do not all record precipitation at the same time. These time lags had a "smoothing out" effect on precipitation events; that is, large events were sometimes sharply reduced by a factor of 1/3 or more. Values of zero, or trace amounts, were often averaged along with the other values, thereby producing a distance weighted average that was no longer representative of the true nature of the storm event.

For example, Seymour reported 55.9 mm of rainfall 10/17/1984, while Green Bay reported 52.3 mm on the following day (Appleton values were missing). However, rainfall amounts of 20.5 and 36.4 mm were calculated for subwatershed LF0501 on 10/17/1984 and 10/18/1984, respectively. Although the calculated total rainfall is acceptable, the daily distance-estimated point values are not always representative of a storms impact on erosion.

Because of the aforementioned problems with the distance-weighting method, it was rejected in favor of the simpler, but more reliable method of assigning the closest weather station to each subwatershed. SWAT simulates sediment loads on a subwatershed basis, so even if a precipitation event in a watershed is misreported as occurring on separate days at two locations, the selected method will at least estimate sediment loads based on the entire event occurring within a single day. Table 1 illustrates how the temperature and precipitation data sets for each weather station were assigned to the subwatersheds in the Basin.

III-B. Soils

Area-weighted values for SWAT-required parameters were created by processing digital soil surveys and tables as described in the sections that follow. This procedure was judged to be more robust than assuming that the soil parameters associated with the dominant soil series in a subwatershed are representative of an entire subwatershed.

Creation of Basin Soil Coverage: Digital GIS soil coverages and accompanying tables for three counties were obtained from the following sources: (1) Calumet County - National Resource Conservation Service Office in Madison, Wisconsin (NRCS); (2) Brown County - Brown County Planning Department[2]; and (3) Outagamie County - Outagamie County Planning Department. Digital soil coverages were not yet available for Winnebago County. The locations of these counties are

[2] The soil tables for Brown County were somewhat outdated, so the most recent tables were downloaded from the following Internet site and processed to provide normalized values: www.statlab.iastate.edu/soils/muir.

displayed in Figure 1. The digital soils series are based in part, on previous NRCS work performed by Link et al. (1974), Barndt et al. (1978), and Otter et al. (1980).

Table 1. Sources of Climatological Data used in SWAT Model Simulations, and Assignment of Climatological Data to Subwatersheds.

Weather Station	Station Type	Period used in Simulations	Subwatersheds Assignments (see Fig. 1 for subwatershed locations)
Green Bay Austin Straubel International Airport	NOAA NWS site	Precip. and Min./Max. Temperature 1953-96	LFM1 - precip & temp: All LF01 - temp: All LF01 - precip: subs 18,19,20 LF02 - precip & temp: subs 5,6,7,8,9 (Dutch. & Ash.) LF05 - precip: all except 13 LF05 - temp: All
WHBY Radio in Appleton	coop. observer	Precip. and Min./Max. Temperature 1953-96	LF02 - precip & temp: sub 1,2,3, and 5 (Apple Cr.) LF03 - precip: subs 1,2,5,6,7,8,9,10 LF03 - temp: All LF04 - precip./temp.: All LF05 - precip: sub 13 only LF06 - precip & temp: All
Brillion	coop. observer	Precip. 1953-96	LF01 - precip: subs 1,5,7,8 LF03 - precip: subs 3,4
USGS Bower Creek Rain Gages (average of up to 3 gages)	USGS	Rainfall 1990-1996 with some missing periods	LF01 - precip: all except subs 1,5,7,8, 18,19, 20; But Green Bay was used during rest of record
Seymour Cooperative	coop. obs.	Precip. 1983-96	none (not used, see narrative)

All of the GIS soil coverages used in this project were provisional. That is, they were not yet officially certified by NRCS, and may contain minor errors. Soil coverages were supplied in an ARC/INFO export format. The export files were: (1) imported, and built into PC ARC/INFO polygon coverages; (2) appended into a single county-wide coverage; (3) inspected for obvious errors and cleaned up accordingly; (4) appended into a single three-county soils coverage; (5) "clipped" using the outline of the Lower Fox River Basin Watershed to produce a soil coverage that coincided with the Basin outline; and (6) "cleaned" and "built" into a basin-wide polygon coverage for soils with WTM, NAD27 coordinates (Wisconsin Transverse Mercator, North American Datum of 1927). A "county" field was added to the ARC/INFO polygon table so that individual county NRCS soil tables could be linked to the combined ARC/INFO soils coverage.

Soil Table processing: County-specific NRCS soil database tables contained information relating each soil series with the soil parameters required by SWAT (e.g., bulk density, available water capacity, etc.). Each of the county NRCS soil tables had to be processed separately because a soil series in one county does not necessarily have the same parameter values as the identically labeled soil series in another county. SWAT requires information for each soil layer that is associated with a soil series. The soil series in the Basin had anywhere from 2 to 5 layers listed in the tables, and each layer has specific values assigned to the required soil parameters. Because area-weighted values were desired for each subwatershed, the different soil series depths were "normalized" by assuming that all soil series contained four layers. Parameter values for the deepest individual layer within each soil series were then extended to the remaining layers below it. Thus, if a soil series had only 3 layers, the parameter values associated with the last layer were assumed to extend to the required fourth layer below it. Soil layers were assumed to extend to the following depths: 1st = 203 mm, 2nd = 686 mm, 3rd = 1067 mm, and 4th = 1524 mm.[3] While this depth-normalizing procedure was relatively crude, it seemed to be an appropriate shortcut given that there were over 100 soil series in the Outagamie County portion of the Basin alone.

Subwatershed-specific soils determination: Area-weighted average values for soil parameters including: slope, slope length, USLE K-factor, NRCS hydrologic group, available water capacity, saturated conductivity, clay percentage, organic carbon and bulk density were generated for each subwatershed in the following manner:

(1) The final basin-wide GIS soils coverage was overlaid with the subwatershed boundary coverage using PC ARC/INFO. This operation produced a soils coverage that was also delineated by subwatershed boundaries; thereby, permitting the determination of all of the soil series contained within each subwatershed.

(2) The database file associated with the resulting polygon coverage was imported into a database program where the soil name and subwatershed id fields were related together and cross-tabulated against the subwatershed area field. This operation identified all of the soil series located within each subwatershed, as well as the corresponding area of the soil series. In addition, each soil series had an associated set of parameters for each soil layer which had been obtained by processing the NRCS soil tables in the manner previously described.

(3) Subwatershed specific area-weighted averages for the required soil parameters were then calculated by multiplying the fractional area corresponding to each soil series within a subwatershed, by the value corresponding to each of the soil parameters associated with that soil series. This operation was performed for each of the four assumed soil layers.

Averaging of hydrologic groups was made possible by assigning numerical values of 1, 2, 3 and 4 to each soil series with a hydro group of A, B, C and D, respectively. Soil albedo, which was the only SWAT-required soil parameter that was not determined with the above procedure, was assumed to be 14. Overland slope and slope length were the only "non-soil" parameters that were generated with the soils GIS layer. Default slope lengths for each soil series (and its associated slope) were obtained from Brown and Outagamie County NRCS offices and assigned to Brown and Outagamie County soils. Default slope lengths were not available for Calumet County, so values from both of the other counties were utilized when applicable. A small number of soil series in Calumet County were not present in either Brown or Outagamie County, so their slope length values were assigned based on similar soils in these two counties.

Since the Winnebago County digital GIS soil layer was not available, soils information from the published Winnebago County Soil Survey (Mitchell et al. 1980) was used to supply estimated area-weighted average inputs to the SWAT model for subwatersheds in Winnebago County (all in watershed LF06). In addition, USGS 1:24,000 topographic maps were used to estimate overland slope for these same subwatersheds.

[3] Adding an extra layer to a Kewaunee soil series file increased the simulated sediment yield of a test watershed only slightly (42.3 vs 43.0 t/ha), thereby indicating that the process of adding an additional soil layer was not likely to affect sediment loads.

LOTUS 1-2-3 was utilized to create a script (macro) that automatically exported subwatershed-specific soil files (e.g., LF0205.sol) into a SWAT compatible text file format for all 67 subwatersheds in a single operation. This operation was also done for routing reach and subwatershed input files.

III-C. Land Cover/Use, and Modeling Methods

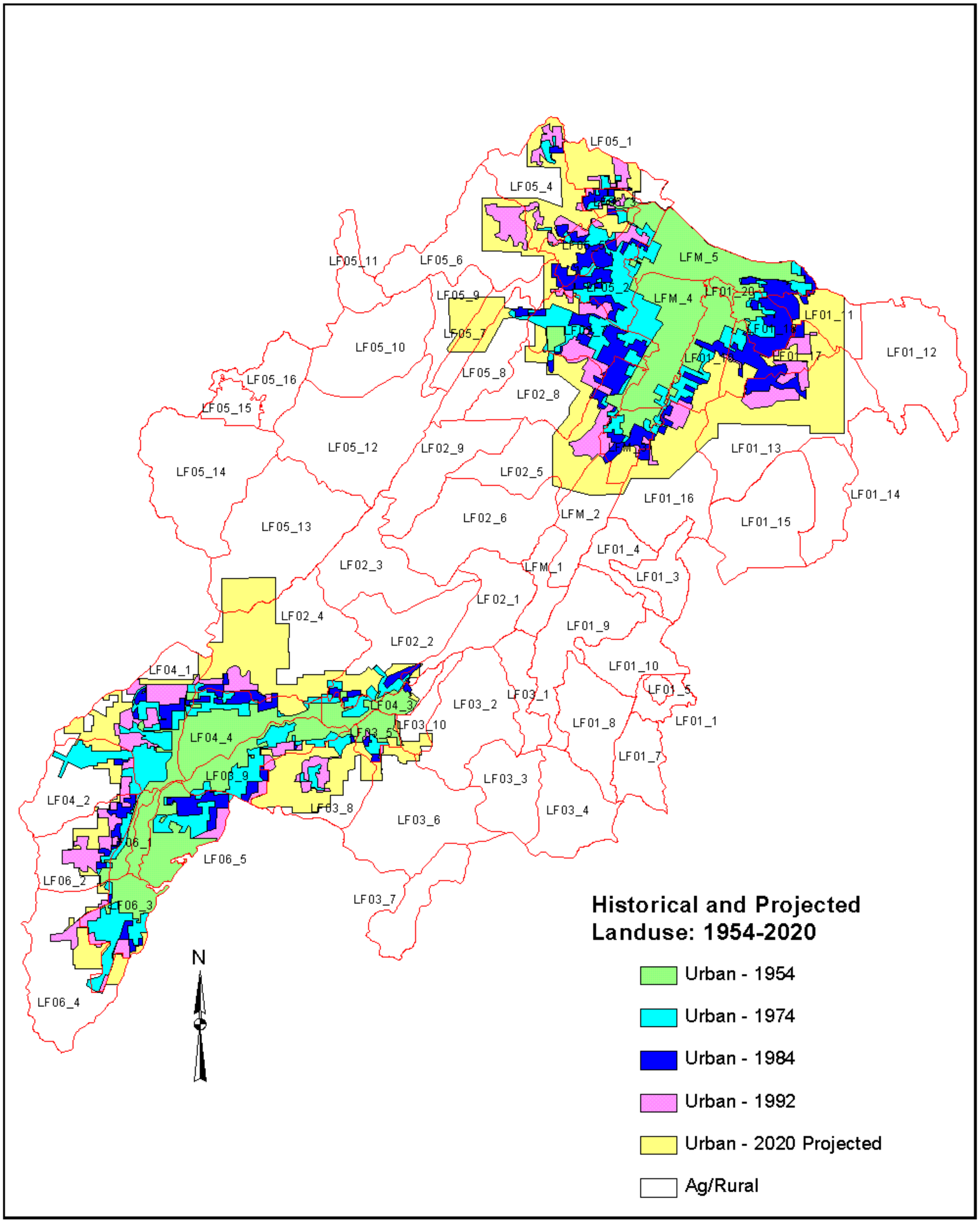
Four distinct landuses/land covers were modeled in this project. Each of the subwatersheds in the Basin were assigned up to four landuses according to the following categories: (1) agricultural; (2) urban; (3) wetland; and (4) urbanizing land. Rural agricultural areas that were undergoing urbanization were considered transitional urban areas. These four landuse categories were modeled using different methodologies that are described later in this section.

Rural/Urban Landuse: Historical, current and projected land cover/use was required in this project. A number of different sources were utilized for determining land cover/uses, including: (1) the WISCLAND classified land cover GIS coverage based on 1992 Landsat Thematic Mapper images, which was obtained from the WDNR (30 meter cells); (2) WDNR land cover GIS coverage at a 1:250,000 scale; (3) USGS 1:24,000 and 1:62,500 topographic hard-copy maps from 1954 to 1992, and digital raster graphic images of the 1992 topographic maps which were obtained from WDNR; and (4) current and projected sewer service GIS coverages were obtained from both the Green Bay Metropolitan Sewerage District and the East Central Regional Planning Commission.

While the SLAMM (Pitt 1995) and SWMM (Huber and Dickinson 1988) computer models were specifically designed to estimate pollutant loads and runoff from urban areas, the SWAT model is not normally intended for this purpose. However, it can be adopted for this purpose by changing the management file or adjusting appropriate parameters to better reflect urban runoff characteristics. Therefore, a detailed breakdown into many urban classes was not likely to improve the accuracy of the simulation of urban loads and runoff with the SWAT model. This seems reasonable, for Fox-Wolf Basin 2000 is not aware of any major urban monitoring effort which has been conducted in the Fox River Valley that could provide a basis for calibration of the model to the urban areas within it, particularly given the highly variable nature of urban loads (Bannerman et al. 1996, Steuer et al. 1996 & 1997, Owens et al. 1997). In addition the scale of the basin and the current dominance of rural landuse preclude placing a major emphasis on modeling urban loads. Hence, the emphasis was placed on primarily distinguishing the location of the boundary between urban and rural landuses, and how this changed between 1954 and 1996. The simplest and most consistent method of determining this distinction was with USGS 1:24,000 and 1:62,500 topographic maps ranging from published dates of 1954 to 1992.

ARCVIEW was used to digitize urban boundaries within the basin to create coverages representing four time periods: approximately 1954-55, 1971-74, 1982-84 and 1992. Figure 2 shows the increase in urban landuse from 1954 to 1992. Each of the four landuse coverages only distinguished between

Figure 2. Increases in Urban Landuse from 1954 to 1992, and Projected Development through 2020 -- as modeled with SWAT.



urban and rural landuses. ARCVIEW Spatial Analyst was then used to convert these four coverages, and the watershed boundary coverage into a grid format with a 10 meter cell size. Each of these landuse coverages was overlaid with the subwatershed coverage to create a table which showed the amount of urban and rural landuse within each subwatershed. From these tables, it is estimated that urban areas within the Basin have been growing at a fairly consistent rate of 2.6% per year over the last 40 years. The estimated increase in urban landuse that occurred during each simulation period was utilized in the urban component of this modeling effort, which is described later.

Urban Growth: For the entire Basin, there was approximately a 2.6% annual increase in urban area between 1954 and 1992. This growth rate was fairly consistent between digitized landuse periods. The amount of urban area will double every 27 years if this rate continues. The estimated urban landuse for the following years is:

1954 ----- 130 km^2 (8.2%)
1974 ----- 217 km^2 (13.7%)
1984 ----- 277 km^2 (17.7%)
1992 ----- 340 km^2 (21.6%)

A 7.9 km^2 increase per/year in urbanized area was estimated for the period between 1984 and 1992, whereas urbanization over the entire period was estimated to occur at a rate of 5.5 km^2/year.

Projected land cover/use: Current and projected sewer service GIS coverages were obtained from both the Green Bay Metropolitan Sewerage District and the East Central Regional Planning Commission. The projected sewer service coverages were processed to create the projected 2020 landuse coverage shown in Figure 2. Urban and rural landuses from this coverage were then used in combination with the 1992 landuse coverage to provide landuse information that was utilized to simulate future flows and TSS loads.

Based on the projected 2020 landuse coverage, urban landuse in the Basin is estimated to be 535 km^2 by 2020, or 34% of the total Basin area. The annual rate of increase between 1992 and 2020 is estimated to be 1.6%. This rate is lower than the estimated historical urbanization rate of 2.6% (1954-92). This difference is not unexpected, for the two sources that provided the GIS coverages generally do not include dispersed, non-sewered developed areas in their projected sewer service area plans. However, there is also reason to expect that the growth rate within the Basin boundaries could slow down. Some urban areas already extend beyond the Basin boundary, while other areas will soon follow suit. Future urban expansion beyond the Basin boundary will effectively reduce the urbanization rate within the Basin. Furthermore, there is no way of knowing precisely when and where un-sewered development will take place during the forecast period. Therefore, the projected 2020 landuse coverage was assumed to be sufficient for the purposes of providing inputs for the simulation of future loads and flows in the Basin.

Land Cover Analysis With WISCLAND Classified Land Cover Image: ARCVIEW and ARCVIEW Spatial Analyst were used to process and analyze the WISCLAND Land Cover Image provided by the WDNR. Estimated 1992 land cover for the Basin, based on an eight level classification of the WISCLAND land cover image, is illustrated in Figure 3. Based on a six-class analysis, areal estimates of land cover for each of the subwatersheds are summarized in Table 2. As shown in Figure 4, agricultural land cover was the most prevalent land cover in the Basin.

Figure 3. Lower Fox River Basin Land Cover - 1992 WISCLAND Imagery

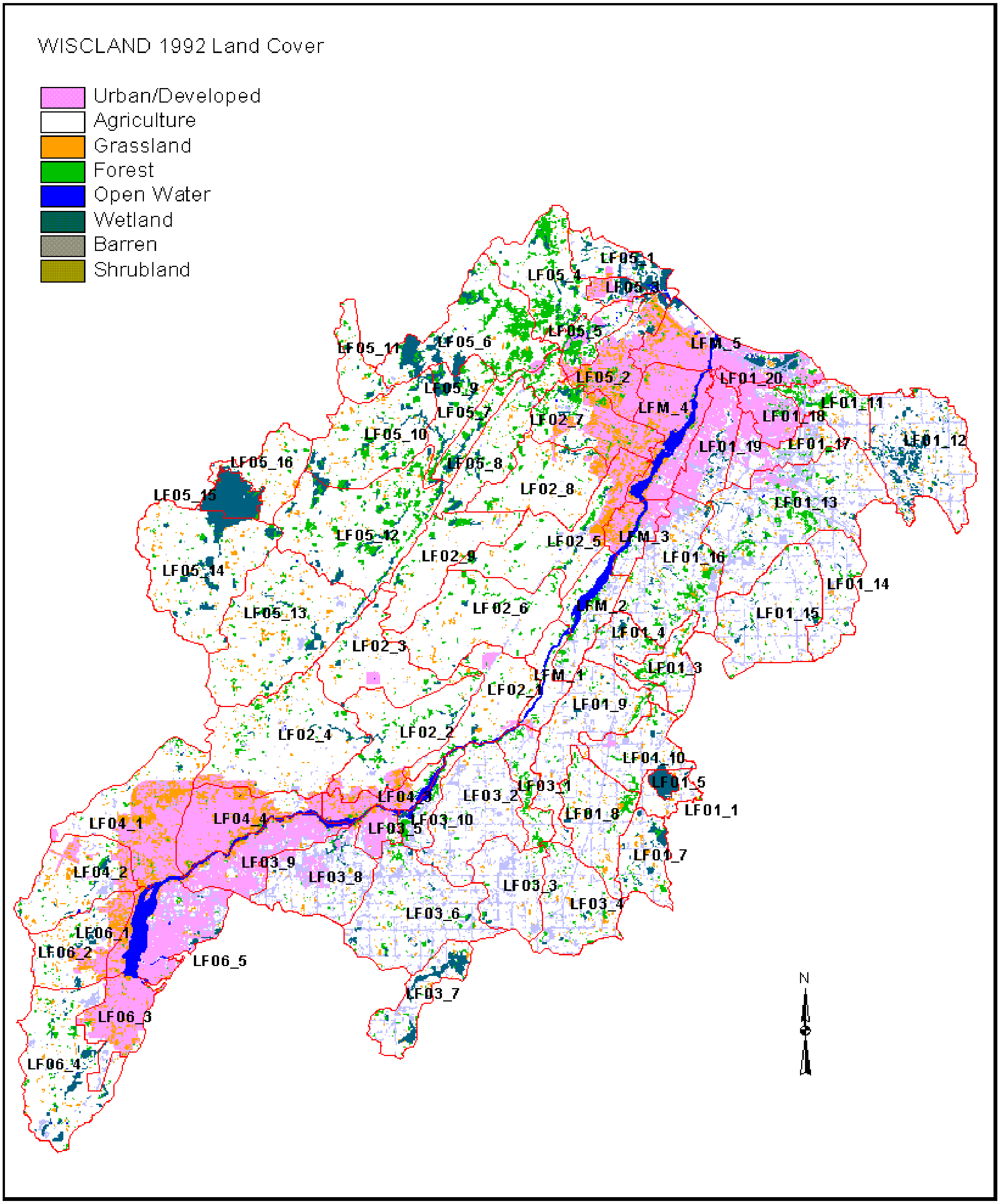
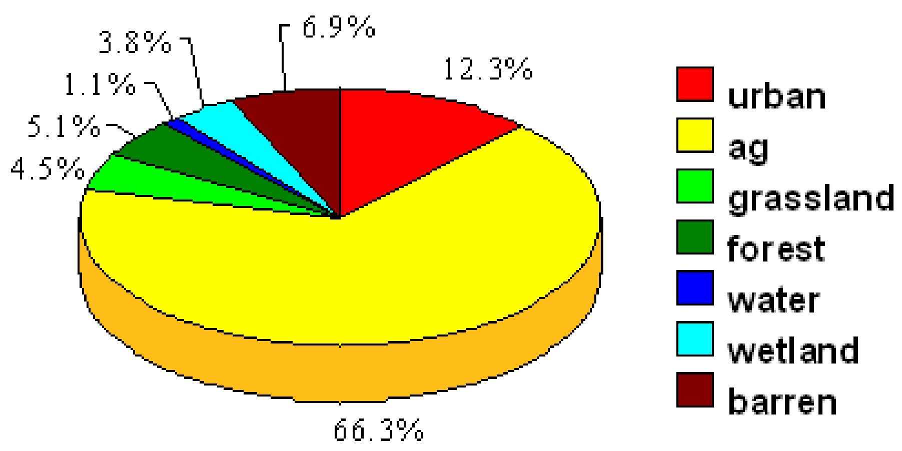


Table 2. Lower Fox River Basin Land Cover. Based on WISCLAND Land Cover Image derived from 1992 Landsat Thematic Mapper Images (this data was based on a pre-release WISCLAND coverage obtained from the WDNR, and is therefore subject to revision).

Table 2. subwatershed	urban	agriculture	grassland	forest	wetland	barren
LF01_1	0.0%	85.0%	4.2%	0.8%	1.4%	8.7%
LF01_3	0.0%	75.9%	2.8%	11.5%	0.6%	9.2%
LF01_4	0.0%	76.2%	2.9%	7.0%	2.9%	11.0%
LF01_5	0.0%	4.7%	0.2%	0.2%	94.3%	0.6%
LF01_7	0.0%	74.8%	3.4%	4.2%	9.0%	8.5%
LF01_8	0.0%	79.5%	3.5%	6.4%	0.5%	10.2%
LF01_9	0.0%	82.0%	2.4%	2.8%	0.9%	11.9%
LF01_10	1.4%	75.4%	2.2%	4.3%	2.7%	14.0%
LF01_11	2.9%	63.0%	3.6%	14.1%	1.1%	15.4%
LF01_12	0.0%	73.6%	2.8%	1.2%	10.5%	12.0%
LF01_13	2.3%	67.1%	2.3%	6.9%	1.4%	20.0%
LF01_14	0.0%	81.9%	1.7%	2.3%	1.4%	12.7%
LF01_15	0.0%	83.7%	1.1%	2.5%	1.7%	11.0%
LF01_16	4.1%	67.3%	3.0%	6.9%	1.8%	16.9%
LF01_17	21.8%	49.2%	2.8%	2.4%	0.3%	23.6%
LF01_18	72.3%	11.0%	0.7%	3.7%	0.0%	12.3%
LF01_19	61.3%	21.9%	1.5%	0.3%	4.0%	11.0%
LF01_20	99.5%	0.0%	0.0%	0.0%	0.0%	0.5%
LF02_1	4.6%	86.8%	3.2%	3.2%	0.9%	1.3%
LF02_2	5.9%	83.3%	4.0%	3.9%	1.7%	1.1%
LF02_3	2.2%	91.7%	1.9%	2.2%	1.1%	0.8%
LF02_4	3.3%	86.6%	4.0%	3.2%	1.3%	1.7%
LF02_5	12.2%	69.6%	9.5%	4.8%	1.1%	2.9%
LF02_6	0.0%	92.8%	1.8%	4.0%	0.5%	0.9%
LF02_7	34.7%	32.2%	18.0%	10.0%	2.7%	2.3%
LF02_8	3.0%	85.7%	5.4%	4.1%	1.1%	0.8%
LF02_9	0.0%	91.7%	1.5%	4.8%	1.4%	0.7%
LF03_1	0.9%	74.3%	2.0%	14.1%	0.0%	8.7%
LF03_2	0.0%	81.3%	1.2%	1.5%	0.3%	15.7%
LF03_3	0.0%	77.2%	1.1%	1.9%	0.6%	19.2%
LF03_4	0.0%	78.1%	2.3%	4.2%	1.0%	14.5%
LF03_5	61.7%	18.1%	4.1%	5.3%	0.1%	10.6%
LF03_6	0.1%	75.5%	1.7%	3.3%	1.4%	18.1%
LF03_7	0.0%	66.2%	2.4%	3.4%	17.1%	10.9%
LF03_8	10.6%	60.6%	1.7%	1.6%	1.5%	24.0%
LF03_9	72.6%	9.8%	6.3%	0.7%	0.1%	10.5%
LF03_10	0.4%	59.8%	0.6%	16.6%	2.7%	19.8%
LF04_1	37.7%	39.7%	17.6%	1.9%	0.5%	2.6%
LF04_2	11.1%	71.5%	9.1%	2.4%	2.0%	3.8%
LF04_3	58.9%	17.4%	16.9%	5.1%	0.0%	1.7%
LF04_4	72.8%	8.3%	16.2%	1.1%	0.0%	1.7%
LF05_1	1.8%	67.6%	1.7%	3.7%	19.8%	5.4%
LF05_2	54.7%	10.3%	22.4%	4.6%	4.8%	3.2%
LF05_3	34.0%	30.7%	7.9%	2.7%	18.6%	6.1%
LF05_4	0.0%	73.3%	1.0%	20.8%	3.5%	1.4%

Table 2. **subwatershed**	**urban**	**agriculture**	**grassland**	**forest**	**wetland**	**barren**
LF05_5	16.8%	53.2%	3.4%	21.3%	2.2%	3.1%
LF05_6	1.0%	67.8%	0.9%	18.1%	11.6%	0.6%
LF05_7	2.9%	66.4%	2.7%	20.4%	6.5%	1.1%
LF05_8	0.0%	85.4%	2.1%	7.6%	3.4%	1.5%
LF05_9	0.0%	72.2%	1.6%	12.3%	13.5%	0.3%
LF05_10	0.0%	82.1%	3.0%	7.8%	6.9%	0.3%
LF05_11	0.0%	90.2%	1.6%	4.8%	2.9%	0.6%
LF05_12	0.0%	80.9%	2.1%	11.3%	5.3%	0.4%
LF05_13	0.0%	88.7%	3.4%	3.0%	3.3%	1.6%
LF05_14	0.0%	85.3%	2.7%	2.6%	9.2%	0.3%
LF05_15	0.0%	2.6%	0.1%	2.6%	94.7%	0.0%
LF05_16	0.0%	89.8%	3.9%	3.2%	3.0%	0.1%
LF06_1	63.6%	0.0%	34.7%	1.0%	0.0%	0.7%
LF06_2	17.4%	60.4%	14.7%	1.7%	2.8%	2.9%
LF06_3	65.4%	17.9%	11.2%	1.2%	0.4%	3.9%
LF06_4	0.3%	85.4%	2.3%	3.5%	5.3%	3.3%
LF06_5	69.9%	11.9%	2.5%	1.0%	2.0%	12.6%
LFM_1	2.1%	88.8%	1.4%	4.3%	0.0%	3.3%
LFM_2	0.2%	77.4%	1.7%	8.2%	1.0%	11.5%
LFM_3	43.5%	27.3%	15.8%	3.6%	0.0%	9.8%
LFM_4	82.7%	2.3%	10.5%	1.2%	0.1%	3.1%
LFM_5	58.5%	14.4%	8.4%	2.3%	7.5%	9.0%

Figure 4. Lower Fox River Basin 1992 Land Cover.



Wetlands and forested areas are relatively small components compared to agriculture and urban land covers. The WISCLAND image used in this project was a pre-release version that was provided by the WDNR. Therefore, the data shown in Table 2, Figure 3, and Figure 4 is subject to revision.[4]

Unfortunately, the classified image could not be used more fully because, from a historical perspective, it was not a consistent source of information that could be applied throughout the required historical simulation period. However, the fractional area of wetlands was directly used as an input to the SWAT model.

Agricultural Land Cover/Use, Crop and Tillage Methodology: A six year crop rotation that is typical for dairy farm operations in N.E. Wisconsin was utilized in all simulations of agricultural areas. The six year rotation consisted of: (1) corn grain; (2) corn silage; (3) oats and alfalfa; (4) alfalfa; (5) alfalfa; and (6) alfalfa. The third year of the rotation consisted of oats followed by alfalfa because SWAT does not allow two crops to be grown simultaneously.

Sugaharto et al. (1992, 1994) and McIntosh (1993a, 1993b, 1994) found that the 6 year crop rotation and associated management practices were typical of the average dairy operations in the East River Watershed. The 6 year crop rotation was also recommended by University of Wisconsin (UW) Extension Agricultural Agent Kevin Erb (personal comm. 1997). The Outagamie County Land Conservation Department (LCD) used this same rotation to represent the cropping patterns of the Duck, Apple and Ashwaubenon watersheds in modeling that was conducted as part of the Duck, Apple, Ashwaubenon Priority Watershed Project (Roy Burton, Outagamie County LCD Director, personal comm. 1997).

At any time, not all the farm fields are in the same year of the rotation. To represent average conditions, 1/6 of the fields were assumed to be in one of the 6 years of the rotation. Therefore, it was necessary to average the results of 6 model simulations to represent average conditions. Each of the six model simulations started at a different phase of the six year crop rotation. Thus, the 6 years of the typical crop rotation were represented by averaging the results of 6 separate model simulations, each of which represented a different phase of the rotation. Daily results of sediment and stream flow from the 6 separate SWAT runs were therefore averaged to produce the final daily results for each of the simulation periods.

This facet of the approach that was used here to approximate the cropping sequences in the area is important, for any anticipated changes (e.g., BMPs involving tillage changes) would likely require that another 6 model runs be conducted and compared/averaged with the original 6 model runs.

Conventional farming practices (e.g., moldboard plow) were assumed to be used in the entire basin throughout the historical simulation period (1957-96). This assumption seems reasonable for the following reasons: (1) the calibration site, Upper Bower Creek is a WDNR BMP evaluation site (Owens et al. 1997) that is already in the BMP implementation phase, yet observations by Fox-Wolf Basin 2000 in 1996 found that it contained only an insignificant amount of chisel-plowed fields; (2) a 1996 transect survey overseen by the UW Extension Agricultural Agent found that only about 6% of the tilled fields surveyed in Brown County used conservation tillage; and (3) a similar transect survey in Outagamie County indicated that chisel plowing in the Duck, Apple and Ashwaubenon

[4] In the pre-release WISCLAND image provided to Fox-Wolf Basin 2000, paved rural roads are labeled as "barren" on the east side of the Fox River, thereby exaggerating the amount of actual barren land shown in Table 2 and Figure 4.

portions of Outagamie County was 11% in 1996 (Ann Francourt, Outagamie County LCD, personal comm. 1998). The recent creation of the Duck, Apple and Ashwaubenon Priority Watershed Project is testament of the low amount of conservation tillage that is currently practiced in this area (WDNR 1997).

For modeling purposes, it was also assumed that conventional farming practices would be utilized in the future. This assumption seems reasonable, for there has been a recent steady trend toward increasing the amount of corn harvested as silage versus that harvested as grain (Kevin Erb, UW-Extension Agricultural Agent, personal comm. 1997; Ann Francourt, Outagamie County LCD, personal comm. 1997). Erosion resulting from expected increased acreage harvested as corn silage could offset the effect of increased implementation of conservation tillage, because harvesting corn as silage leaves little protective residue on the ground compared to that left after corn is harvested as grain. According to UW-Extension Agricultural Agent Kevin Erb (personal comm. 1998), future gains made from increased adoption of conservation tillage may be offset by farmers harvesting a greater percentage of their corn crop as silage.

Tracking such trends is difficult, for it appears that the published crop acreage may not be accurate at times. For example, in 1955-56, corn grain represented 37% of the total corn crop that was harvested in Brown, Calumet, Outagamie, and Winnebago Counties (Wisconsin Agricultural Statistics 1956-96). By 1994-95, the reported percentage of corn harvested as grain had risen to 79%. However, local agricultural experts estimate that approximately equal amounts of corn-grain and corn-silage are currently harvested, with a future trend towards increased harvest of corn silage (Jim Rait, NRCS-FSA Brown County Executive Director; Doug Sutter, NRCS Brown County Ag. Agent; Kevin Erb, UW-Extension Ag. Agent; Roy Burton, Outagamie County LCD Director - personal communications, 1997).[5]

Statewide average crop planting and harvesting dates were obtained in digital form directly from the Wisconsin Statistical Reporting Service, Madison, Wisconsin. The average statewide dates were adapted to N.E. Wisconsin by adding 3 days to the specified date. This was necessary because average dates were apparently not available by county, even though crop yields are published by county (Kevin Erb, UW-Extension agent, personal comm. 1997; Steve Wilson, Wisconsin Agricultural Statistician, personal comm. 1997).

Wetland Land Cover: Wetlands areas were modeled in two separate manners. LF0105 and LF0515 were considered 100% wetland and SWAT's default wetland data set was used in place of the crop data set for modeling purposes. In addition, wetlands within other subwatersheds were assumed to contribute zero sediment load. The percentage of wetland present in each of these subwatersheds was based on those areas designated as wetlands in the Classified Thematic Landsat Land Cover image.

Simulations using the first method indicated that TSS loads were approximately 0.5% of the loads from wholly agricultural areas. Based on this result, the latter method assumed that wetlands did not contribute TSS. Wetland areas within a subwatershed were therefore simulated by assigning a value that represented 1 minus the fraction of wetland present in a subwatershed to the subwatershed-

[5] It is possible that the amount of corn harvested as grain is exaggerated by farmers because monies paid out for crop insurance will be higher for corn-grain, than for corn-silage, if a hail storm or other natural disaster occurs.

specific erosion-control factor (i.e., the USLE P factor). Thus, a subwatershed with 5% wetlands had its TSS load multiplied by a P factor of 0.95 within the SWAT model.

Wetland areas can sometimes act as sinks or sources of abiotic suspended solids. Wetland areas can also contribute biotic suspended solids. However, precise quantification of potential loads from wetlands was beyond the scope of this effort. While, wetland areas within the Lower Fox River Basin are ecologically important, they currently constitute only 3.8% of the total land surface area (WISCLAND Land Cover, see Figure 4), and are therefore not likely to be major sources of TSS.

Urban Landuse Simulation: Urbanization and associated land use changes for the simulation period are by their nature continuous. Therefore, the problem of constructing a model framework for simulating the spatial and time dependant nature of this change throughout the simulation period did not render a simple or obvious solution.

Subwatersheds could have been delineated such that urban areas were separate from rural areas, but this method would have required a minimum of four separate basin delineations to cover the required 1954-2020 simulation period. One drawback of this approach was that major landuse, and the associated parameter changes, would occur abruptly when the basin delineations were changed from one period to the next. The other major drawback was that each delineation would require the creation of a new SWAT data set to represent the new boundaries (subwatershed-specific channel lengths, areas, slope, soil, etc.). Hence, alternative procedures were evaluated for their ability to simulate the changing landuse in the basin, and the associated affect on modeled outputs over time.

The unmodified version of SWAT does not permit direct, continuous stimulation of landuse changes over time. To simulate the effect of temporal landuse changes, two methods were explored: (1) Internal Weighted-Average Method, and (2) Weighted-Average Multiple Run Method.

(1) Internal Weighted-Average Method. In the selected procedure, SWAT's computer code was modified to allow a subwatershed to be simulated as containing both urban and agricultural land uses at the same time. In this procedure, the initial urban fraction within the subwatershed, and the incremental change per year are included in the subwatershed input files. Surface runoff from urban areas is assumed to be from about 1.3 to 1.4 times the surface runoff simulated for rural areas. These urban runoff volume multiplier factors were based on the average SWAT-simulated increase in surface runoff when rural landuse was changed to an urban landuse. This change was made by applying SWAT's own urban management data set on the Duck Creek Watershed. Larger increases are assigned the more permeable B2 and C1 soil hydrological groups because urban soils are often compacted and mixed with lower less permeable layers (Bannerman et al., 1996). Legg et al. (1995) also found evidence which seemed to indicate that soil texture had little effect on runoff volumes from residential lawns in a rainfall simulator study.

The model calculates the weighted-average surface runoff volume according to the urban and rural land uses present in any year. Each year, the model increases the urban fraction according to the incremental change per year that is input in the subwatershed file - as long as the urban fraction is less than one.[6]

[6] This programming procedure is implemented in the surface.for file, directly after the statement that calls the "compute surface runoff volume) subroutine. It is only used for subwatersheds that have been designated as urban in the subwatershed input file (urbsub = 1), and can only be utilized if the sediment formula code in the *.cod file is equal to 9. This entire "urban" routine is not utilized for rural subwatersheds to ensure that even slight calculation discrepancies will not occur.

The rural portion of TSS loads is computed normally, as if the subwatershed was entirely rural. For urban sources, the following modification of the Universal Soil Loss Equation (USLE) was used for simulating TSS loads from urban sources (modification in ysed.for).

$$\text{TSS load} = (TSS_{urb}) * (Q_{urb}) * (DA/1000) * (KLS/KLS_{avg}) \quad \text{(Eq. 1)}$$

where:

TSS load	=	TSS load in metric tons (Mg)
Q_{urb}	=	urban runoff = (original Q) * (1.3 to 1.4), (mm)
TSS_{urb}	=	urban TSS concentration (mg/L)
DA	=	drainage area (km^2)
KLS	=	soil erodability & slope length/steepness factors
KLS_{avg}	=	basin-wide average KLS factor

For this project, the urban TSS concentration was assumed to be 200 mg/L. This value was based on a review of the following urban storm sewer TSS data: (1) 14 Wisconsin sites with a median and mean of 120 mg/L and 237 mg/L TSS, respectively (Bannerman et al. 1996); (2) 8 Lake Superior sites with a median and mean of 284 mg/L and 433 mg/L TSS, respectively (Steuer et al. 1996); (3) Marquette, Michigan with a geometric mean of 159 mg/L TSS (Steuer et al. 1997); and (4) Madison, Wisconsin with a median and mean of 93 mg/L and 106 mg/L TSS, respectively (Waschbusch 1995). Because the TSS concentration is multiplied by the direct surface runoff to compute the urban TSS load in the modified SWAT model, rather than total water yield, data from storm sewer sites were primarily used in determining the representative TSS concentration that was used to compute urban loads.

The K (soil erodibility) and LS (slope & slope length) factors of all of the subwatersheds in the Lower Fox River Basin were averaged to provide the "normalized" KLS factor used in the above equation. The basin-wide average KLS factor was 0.22. The composite TSS load for the subwatershed was then computed based on the area-weighted average of the rural and urban computed TSS loads.

(2) Weighted-Average Multiple Run Method. This alternative urban simulation method was rejected for reasons that will be stated later in this section. In this approach, a separate model simulation is needed for each subwatershed that contains a significant mixture of urban and rural land uses (whenever a subwatershed cannot be modeled exclusively as one land use). In each of these simulations, the subwatershed to be evaluated is compared to a "default" rural simulation to determine the difference between what the sediment load and surface volume are when the subwatershed is 100% urban to what it is when it is 100% rural. The values are then adjusted each year within a spreadsheet according to the estimated percent of urban land use. A composite of the 6 simulations required for computing the rural values, plus the computed differences between the rural and urban values would represent the estimated daily sediment loads and runoff volumes for the entire watershed.

Besides the undesirable complexity of this approach, this method has other flaws that were discovered when it was tried in the East River Watershed. First, it was found that SWAT has a "quirk" where changing the management practice file that is used by one subwatershed affects the results of other subwatersheds. For example, changing the management of the 2nd subwatershed in the SWAT input/output file from an agricultural landuse to an urban landuse (e.g., urban.mgt), resulted in increases and decreases in subsequent subwatersheds until another urban subwatershed was accessed by the SWAT file (the 6th one). Because of this quirk, differences were observed where none should have occurred, and these differences amounted to up to 10% of the estimated difference between SWAT simulated urban and agricultural land uses. The other major problem was that the computed difference was only partly correct; that is, the comparison was between urban and only one phase of the agricultural rotation. But, comparing the urban to all phases of the agricultural crop rotation is not feasible because each subwatershed that underwent urbanization would require 6 additional runs, which would then have to be compared to the 6 runs of the agricultural crop rotation to compute the difference.

Overall, the internal weighted-average method produced a hydrograph that was generally more desirable than when the urban management routine was used within SWAT. Simulated peak daily flows with the selected method were higher than the standard rural simulation; whereas, the hydrograph produced with the alternative method was often too similar to the hydrograph generated with the standard rural simulation.

Urbanization Landuse Simulation: Urbanization is the transitional stage between rural and urban landuse. This transition was simulated by making additions to the aforementioned urban component of the modified SWAT FORTRAN code. The added urbanization component computed water yields and sediment loads for urbanizing areas based on the following underlying assumptions: (1) the runoff characteristics were the same as with urban landuse; (2) the amount of land undergoing urbanization each year was the same as the annual estimated increase in urban landuse; and (3) the TSS concentration in direct surface runoff from land undergoing development was 5,000 mg/L (compared to the 200 mg/L value assumed for urban landuse).

In a study conducted from Spring 1977 to Summer 1978, Madison et al. (1979) found that the mean TSS concentration from rapidly urbanizing watersheds in Germantown, Wisconsin was approximately 6,900 mg/L during monitored runoff events. While erosion controls were implemented in the non-control watershed, they were judged to be ineffective due to drought conditions. Hence, 6,900 mg/L of TSS was assumed to be somewhat high given that some controls are currently being implemented in the Basin.

IV. Other Model Inputs

NRCS (SCS) curve numbers: Default condition II curve numbers furnished with SWAT were utilized for all crops and bare land. These curve numbers are the same as those recommended by NRCS in their National Engineering Handbook (USDA 1972). The curve numbers were altered throughout the rotation periods according to changes in crop type, crop growth, and tillage. Different curve number data sets were created to represent the four expanded soil hydrologic groups of B2, C1, C2, and C3. For example, if hydro-groups A, B, C and D are assumed to be equal to 1, 2, 3 and 4, then B2 = 2.15-2.4 (2.28 mean); C1 = 2.4-2.65 (2.53 mean), C2 = 2.65-2.9 (2.78 mean) and C3 = 2.9-3.16 (3.03 mean). Accounting for these four hydro-groups required that the six management files used to represent the different phases of the typical 6 year dairy crop rotation had to be expanded to a total of 24 management files.

Subwatershed channel width, depth and Manning's n: The channel widths for main and routing reach channels, and the channel depths for routing channels, were estimated using a modified form of the following equations which were adopted from Theurer and Comer (1992, SCS SWRRBWQ Evaluation).

$$\text{channel width} = 1.29 * DA^{0.6} \quad \text{(Eq. 2)}$$

$$\text{channel depth} = 0.131 * DA^{0.4} \quad \text{(Eq. 3)}$$

The modified equations used for SWAT model inputs were:

$$\text{channel width} = (1.29 * DA^{0.6})/1.8 \quad \text{(Eq. 4)}$$

$$\text{channel depth} = 0.15 * DA^{0.5} * (0.001/\text{slope}_{\text{channel}})^{0.4} \quad \text{(Eq. 5)}$$

where:

channel width and depth are in meters
DA = drainage area in km^2 (routing reach cumulative area)

Channel depths and widths that were estimated with the above equations were similar to measured values for the Upper East River (USGS, 1994 unpublished transect data), and for the main stem of the East River (Quinlan 1989).

Subwatershed main channel width is not a critical parameter within the SWAT model framework. A review of the FORTRAN source code shows that this parameter only affects transmission losses to the stream bed. Therefore, TSS is not affected by this parameter because only surface runoff affects TSS yields; whereas, water yield is only slightly affected by subwatershed channel width. Substitution of channel width values ranging from 0.1 meter to 120 meters confirmed that simulated TSS yields from a subwatershed were not affected by channel width values.

Channel n and overland n: Manning's n values of 0.065 were used for all routing reaches except reaches near the outlet of large watersheds were assigned a value of 0.04. A Manning's n value of 0.065 was utilized for the main channels of all subwatersheds.

As discussed later in this report, simulated subwatershed peak flows were close to observed values so these values seem reasonable. With regard to runoff and sediment load, SWAT was not sensitive to the overland n input, even over an extreme range of values. A value of 0.1 was input for all subwatersheds.

Groundwater inputs: Inspection of the FORTRAN code indicates that the specific yield input variable is only used to compute groundwater height. Test simulations revealed that neither of these parameters has any other effect on stream hydrology or sediment computations. Therefore, the specific yield input value was essentially ignored.

Both the revaporation storage and revaporation coefficient parameters were set at zero for all simulations. Assigning a value greater than zero often caused the SWAT program to crash during long-term simulations. This problem seemed to occur during low soil moisture conditions. It was later discovered that some of these crashes may have been avoided by setting the initial soil moisture parameter higher than the anticipated value. Because revaporation does not contribute to surface water or recharge, it can be considered an overall loss that can be accounted for elsewhere in the model. Increasing revaporation when simulated water yields to the stream were already too low (until evapotranspiration was lowered), seemed counter-productive, particularly in light of the program crashes. The aforementioned problems with evapotranspiration implied that revaporation could be ignored, for it simply decreased the water available for surface water runoff or recharge.

The groundwater recession alpha factor (ABF) and groundwater delay value (DELAY) were adjusted so that the simulated hydrograph recession matched the observed recession. ABF characterizes the groundwater recession and the rate at which groundwater flow is returned to the stream, whereas, DELAY is the time it takes for water leaving the bottom of the root zone until it reaches the shallow aquifer where it becomes groundwater flow (Arnold et al. 1996). ABF can be thought of as defining the slope of the recession curve. ABF and DELAY were set at 0.2 and 1.0 days, respectively. These values were chosen to fit the measured hydrograph, rather than reflect what the anticipated groundwater recession curve would actually look like.[7] The chosen set of values worked relatively well for the calibration subwatershed (Upper Bower Creek - 35 km^2), which is rather "flashy", but they did not work as well on the much larger Duck Creek watershed (276 km^2), at County Highway FF. This problem will be discussed in the following section.

The selection of appropriate deep percolation coefficients is discussed later in the "Model Calibration - Hydrology" section.

Sediment Routing Submodel: SWAT currently uses a routine to determine routing channel sediment deposition/resuspension that is not documented in the latest user's manual. This new routine relies on the concept of stream carrying capacity for sediment. After discussions with SWAT model developers J.G. Arnold and J.R. Williams, the following values which affect sediment deposition/resuspension in the routing reaches were used for all simulations: (1) SPCONC = 2,000 mg/L TSS; (2) SPEXP = 1.5; and (3) PRF = 1.25. The calibrated version of the model was apparently not sensitive to minor adjustments to these parameters since most of the sediment exported from the individual subwatersheds was routed to the watershed outlet by the model. Both model developers J.G. Arnold and J.R. Williams (personal comm. 1998) stated that the equations currently used in the SWAT model produced better results than the previously used method which

[7] If the goal is to reflect groundwater inputs from recharge due to the upper aquifer only, then the ABF should be set lower and the DELAY should be longer. However, the objective was to instead match the overall hydrograph recession after a runoff event.

relied on computing deposition based on fall velocity and Stoke's Law, and also applying Bagnold's (1975) stream power equation to compute degradation.

Preliminary model simulations indicated that the routing reach channels produced apparently unreasonably high amounts of channel degradation even with very low USLE soil erodibility (K) and USLE cover (C) factors. Therefore, the routing channel degradation component of the model was essentially "turned off" by assigning a value of zero to both the K and C factors within a channel routing reach. Hence, only deposition was tracked by the model. Channel degradation/deposition within a subwatershed is already accounted for, so this alteration is assumed to be acceptable. The lack of sufficient measured TSS loads from watershed-scale areas pre-empted attempts to fully calibrate this important aspect of the model.

V. Modifications to SWAT FORTRAN Code

Numerous modifications of the SWAT program code were performed on the version of the model that was used in this project. Most of these modifications were initiated prior to beginning this project, but they have been described here and elsewhere in this report because these modifications were important to the completion of the project. Nearly all of the modifications that are described below were made after consulting with the developers of SWAT. A number of the changes cited in this section have also been incorporated into the 1998 version of SWAT, which was not available until this project was nearly completed.

Evapotranspiration Routine: Balancing the water budget to provide the expected long-term surface volume runoff of about 200 mm/year (Gebert et al. 1987) was not readily feasible without extreme modifications to key parameters. Water yields from 42 year simulations with the uncalibrated SWAT model were approximately 100 mm too low, or half the expected amount. Simulated runoff for the Upper Bower Creek subwatershed was essentially zero in 1994. However, observed runoff for calendar year 1994 was actually 95 mm (USGS Water Resources Data, Wisconsin. Water Year 1995). Increasing the NRCS curve number did not greatly affect the total water yield to the stream; instead, it increased surface runoff at the expense of recharge to the stream. Changing key soil parameters such as available water capacity and saturated conductivity also had little effect on water yield. In addition, the soil parameters were obtained using a relatively robust approach, so it did not seem wise to change them without strong evidence which would indicate that the values were wrong.

After reviewing SWAT documentation/code and published articles concerning evapotranspiration equations, the simulated water budget was balanced by reducing the SWAT-computed potential evapotranspiration by an adjustment factor. As a check, the Agricultural Productivity Extender model (APEX)[8] was applied to a similar data set to determine whether the problem was due to a data input error, or possibly the model code. Precipitation and temperature data sets identical to those used in SWAT were used in this evaluation. Similar problems with the water budget were encountered, so the APEX data set was forwarded to J.R. Williams (USDA-ARS, Texas - EPIC, SWRRBWQ, SWAT and APEX model developer) for further evaluation. Williams was able to get the water budget to balance by altering both the leading coefficient and exponent of the Hargreaves and Samani (1985) potential evapotranspiration (PET) equation, and changing some of the inputs used in the Green-Ampt. equation. However, SWAT and the version of APEX used by Fox-Wolf Basin 2000 did not use the Green-Ampt. equation on daily time step computations, so only the PET equation could be adjusted in this project (SWAT offers the Green-Ampt. equation as an option, but only when applied at a sub-daily time step).

Therefore, a variable was added to each of the three PET equations used by SWAT (in etact.for and etpot.for), which simply reduced the PET by a factor that was input by the user in the control-input/output file. Evaluations of the calibration data set, which was applied to Upper Bower Creek, found that all three PET equations produced similar hydrograph responses throughout the year once they were adjusted by the appropriate PET multiplier factor. To calibrate the model, the PET factor was adjusted until the simulated long-term water yield to the stream was approximately the same as the observed stream volume. A value of 0.65 was chosen for the selected Hargreaves and Samani (1985) PET equation, and this value was used in all simulations.

[8] The APEX model is essentially the same as the EPIC model, except multiple watersheds can be modeled and routed to an outlet.

Measured Temperature Input: The clicon.for file was modified to remove a problem whereby SWAT automatically substituted a generated temperature value whenever the measured maximum or minimum temperature was zero degrees Celsius. This is not as insignificant as it seems, for precipitation that occurs when the measured temperature is zero should be simulated by default as snow, but this may not be the case when a simulated temperature value is substituted.

Sediment Equations: The ysed.for file was modified to permit the selection of different sediment yield equations, and to allow user inputs for sediment equation coefficients and exponents so that the model could be calibrated. This change simply reflects the same approach that is used in EPIC (Sharpley and Williams 1990), APEX (Williams et al. 1995) and the NRCS version of SWRRBWQ (Arnold et al. 1990, 1994). These models were developed by some of the same researchers who helped develop the SWAT model.

To improve the simulation of TSS loads, a routine was added to the surface.for and surfstor.for files which allowed the sediment load to be calculated on the basis of delayed surface runoff, even when no precipitation occurred. Prior to this change, sediment loads were only computed on days when precipitation occurred. An added input parameter in the control code file (*.cod) allows this option to be turned off. An urban component was also added which is described later in this report.

Snowfall Threshold Temperature: A variable was added to the *.cod file which allows adjustment of the snowfall threshold temperature (in snom.for). Increasing the temperature over the default value of zero Celsius produced more realistic results (Baumgart 1998). The latest version of the SWAT model (SWAT98.1) was obtained near the completion of this project. A similar change to that described here has now been incorporated into this latest version of SWAT.

Snow Melt Rate: Because the snow melt rate was judged to be too rapid (Baumgart 1998), an input variable was added to the snom.for file which allowed adjusting the snow melt rate. Also, changes were made in the snow melt formula so it would conform more closely to what was cited in the original SWAT documentation. SWAT does not account for wind speed, sunlight and relative humidity when it calculates snow melt, so even with this modification, it is not reasonable to expect the model to predict snow melt with a great degree of accuracy. A similar change to that described here has now been incorporated into the latest version of SWAT (SWAT98.1).

Snow Cover Reduction Equation: SWAT does not appear to account for the effect of snow cover on erosion. Substantial erosion is still simulated by SWAT even when 1,000 cm of snow cover was forced to accumulate in trial model runs. To compensate for this problem, the ysed.for file was modified to better reflect the erodibility of the soil under snow pack or frozen conditions. This was accomplished by adding a simple decay function to the model which multiplied the computed sediment yield by a factor which was based on the amount of snow pack simulated by SWAT. This equation is shown in equation 6 below.

$$Ym = Yo * 1/\exp(snow * 3/25.4) \qquad \text{(Eq. 6)}$$

where:

Ym= sediment yield modified to reflect snow cover in metric tons/ha(Mg/ha)
Yo = original unmodified sediment yield
snow = simulated snow cover in mm (melted)

Equation 6 reduces TSS loads whenever simulated snow cover is present. This modification reduced simulated 1976-96 total TSS loads by 13% at the Duck Creek monitoring site on CTH FF, while simulated March loads during this same period dropped by 55%.

Read subwatershed input file: The readsub.for file was altered to change the input structure to 8 characters of fixed length for all variables. This change simplified automation of the input file process through a script (macro) within a Lotus spreadsheet. In one operation, all subwatershed input files were exported into the required SWAT input format. Routing reach and soil input files were also automated, but the file structure was maintained.

Storage file: The surfstor.for file was modified to correct an error which prevented subsurface flow from being computed whenever routing was performed by the model. SWAT developer, J.G. Arnold, was informed of this problem.

Groundwater module: It was discovered that the delay component in the groundwater sub-model was commented out. The delay component was reactivated by removing the comment. SWAT developer J.G. Arnold later confirmed that this comment should be removed.

Erosion Control P Factor: Removed statement that altered the P factor when the slope was over 0.0506. This was intended for the HUMUS project, but was apparently left in the code, so it affected all user's simulations. SWAT developer, J.G. Arnold, was informed of this problem.

Transmission losses: It was discovered that statements in the route.for and surface.for files seemed to introduce accounting errors regarding total water yield to the stream and groundwater recharge. These statements had the effect of adding the amount of water that was associated with transmission losses back to shallow storage. This effect was observed at both the subwatershed and routing reach levels. Because simulated transmission loss should probably be considered a net loss to the system, the following statements were commented out: (1) in route.for: (shallst = shallst + TLC/(1000*da*flu(j)); and (2) in surface.for: (shallst = shallst + qt1). Commenting out these statements seemed to clear up the accounting errors observed in the standard output file and the routing reach output file regarding total water yield and groundwater recharge.

The "call" statement to the subwatershed transmission loss subroutine in SWAT code was found to be commented out. Reactivating this statement made the routine function correctly, as the expected effect was verified in the routing output files (*.eve and *.rch).

Output modification: Normally, SWAT does not provide daily output from only one reach. However, USDA-ARS SWAT developer J.G. Arnold recommended that SWAT's "SAVE" command may work. This command is used to provide output for daily routed loads and water yield, and it is implemented through the routing file (*.fig). Unfortunately, the SAVE command did not work correctly at first. It was determined that a "9" command needed to be assigned in the routing file instead of the "8" that the documentation and "util help" had erroneously indicated. There was also a minor formatting error in the FORTRAN code (save.for) that made the program crash until it was fixed. Comparisons between the routed output in the reach and event (*.eve) files agreed, thereby indicating that the SAVE command functioned correctly. In addition, the formatting in the write statement was modified to: (1) add the year, month and day; (2) remove the header and reduce unnecessary spaces; and (3) only include sediment load and water yield as modeled output.

VI. Model Calibration

SWAT model versions: The SWAT96.2 version of SWAT was utilized initially for this project. However, it became apparent that the model was over-estimating soil moisture in the fall season whenever the alfalfa crop was "growing". This problem caused model simulations to overstate runoff in the fall. Apparently, the alfalfa crop was not growing sufficiently in the fall; thereby, reducing ET, increasing soil moisture, and increasing runoff potential. Attempts were made to fix the model code by bringing in the crop growth code from the SWAT97.2 version, but this failed. After testing of the SWAT97.2 version, it was decided that the project would proceed cautiously with the updated model. This decision was made the last week of January, 1998. User-modifications in the SWAT96.2 code were transferred to SWAT97.2 and throughly tested before proceeding further with this project. All results reported here were simulated with a modified form of the SWAT97.2 model.

Primary Calibration site: The Upper Bower Creek watershed (LF0115, 35 km^2) was used as the model's primary calibration site for stream flow and TSS yields (Figure 1). This site is located in the East River Watershed, and it is jointly funded by the USGS and WDNR (USGS Station #04085119). A 1990 to 1994 data set was used for calibrating the model (50 events), while the data set from 1995 to 1996 was utilized for validation/assessment of the model results. Most of the data from this site was provided in digital format, both on an event basis, and on a daily basis by the USGS, Madison, Wisconsin.

Calibration of Crop submodel: Initial simulated crop yields were much higher than published values, which translates to increased residue, and understated erosion if left as is. SWAT model developers, J.G. Arnold and J.R. Williams of USDA-ARS, Temple Texas suggested changing the potential heat units (PHU) of the crops so that the crop would mature sooner, and have reduced crop yields. The PHU's determines how much energy is required for a plant to mature. However, reducing the PHU's to lower crop yields to observed levels made the crops mature far earlier than they should (e.g., corn matured in early to mid July). Therefore, crop yields were calibrated by altering each crop's biomass energy factor (BE) in the SWAT crop database file. BE's were reduced from default values of 40, 20, and 35, to 24, 14, and 25 for corn, alfalfa and oats, respectively, to correspond more closely with the published crop yields for Brown County from 1988-96.

The alfalfa minimum C value was increased from the default of .01 to .035, since the former value produced essentially no erosion from alfalfa fields - which is unlikely. The nutrient stress component of the model (in grow.for) was deactivated to reduce the potential for problems that might have occurred if insufficient nutrients were supplied to the model through user inputs, or in case this model component didn't function properly.

Further details concerning calibration and assessment of the crop sub-model can be found in Baumgart (1998).

VI-A. Model Calibration - Hydrology

Bower Creek: The first calibration step was to match the simulated long-term (42 year) annual water yields to an expected value of about 200 mm for the Upper Bower Creek subwatershed, which was based on the regional runoff values published by the USGS (Gebert et al. 1987). Calibration was accomplished by altering the "ETCOEF" variable until the simulated and expected long-term annual water yields were similar. As described earlier, the ETCOEF variable is the leading coefficient that was added to the SWAT FORTRAN code by the author of this report to permit adjustments of the potential evapotranspiration (PET) equations utilized by SWAT. Because ETCOEF is a leading coefficient in the PET equations, a value of 1.0 produces the same runoff results as the un-altered version of SWAT.

An ETCOEF value of 0.65 was selected for all project simulations, along with the Hargreaves and Samani (1985) PET equation. All three optional PET equations were tested for fit with the Bower Creek 1990-94 hydrograph, but there was little difference between them once the ETCOEF was adjusted to match the expected total water yield that occurred during the calibration period. The chosen ETCOEF value of 0.65 decreased evapotranspiration and increased runoff. The Bower Creek watershed was "flashy", so no attempts were made to alter the initial values used in the groundwater module, which assumed that percolation to the deep aquifer was low.

Recommended default NRCS curve numbers were used for all model simulations, and were not altered. Curve numbers were adjusted throughout the rotation to accommodate changes in crops and tillage. Attempts were made to improve the fit between the simulated and observed hydrographs by altering the curve number for alfalfa, but no improvements were observed.

Figure 5 compares simulated and observed stream flow volumes from 50 events; whereas, Figure 6 compares the peak flows for each of the events. Data for the observed events was obtained from USGS. The coefficient of determination, R-squared, as determined through linear regression analysis, was 0.53 for stream flow volumes and 0.66 for peak flows. The Nash-Sutcliffe coefficient of efficiency (NSCE) was also used to assess the ability of the model to match observed values (Nash and Sutcliffe 1970).[9] The following equation is used to compute the coefficient of efficiency:

$$NSCE = 1 - \frac{\sum_{i=1}^{n}\left(xo_i - x_i\right)^2}{\sum_{i=1}^{n}\left(xo_i - xo^*\right)^2} \qquad \text{(Eq. 7)}$$

where n is the total number of events, x_i is the simulated flow or TSS load for an event, xo_i is the observed event flow or load, and xo^* is the mean flow or TSS load for all observed events. A NSCE value of 1 indicates a perfect fit.

The NSCE for total event stream flow volumes was 0.41, while the NSCE for peak flows was 0.65. These statistical measures, along with the relationships shown in Figures 5 and 6, indicate that there was a general correspondence between simulated and observed values.

Figures 7a through 7c illustrate daily simulated and observed stream flows during the Oct. 1990 to Dec. 1994 calibration period. Average precipitation from the USGS weather stations is also shown in these figures.

[9] The Nash-Sutcliffe coefficient method has been recommended as a goodness-of-fit criterion by the American Society of Civil Engineers Task Committee on Evaluation Criteria for Watershed Models (ASCE Task Committee 1990).

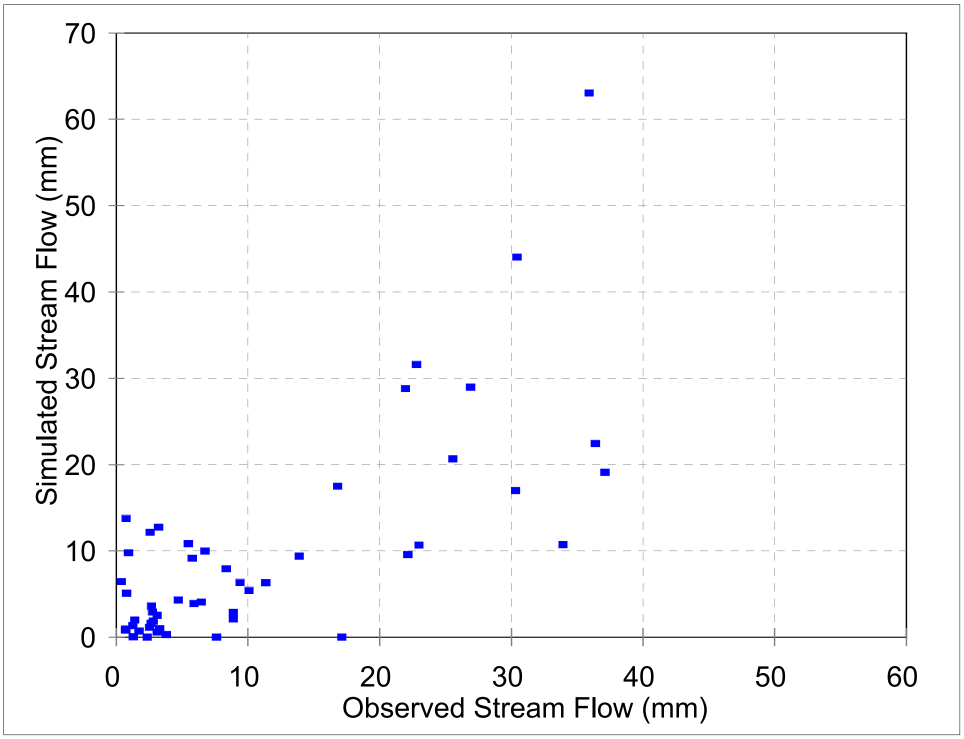


Figure 5. Simulated and Observed Flow Events: Upper Bower Creek 1990-94.

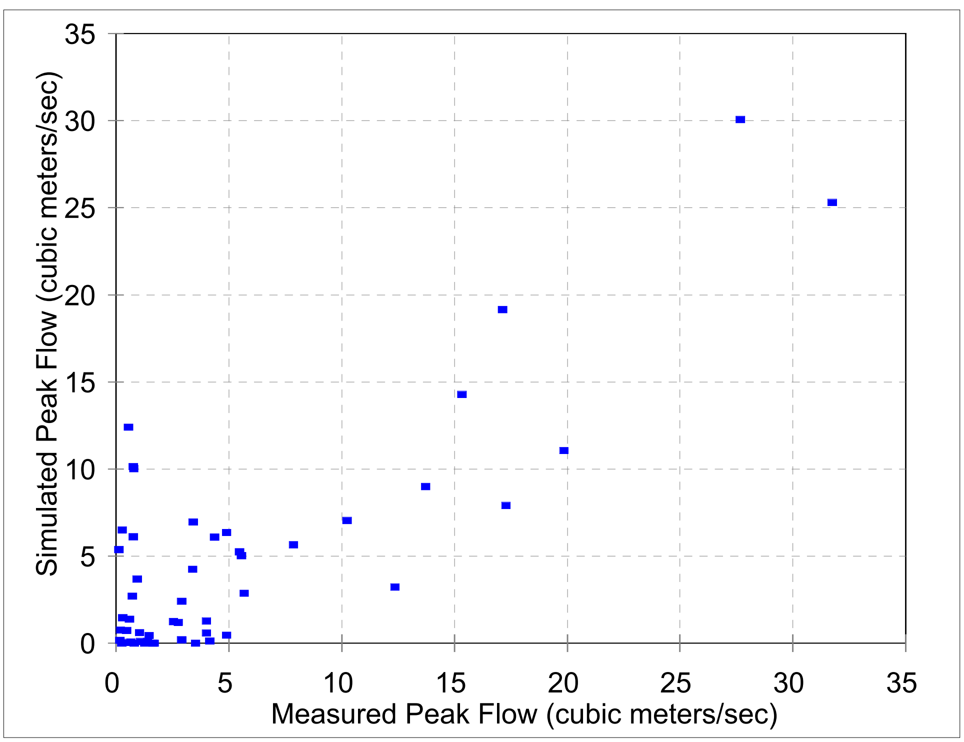


Figure 6. Simulated and Observed Peak Flows: Upper Bower Creek 1990-94.

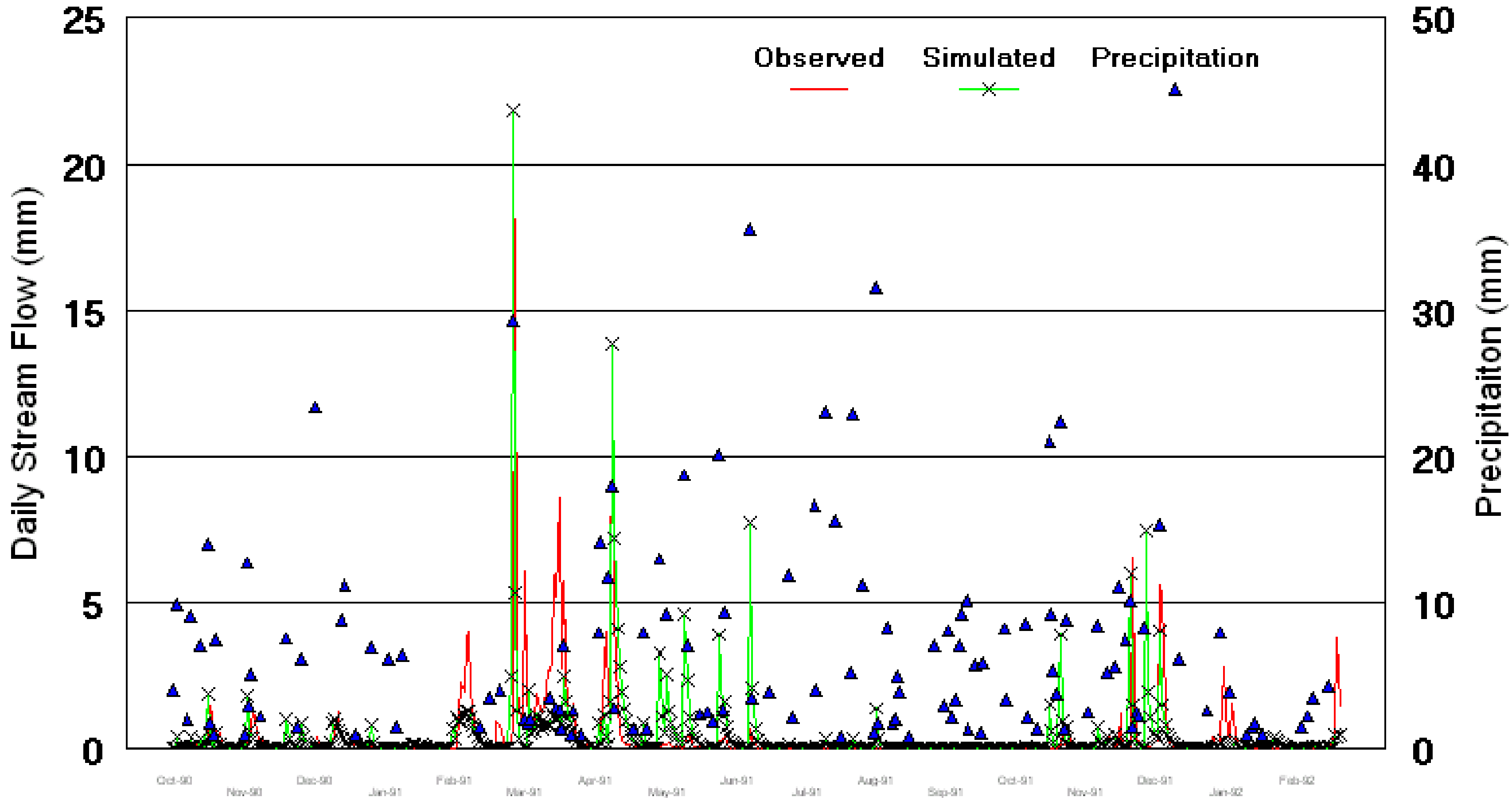


Figure 7a. Observed and Simulated Daily Stream Flow - Bower Creek.

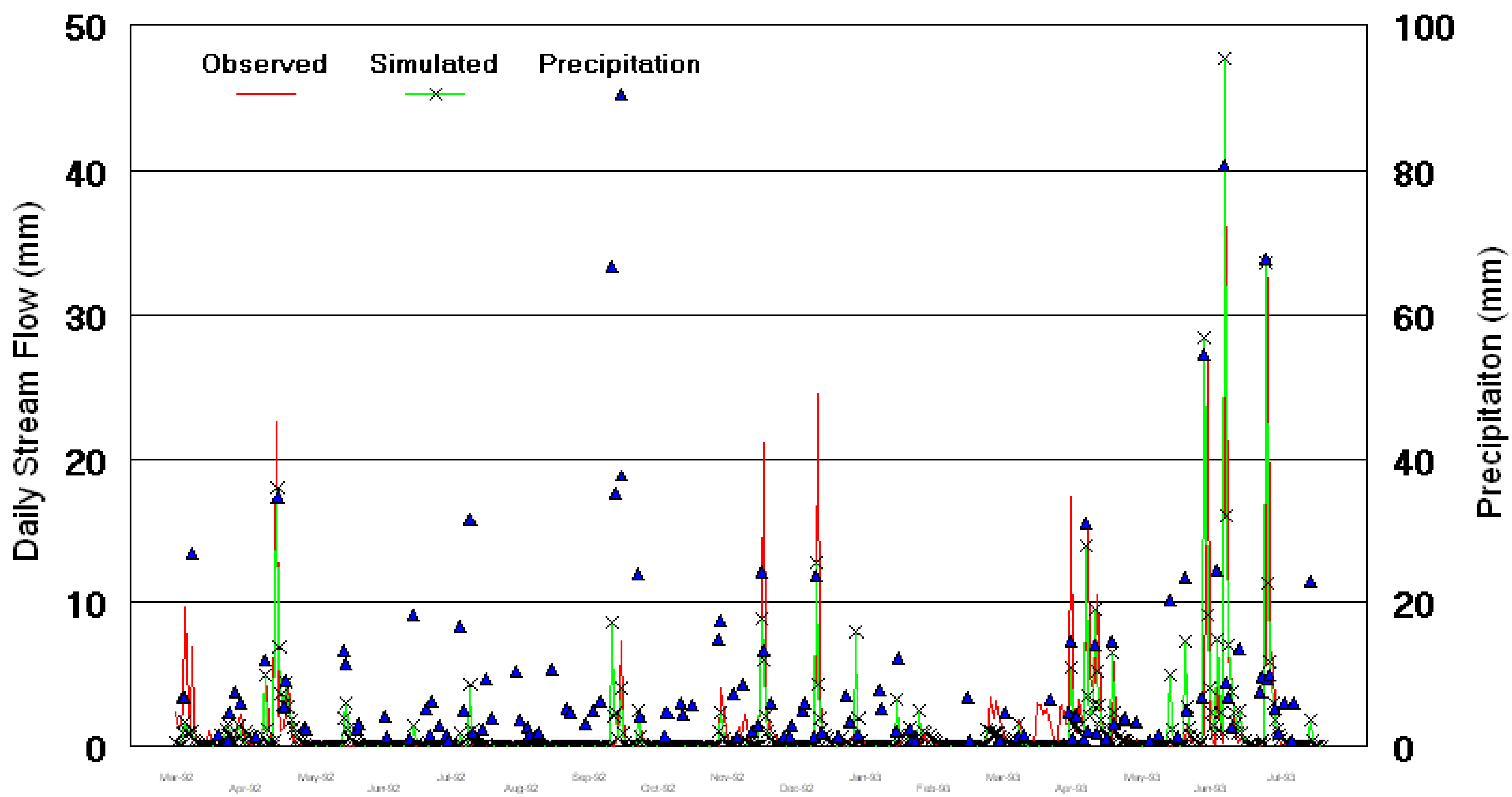


Figure 7b. Observed and Simulated Daily Stream Flow - Bower Creek.

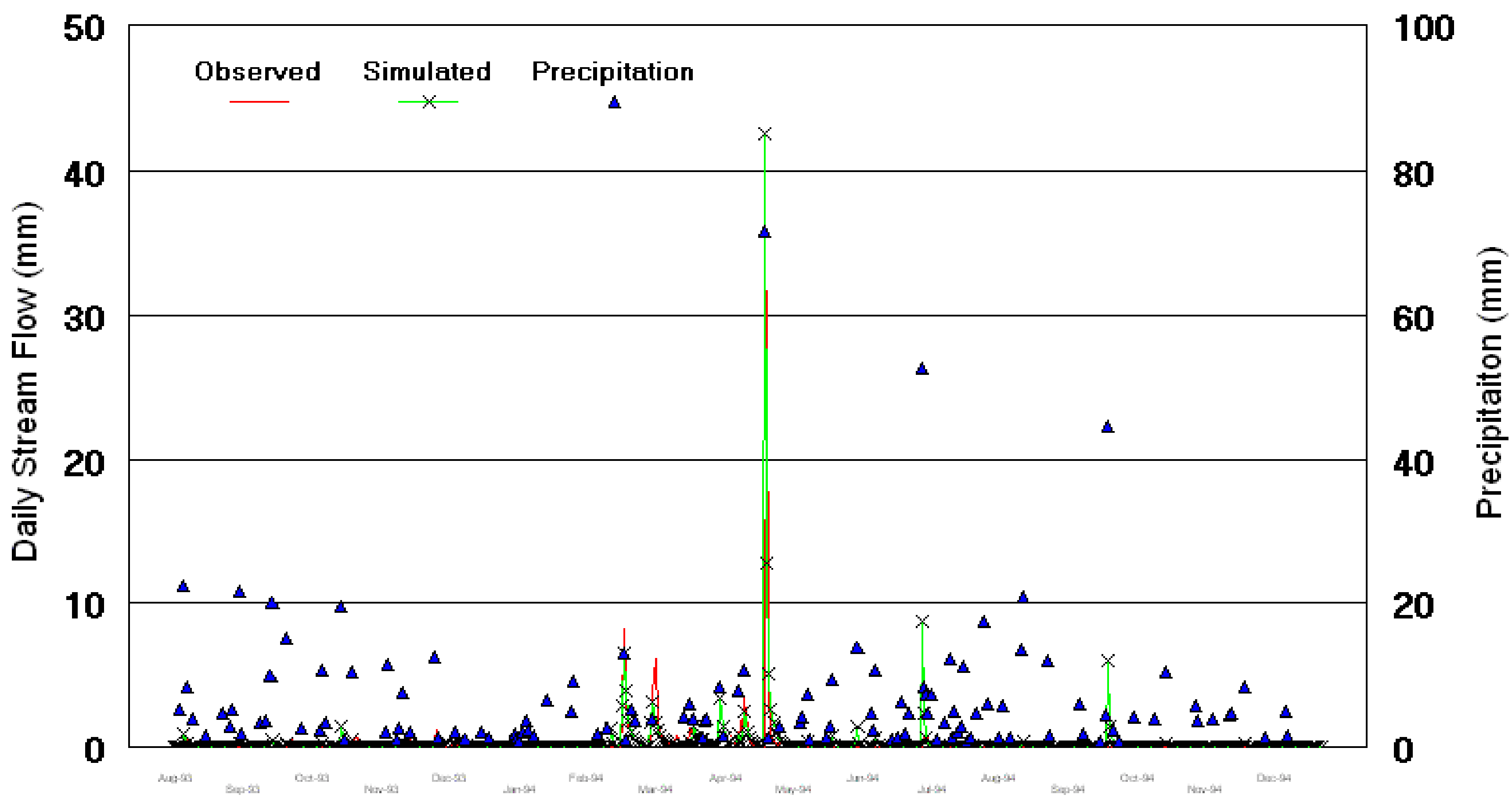


Figure 7c. Observed and Simulated Daily Stream Flow - Bower Creek.

With some exceptions, general peaks and recessions were tracked by the model. Total simulated water yield during this period was 872 mm compared to the observed total of 911 mm. However, simulated flows during the May-June, 1991 period were overstated (Figure 7a). An extended period with much higher than normal temperatures was experienced from May 10-31, 1991. The calibrated model and data set may be overstating runoff when soil moisture has actually been greatly depleted due to high temperatures, clear skies, and high evapotranspiration. Daily solar radiation values can only be simulated by the model; at this time, no option is available for user inputs of measured values. Given this limitation, and the lack of measured values, it is suggested that the model might employ a technique that increases the simulated solar radiation when the maximum temperature is far greater than normal, but only for the period between late spring through early fall.

While the previous example implies that the model overstated soil moisture during dry periods, other evidence suggests that the model is capable of reasonable predictions after long dry spells. For example, simulated flows during a rather wet period in September, 1992 period matched observed values fairly well (Figure 7b). Approximately 140 mm of rainfall occurred from Sept. 14 to Sept. 18, 1992 (66.7, 0.0, 35.2, 0.1, and 37.6 mm, respectively). Despite this high precipitation event, the calibrated model predicted only 19.3 mm of total stream flow from this series of events, which compares favorably to the observed value of 12.3 mm. Given the relatively impermeable nature of the soils in Bower Creek [10], it appears that the model was able to reasonably track soil moisture, even during an extreme period. A comparison between precipitation, observed flow and simulated flow indicates that the model was capable of adequately estimating stream flow over an apparently wide range of soil moisture conditions (Figure 7).

Duck Creek at County Highway FF: The USGS monitoring station located on Duck Creek at County Highway FF (station #04072150) was used to calibrate the model to the hydrologic characteristics of this watershed. This site is located at the outlet of subwatershed LF05_7, and the drainage area at this point is 276 km^2 (Figure 1).

Only the amount of water lost through percolation to the deep aquifer was altered to match simulated and observed total stream volumes. Percolation to the deep aquifer is considered a loss to the system, and it is determined by multiplying computed soil percolation by the deep percolation coefficient. Prior to calibration, the deep percolation coefficient in the groundwater file for Duck Creek was initially set at a value of 0.16, in contrast to the 0.04 value used in the Bower Creek data set, and all other watersheds. The value for Duck Creek was based on data reported by Krohelski (1986, from Fig. 9) which estimated a recharge rate to the lower aquifer of 0.4 inches/year for Brown County, while western areas in the vicinity of Duck Creek were presumed to exceed the average.

Krohelski (1986) also found that stretches of the main branch of Duck Creek were losing; therefore, compared to the East River, a higher value for transmission losses was initially assumed. Because of problems associated with balancing transmission losses with delayed groundwater inputs to the stream, the transmission loss routine was essentially ignored (also see section on modifications to the model).

[10] Values used by the model to represent the soils in the Upper Bower Creek calibration watershed were: (1) saturated conductivity of 27 mm/hr for the top 200 mm of soil, and 9 mm/hr for the deeper layers; and (2) clay content of 21% and 47% for the uppermost, and bottom layers, respectively.

Even low transmission losses caused extended periods with zero or very low flows, which was contrary to observed values. Attempts made to balance the transmission losses with groundwater recharge were unsuccessful. Extending the groundwater hydrograph into the summer months caused undesirable effects in which stream flow remained relatively high for an extended period after a large event. This effect was not seen in the observed flows. Therefore, the higher than average transmission losses were simply counted as losses to the deep aquifer. This was accomplished by raising the deep percolation parameter from 0.16 to 0.40 in the Duck Creek groundwater input file.

Simulated and observed runoff volumes for Duck Creek at CTH FF are compared in Figure 8. Average annual runoff during the Jan. 1, 1989 to Dec. 31, 1993 period for simulated and observed runoff was 188 mm/yr and 191 mm/yr, respectively. In this comparison, the simulated flows were delayed by one day to bring them in phase with the observed flows, and a running average was used to smooth the hydrograph somewhat.

A 3-day running average was selected on the basis of a combination of the highest NSCE, and the best visual fit between the observed and simulated hydrographs. Weighted, running average factors of 0.25, 0.65, and 0.1 were used, along with the 1 day delay mentioned earlier. Most of the largest daily flows were close to the measured values, even without the smoothing operation. However, the smoothing operation helped provide a closer fit for very large events, such as occurred on June 23 and June 24, 1990.[11]

As shown in Figure 8, simulated daily stream flows generally tracked the observed values during the 1989-93 calibration period. However, there was a tendency for the model to over-predict small events, particularly during the summer and fall. A NSCE of 0.64 was determined for the calibration period, while R-squared was 0.68. Without the 1989 initialization year, the NSCE was 0.67 and R-squared was 0.72.

There was insufficient water quality data to calibrate the model for TSS at this site because USGS sampling occurred primarily during low flow events. This was unfortunate, for the sediment routing component of the model needs additional refinement to better define the user-adjustable parameters in the sediment deposition/degradation sub-model.

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[11] For the Duck Creek site, peak flow during the June 23, 1990 event could only be estimated by the USGS. This estimate was based on: (1) a gage height of 21 ft., which was indicated by flood marks; and (2) the rating curves was extended above 1,500 cfs on the basis of contracted flow measurements.

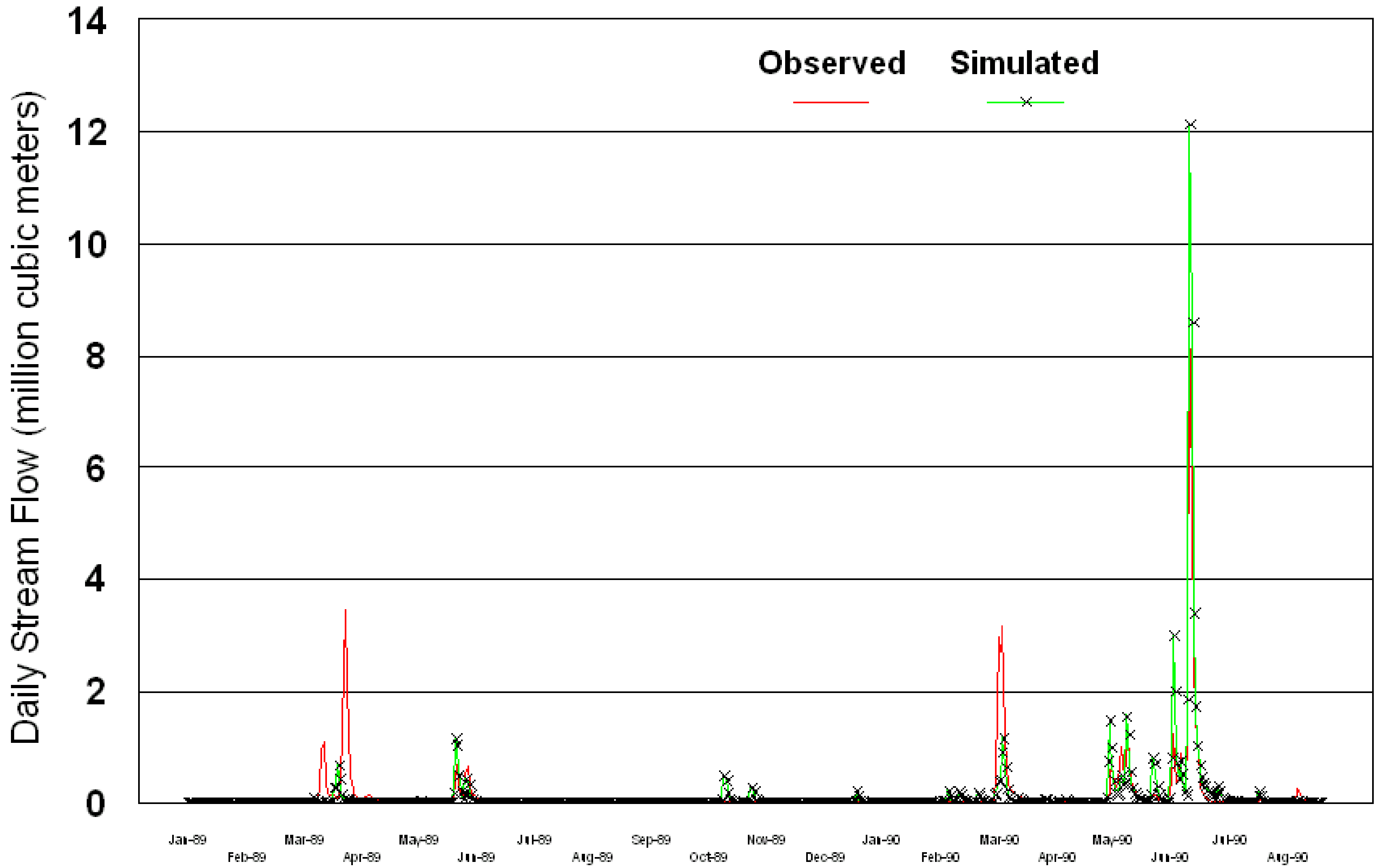

Figure 8a. Observed and Simulated Daily Flow: Duck Creek at CTH FF (276 sq. km).

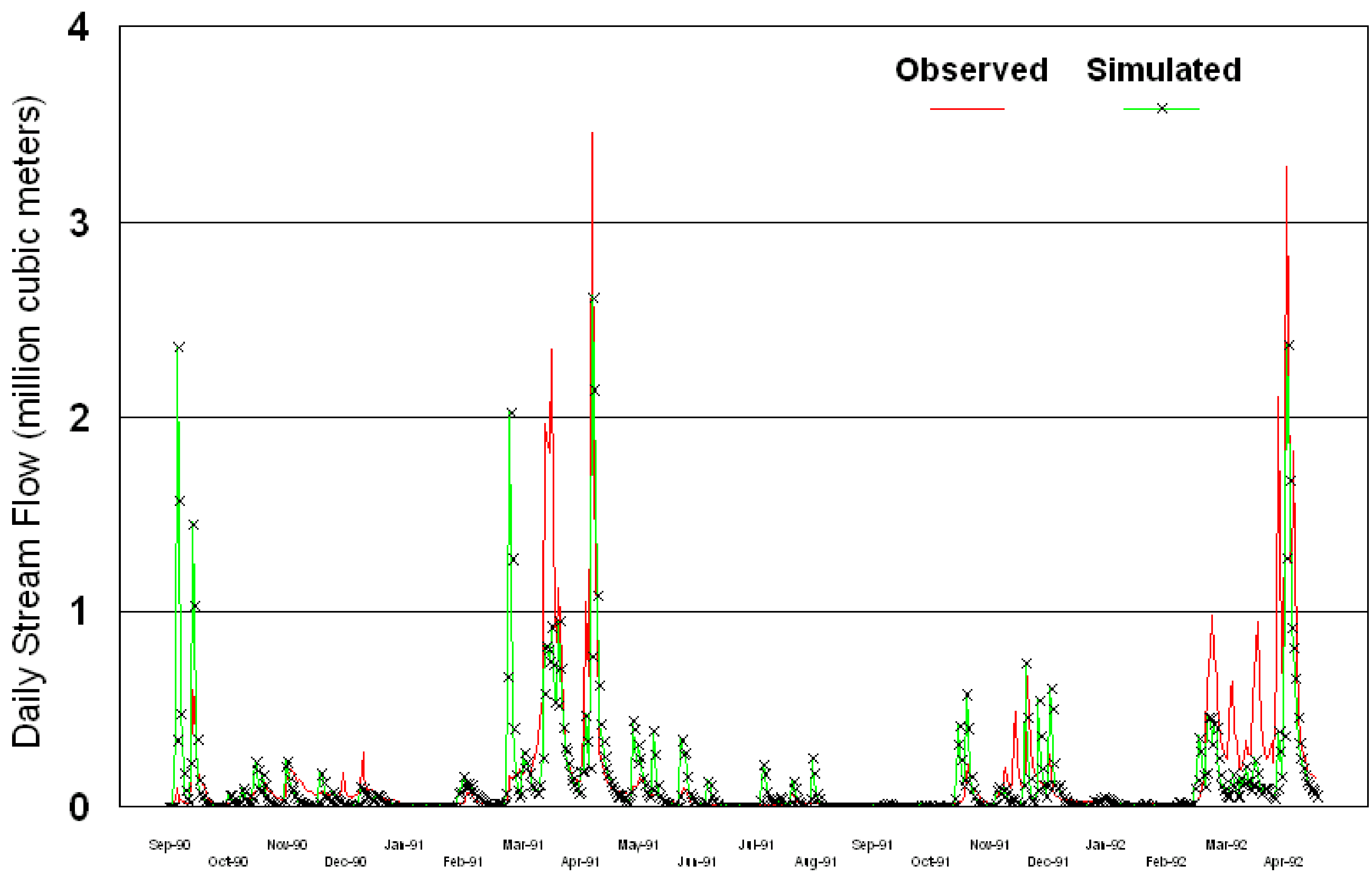

Figure 8b. Observed and Simulated Daily Flow: Duck Creek at CTH FF (276 sq. km).

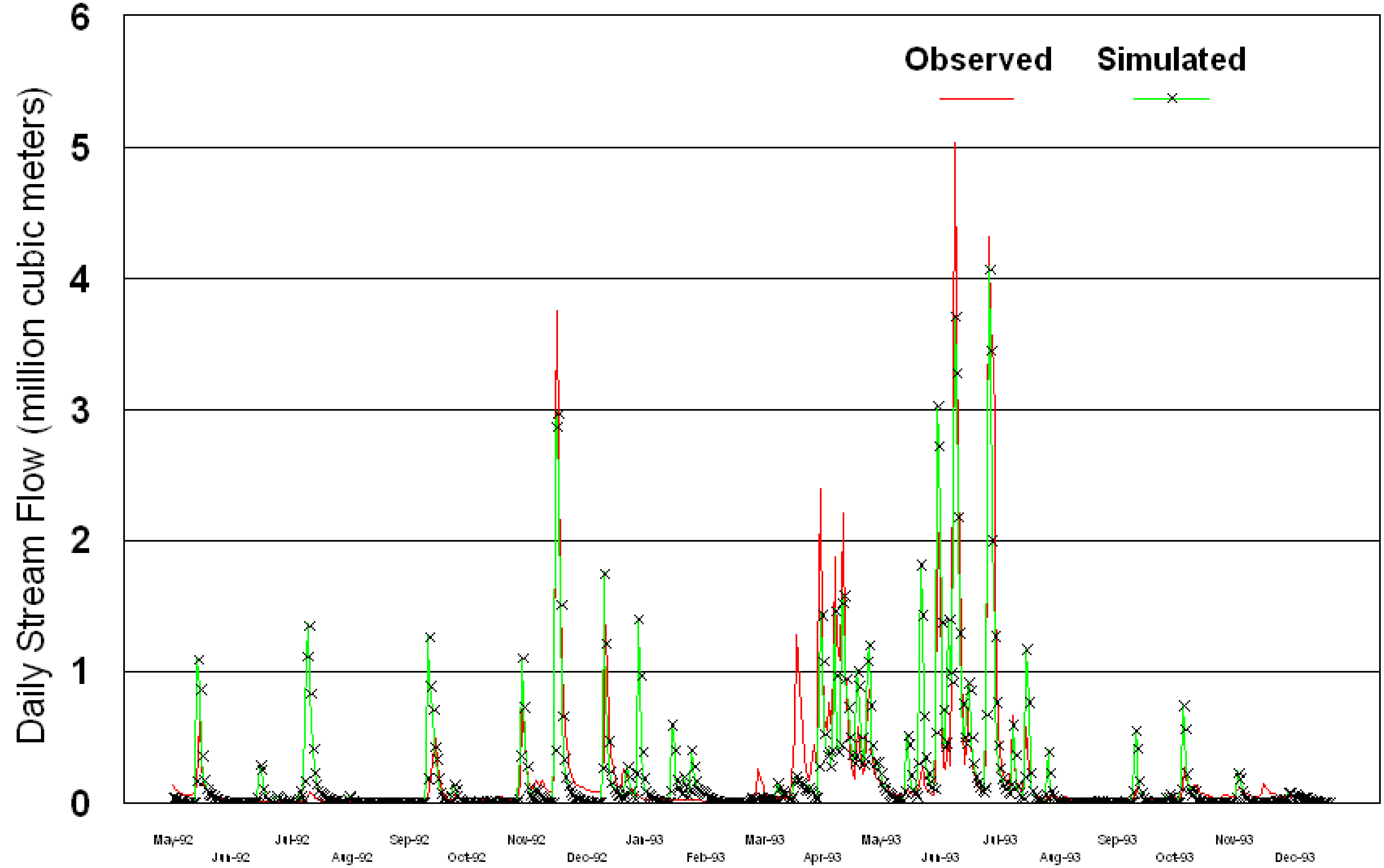

Figure 8c. Observed and Simulated Daily Flow: Duck Creek at CTH FF (276 sq. km).

VI-B. Model Calibration - Suspended Solids

SWRRBWQ (Arnold et al. 1990, 1994), EPIC (Sharpley and Williams 1990), SWAT (Arnold et al. 1996), and APEX (Williams et al. 1995) models all use a form of the Modified Universal Soil Loss Equation (MUSLE) shown below to compute sediment yield for a watershed.

$$\text{MUSLE: } Y = a\,(Q)^b\,(q_p)^c\,(DA)^d\;[(K)\,(C)\,(PE)\,(LS)] \quad \text{(Eq. 8)}$$

where:

Y	=	sediment yield in metric tons/ha (Mg/ha)
Q	=	surface runoff volume in mm
q_p	=	peak flow rate in mm/hr
DA	=	drainage area in hectares
K	=	soil erodibility factor
C	=	crop management factor
LS	=	slope-length and slope-steepness factors
PE	=	erosion control practice factor
a,b,c,d	=	normally set at a = 1.586, b & c = 0.56, d = 0.12, or user-specified values can be used where there is sufficient data for calibration

However, the sediment yield equation in the un-modified version of SWAT does not allow user-specified values for the a, b, c and d parameters. The MUSLE equation in SWAT is also in a slightly different form; whereby, the variables are not in unit area format (e.g., Q is in cubic meters instead of mm and Y is in metric tons instead of tons/ha). To permit calibration of the model to site-specific conditions, equation 1 was therefore inserted into the SWAT code (in ysed.for).

To improve the simulation of TSS loads, the model code was altered so that sediment load was calculated whenever surface runoff occurred. Prior to this change, it was calculated by the model only on days when precipitation occurred. In addition, TSS loads were reduced whenever simulated snow cover was present. This latter modification reduced simulated 1976-96 TSS loads by 13% at the Duck Creek monitoring site on CTH FF, while simulated March TSS loads during this same period dropped by 55%. Both of these changes were described in detail in the section that discussed modifications to the model.

TSS loads from the Upper Bower Creek USGS monitoring station were used to calibrate the model. While a total of 50 events were computed by USGS from 1990 to 1994, only 30 of these events were used for calibration of the sediment equation. This partial data set was selected primarily on the basis of the largest measured events, as well as events which occurred directly after or before the major events (for simplicity). The excluded events had individual TSS loads of less than 50 tons. Information presented later in this section will show that excluding these data points had no meaningful effect on the statistical fit of the calibrated model; in addition, the calibration coefficients were also virtually unaffected (i.e., "a" in MUSLE would change by only 1%).

The Nash-Sutcliffe coefficient of efficiency was used as a criteria to optimize the MUSLE sediment equation (Nash and Sutcliffe 1970). Optimization was performed within a spreadsheet by: (1) importing data from model simulations that are required in the MUSLE equation; (2) calculating the TSS load within the spreadsheet using the MUSLE equation and snow cover sediment reduction equation; and (3) running a built-in spreadsheet optimization routine to find the best MUSLE parameter values. This step was useful because final sediment yields were based on the average of 6 model runs (i.e., 6 different phases of the 6 yr. crop rotation). Thus, a great deal of iteration was avoided. Visual comparison of the simulated and observed values was also utilized to obtain a good fit.

Two calibration data sets for MUSLE variables were selected on the basis of maximizing the Nash-Sutcliffe coefficient of efficiency, and visual comparison of simulated and observed TSS loads:

(1) a = 0.00933, b = 1.7, c = 0 , d = 0.0; and

(2) a = 0.0255; b = 1.3, c = 0.4; d = 0.0.

The first calibration set was selected in case it was decided to not include peak daily flow in the formula (NS = 0.965), and the second set of values (NS = 0.96) was to be used if peak daily flows were to be included in the formula. These values were retained for all later model simulations.

Interestingly, no apparent reduction in the quality of the model simulations was observed when peak flows were not included in the MUSLE sediment equation (i.e., 1st parameter set, where c = 0.0). This finding was not unexpected. In SWAT, peak daily flow is a function of surface water volume, time of concentration and rainfall intensity. Rainfall intensities for individual storm events are generated by the model according to monthly climatological statistics, and an assumed randomly generated exponential distribution; they are not input directly to the model. Therefore, the peak daily flows generated by SWAT for individual precipitation events should not be expected to match up well with the measured values. Hence, it was not surprising to find that the peak flow variable could be eliminated from the sediment load equation without dire consequences.

For this project, the first calibration set was chosen (b = 1.7, c = 0.0) because differences in subwatershed size affect peak flow, which also affects sediment load if peak flow is included in the MUSLE equation. This effect is not necessarily undesirable, for sediment delivery ratios (SDR) should drop with increasing area. However, the peak flow exponent that would be required to correctly reflect the SDR is not easily obtained without extensive TSS loading data from watersheds of varying sizes.

Figures 9a to 9c compare simulated and observed TSS loads for the entire TSS calibration data set of 50 events. These figures all represent the same data, but the scale on the vertical axis is different. The NSCE and R-squared values for the entire data set were both 0.96, so excluding some of the events from calibration had virtually no effect on the statistical fit. The calibrated model did not simulate moderate and small events (less than 250 tons) as well as the larger events. The greatest relative deviations occurred at low levels (Figure 9c).

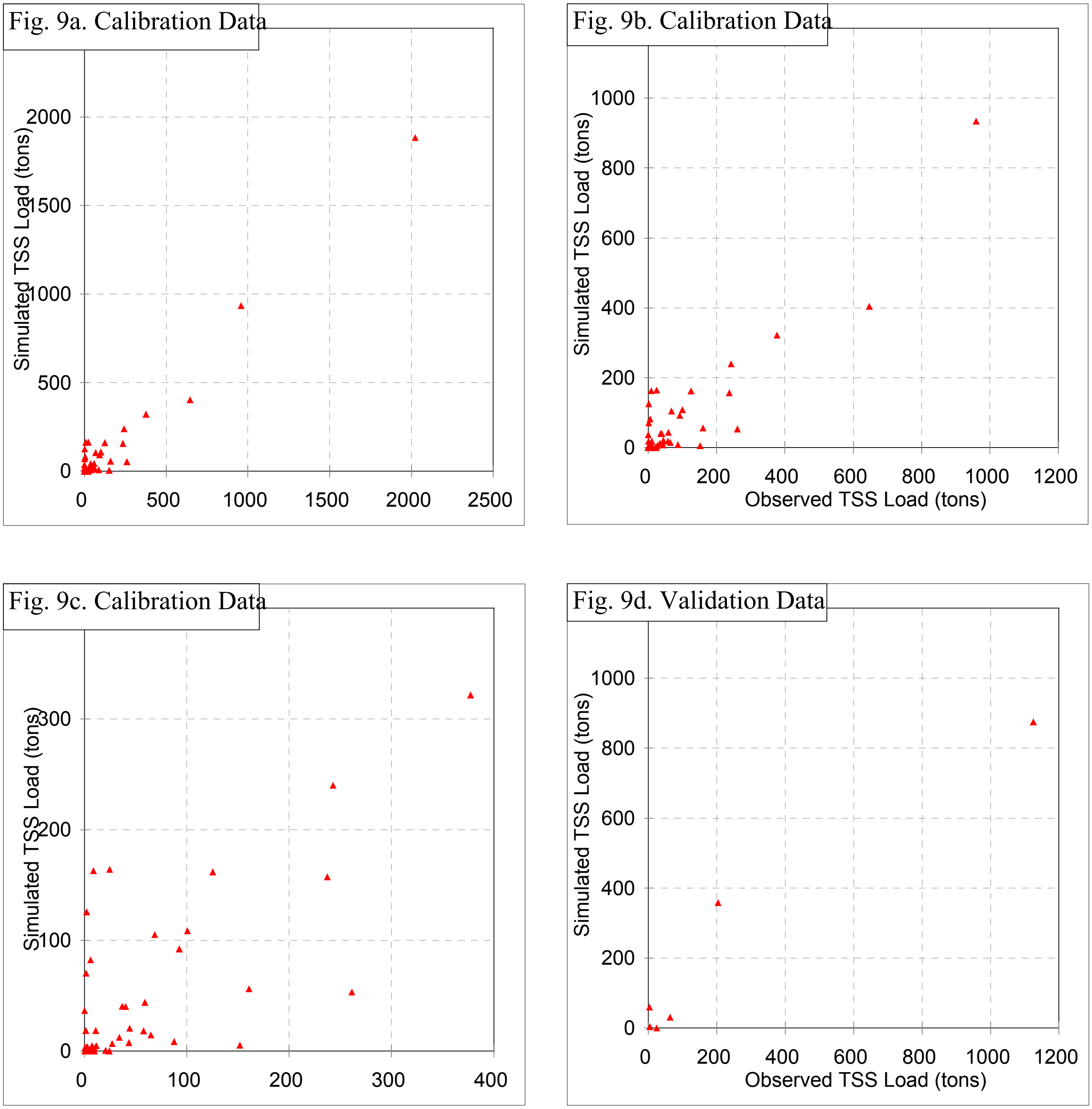

Figure 9. Simulated and Observed TSS Load Events at Upper Bower Creek: Calibration and Validation Data Sets.

VI-C. Model Assessment - Hydrology

All validation and predictive simulations utilized the calibrated SWAT model; that is, no parameters were adjusted to obtain a better fit between simulated and observed values in the model assessment phase.

Duck Creek at County Highway FF: Figures 10a and 10b compare simulated and observed stream flow for Duck Creek at CTH FF during the Jan. 1, 1994 to Dec. 31, 1996 model assessment period. A NSCE of 0.27 and R-squared of 0.57 were determined for this period.[12] Average annual stream flow during the 1994-96 period for simulated and observed runoff was 209 mm/yr and 162 mm/yr respectively.

Simulated stream flow during the 1994-96 period did not track observed flows as well as during the previous calibration period. The average annual stream flow and hydrograph suggest that the model seems to be overstating soil moisture and potential runoff during, or after extended dry periods. This finding was also indicated by the calibration data sets.

Upper Bower Creek, Validation period: Figure 11 compares the simulated and observed daily stream flow at the USGS monitoring station on Upper Bower Creek. Monitoring at this site was interrupted before it resumed April 1, 1996. Average precipitation from the USGS weather stations in the Bower Creek subwatershed is also shown in Figure 11. Total simulated water yield during this period was 171 mm compared to the observed total of 158 mm. Rainfall after the month of June had little affect on either the simulated or observed hydrographs, thereby indicating that soil moisture was being adequately tracked by the model during this period. Figure 11 indicates that there is general agreement between the observed and simulated daily flows over a wide range of precipitation events.

Upper East River Watershed, East River at Midway Rd. (USGS #04085109): Figures 12a and 12b compare the SWAT-simulated daily stream volume and the observed stream flow at USGS Station #04085109, which is located on the Upper East River at Midway Road (122 km^2). This site is located at the outlet of LF01_4, as shown in Figure 1. The simulated hydrograph generally preserved the observed peaks and recessions during the 4/01/93 to 4/04/94 period (Figure 12a). A NSCE of 0.53, and a R squared coefficient of determination of 0.71 were computed for this period by comparing observed flow with simulated flow that was delayed one day. This delay factor was added to account for phase differences between the model and actual events, but it was not used in Figure 12. Total simulated flow for the first period was 402 mm compared to the observed flow of 439 mm. Overall, simulated flow adequately tracked observed flows during the first period.

Although the combined runoff volumes from the first and second simulation periods were identical for both observed and simulated flows (477 mm), the second period (10/01/94 to 9/30/95) was not simulated very well (Figure 12b). Although the peaks and recessions of the simulated flows generally occurred at the same time as the observed events, simulated flows greatly overstated observed flows.

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[12] A NSCE of 0.40 could have been obtained by "tweaking" the running average values used to bring the simulated hydrograph into phase with the observed hydrograph. However, adjusting parameters to provide a better fit during the model assessment phase was not considered a valid approach.

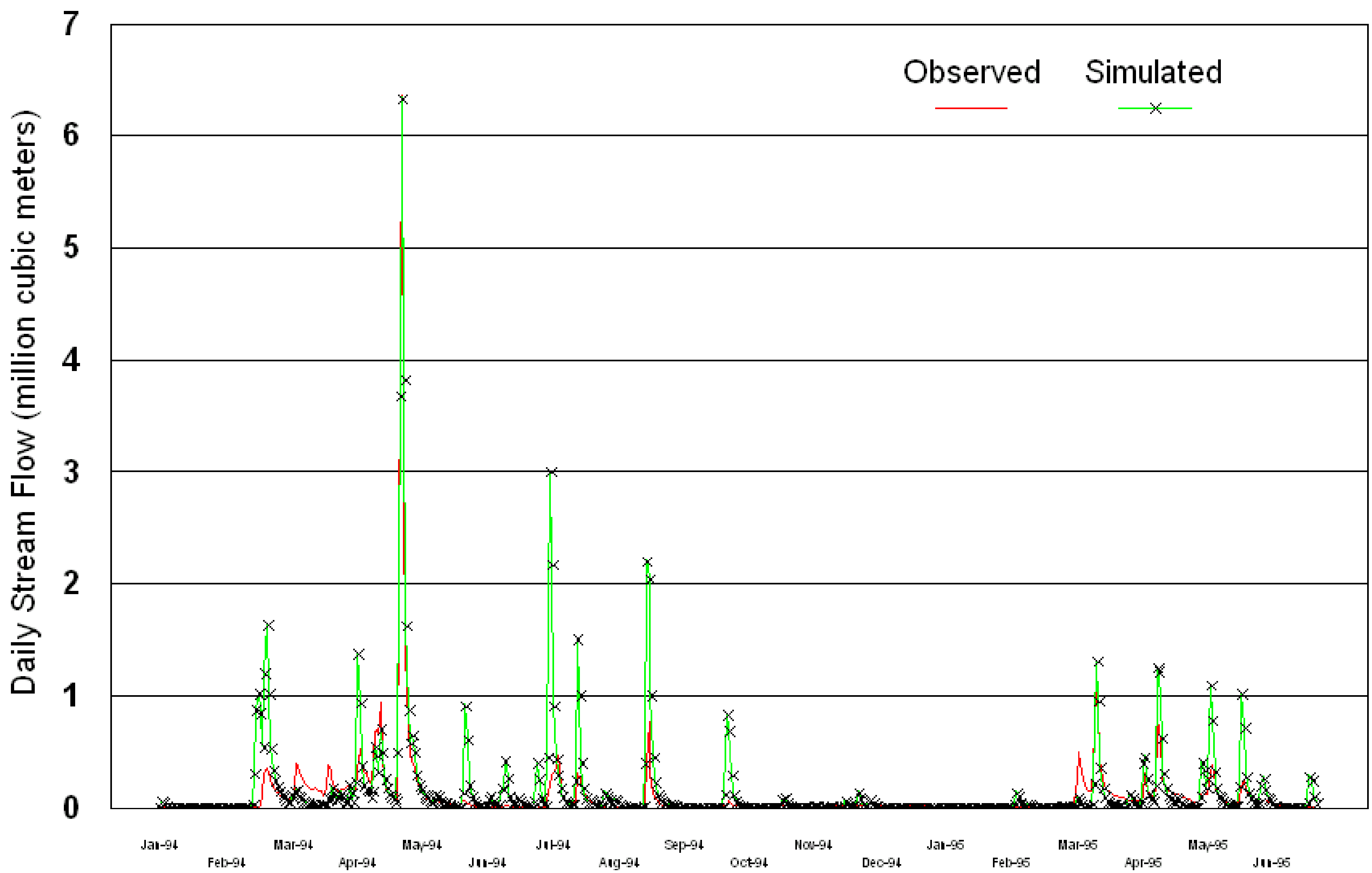

Figure 10a. Observed and Daily Simulated Flow: Duck Creek at CTH FF (276 sq. km).

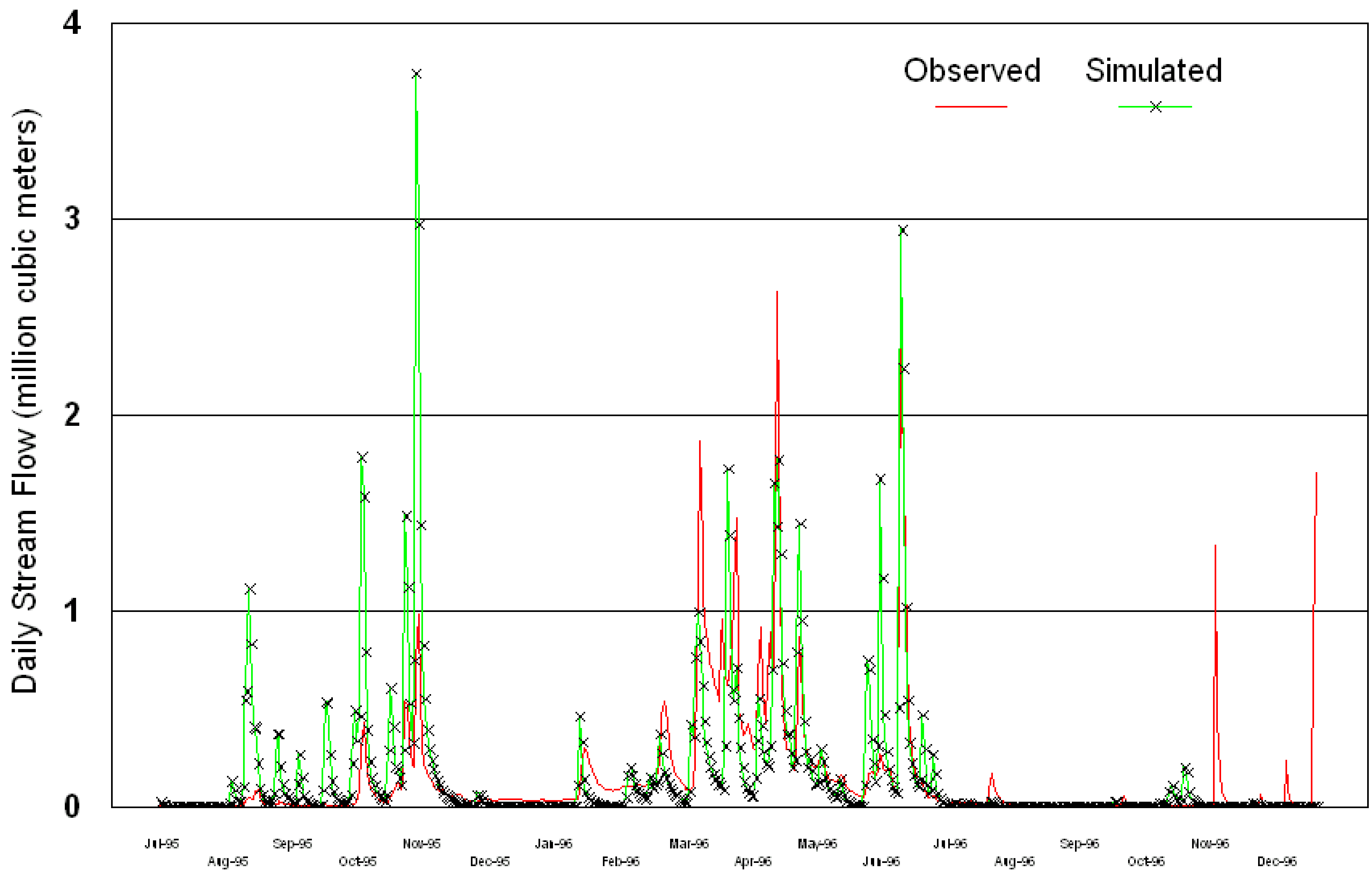

Figure 10b. Observed and Daily Simulated Flow: Duck Creek at CTH FF (276 sq. km).

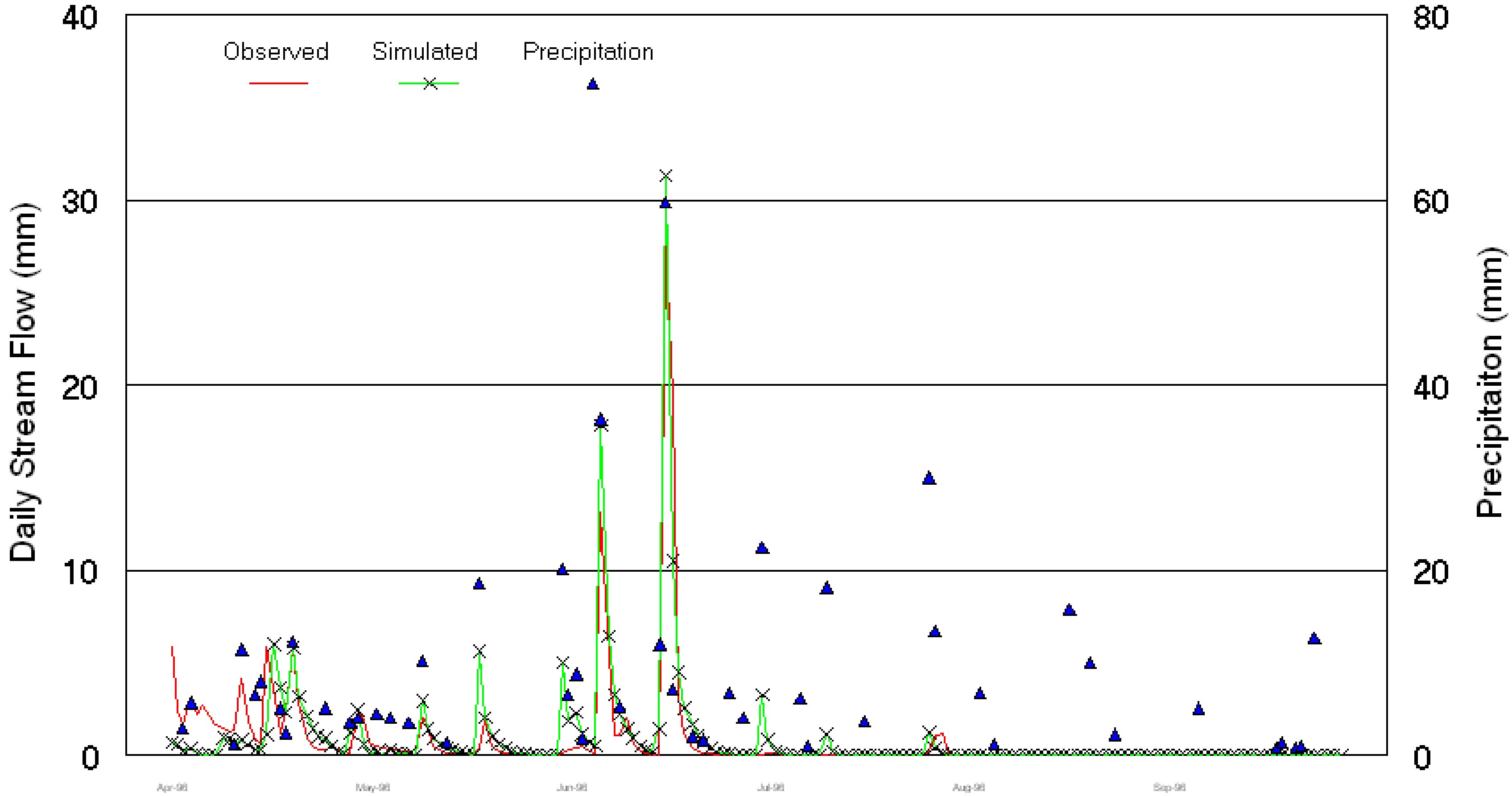

Figure 11. Observed and Simulated Daily Stream Flow - Bower Creek.

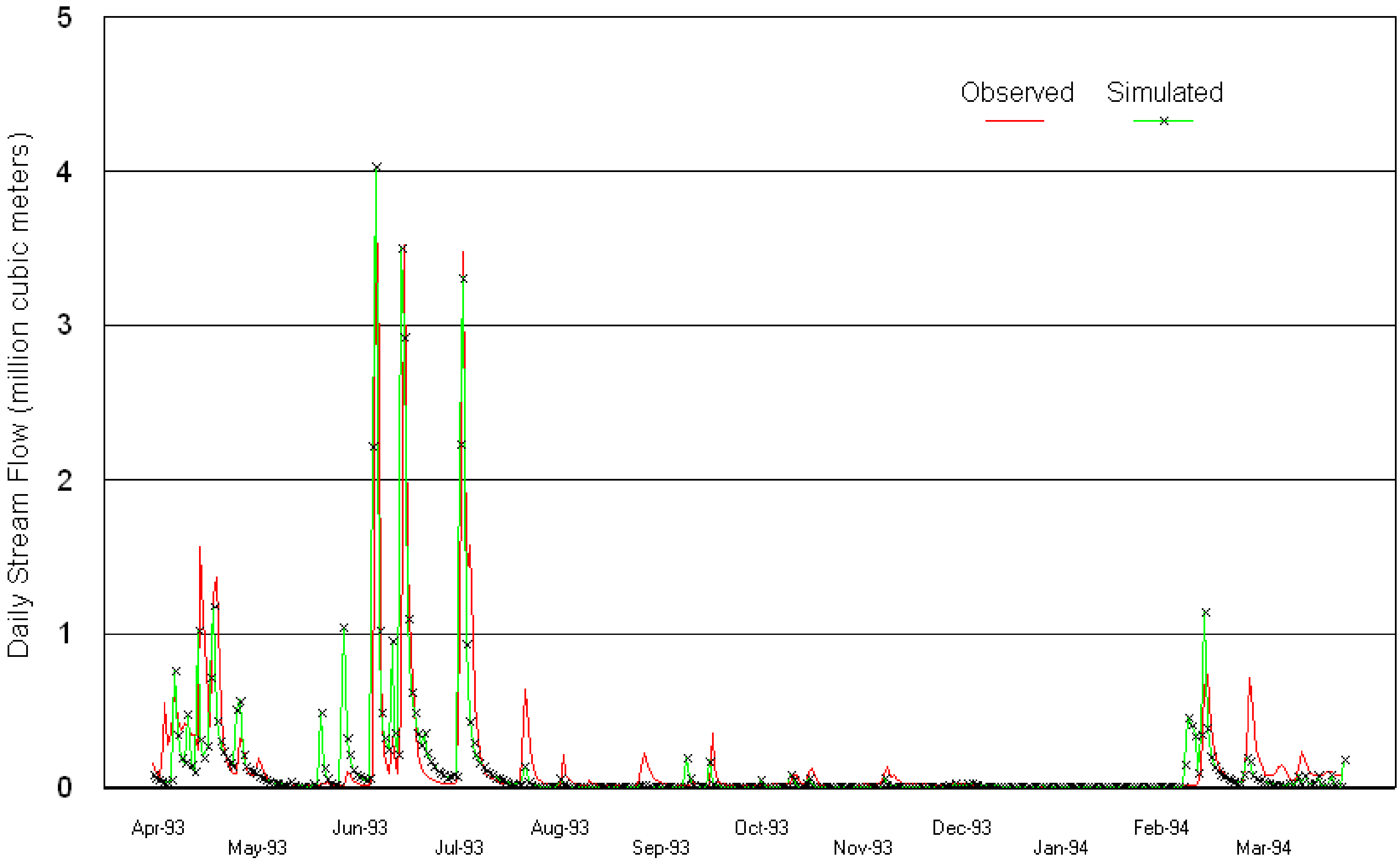

Figure 12a. Observed and Simulated Daily Stream Flow: 1st Period, 4/01/93 to 4/04/94 - East River, Midway Rd. (122 sq. km).
Total Volume for 1st period (402 mm simulated vs 439 mm observed).

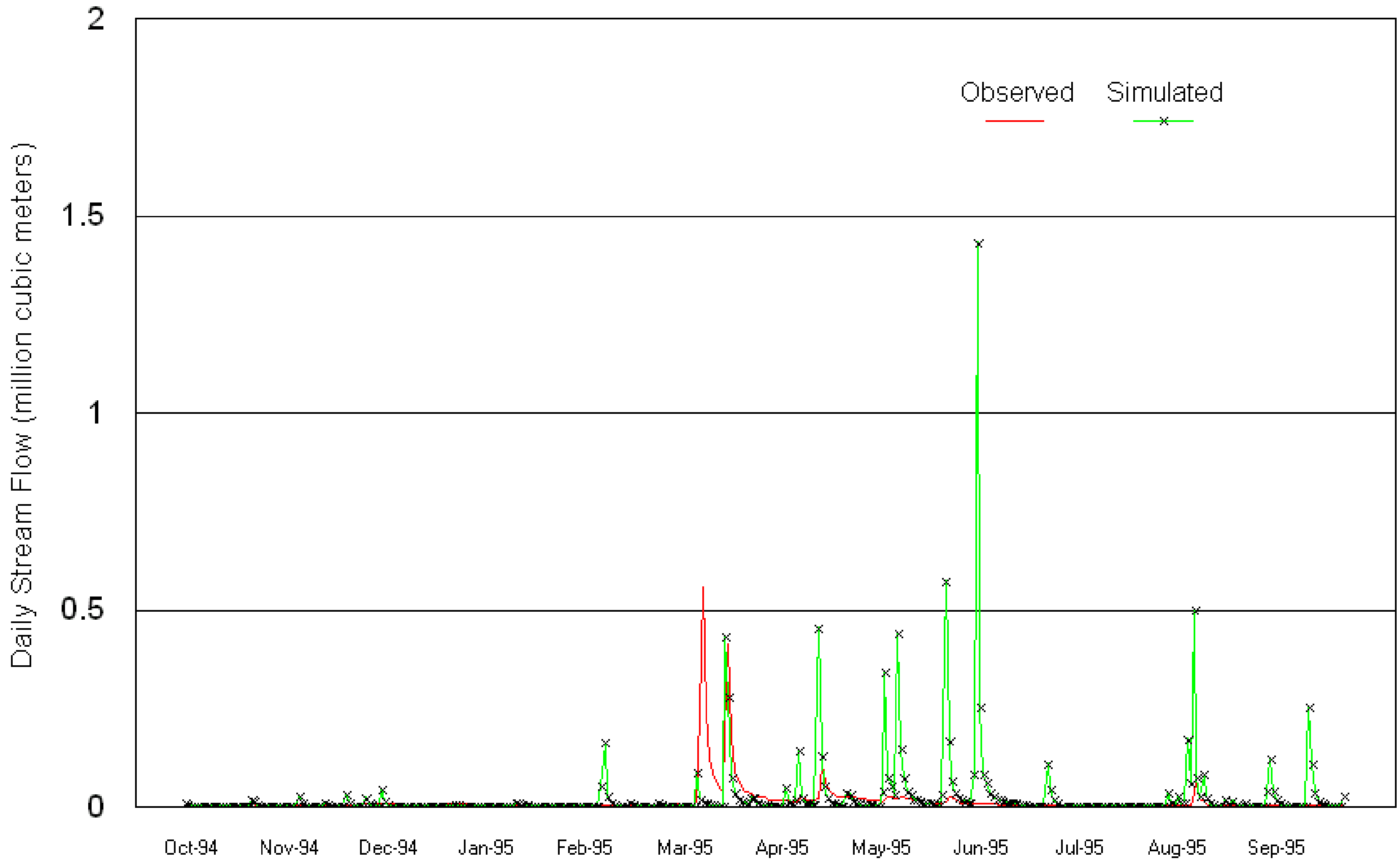

Figure 12b. Observed and Simulated Daily Stream Flow: 2nd Period, 10/01/94 to 9/30/95 - East River, Midway Rd. (122 sq. km).
Total Volume for 2nd Period (75 mm simulated vs 38 mm observed). Average annual runoff is expected to be 200 mm (Gebert et al. 1987).

Hence, there was little correlation between observed and simulated flows: R squared equal 0.04. This seems to indicate that the calibrated model did not perform as well during extremely hot, and fairly dry periods such as occurred in the summer of 1995. Soil moisture seems to be over-estimated during such periods. Further refinement of the model, or the inputs, may improve the ability of the model to track soil moisture during these periods. However, the total observed flow for the second period was only 38 mm over the entire year (USGS Water Resources Data, Wisconsin, Water Year 1995), compared to an average expected value of approximately 200 mm (Gebert et al. 1987). Therefore, this was an unusual period, and TSS loads should be expected to be quite low.

In addition, the model is limited by inputs such as precipitation, which may vary widely, particularly during summer thunderstorm events. While the model indicates a moderately high flow event for June 7, 1995 (Figure 12b), there was only a slight rise in observed stream flow for that day. But the precipitation for that period varied widely: Green Bay reported no rainfall, while Brillion reported 62 mm on 6/07/98, and the Bower Creek stations recorded an average of 12 mm on 6/06/98. With such a wide variation in precipitation over the area, it seems likely that the large storm event that occurred in Brillion missed most of the upper East River watershed. A simulation that substituted Upper Bower Creek precipitation for Brillion precipitation showed a runoff event that was only 1/10th of the amount from the standard simulation which utilized Brillion precipitation for the four subwatersheds that were normally assigned Brillion precipitation.

VI-D. Model Assessment - Total Suspended Solids

All validation and predictive simulations utilized the calibrated SWAT model; that is, no parameters were adjusted to obtain a better fit between simulated and observed values in the model assessment phase. Thus, the following selected parameters for the MUSLE sediment equation were utilized for all simulations: a = 0.00933, b = 1.7, c = 0.0, and d = 1.0.

Bower Creek: Simulated and observed TSS loads at the Bower Creek monitoring station site are compared in Figure 9d (page 39). Only six TSS load events were recorded by USGS during the 1995-96 period. The fit was acceptable, particularly since the largest events occurred in June, which is a transitional period during which crop growth and cover formation rapidly occur. The Nash-Sutcliffe coefficient of efficiency for the data set was 0.93. R-squared, as determined through linear regression analysis was 0.94. The data set was quite limited, so these statistics are presented here only to illustrate that the results appear to be reasonable. These statistical values should not be cited without this cautionary note.

Duck Creek at CTH FF: One moderate-sized event was sampled by University of Wisconsin-Green Bay (UWGB) students and analyzed for TSS (UWGB 1995). TSS concentrations ranged from 81 to 101 mg/L. The flow-weighted mean TSS concentration of the six samples they collected was 88.9 mg/L. Five daily flow volumes from March 20-24, 1995, as reported by USGS in the 1995 Water Resources Data book, were roughly estimated to constitute the total runoff for the storm event. Multiplying the total estimated runoff by the flow-weighted mean TSS concentration of 88.9 mg/L gave a total estimated TSS event load of 276 tons. The SWAT-simulated load estimate for this event was 722 tons. The simulated load estimate was off by a factor of over 2.5.

Another moderate event which was monitored occurred between March 19 and March 30, 1991. A rough estimate of TSS load was calculated based on 4 daily samples collected March 23-26 by USGS, and analyzed for TSS. TSS concentrations varied between 32 and 39 during this period. The estimated TSS load was 520 tons compared to the simulated load of 470 tons; however, simulated total stream flow during this same period was 28% lower than the observed total stream flow (15.2 vs 10.9 million cubic meters). Currently, there is insufficient site-specific data to speculate further about the ability of the model to estimate TSS loads at this site.

East River at Midway Road: A limited number of events were sampled by the USGS between 1993 and 1995, and TSS loads were not computed by the USGS. However, for two large events, USGS daily flow volumes and limited TSS concentrations were used to estimate TSS loads of 5,900 tons for June 9-11, 1993, and 4,600 tons for July 6-10, 1993. Simulated loads for these events were 6,600 tons and 2,600 tons, respectively.

East River at Monroe Street (USGS #04851378): The USGS operated a monitoring station from March 1985 to October 1986 at essentially the outlet of the East River (367 km^2), where it crosses Monroe Street in Green Bay. Daily TSS loads, as determined by the USGS (Hughes 1993), were compared to simulated values. However, the seiche effect at this site is appreciable (Quinlan 1986, Hughes 1993), and prevented greater use of this data set. Data summarized in Table 3 were judged sufficiently unaffected to be compared to simulated values. Snow melt or mixed rain and snow events such as occurred March 10-16, 1985 were not considered in this comparison. Data from March 1 to April 10, 1986 were also not included because reported flows were only estimated by USGS from the daily discharge record of the Kewaunee River since the acoustic velocity meter was not operating during this period (Hughes 1993). Events with flow reversals which caused a net negative daily flow or load during any day during the event were not considered in this comparison. Event dates reported in Table 3 are for the measured daily loads; whereas, the simulated dates may be slightly different due to phase differences between the model results and measured results.

The Nash-Sutcliffe coefficient of efficiency for the data in Table 3 was -0.72, while R-squared values of 0.97 (un-transformed) and 0.68 (log-transformed) were determined with linear regression analysis. Overall, the simulated TSS loads did not closely match the observed loads; however, in light of the seiche-induced complexity of the system, the simulated values were within a reasonable range of the observed loads. Both a comparison of the simulated and observed values shown in Table 3, and the linear regression slope of 2.1 (un-transformed), suggests a tendency for the model to overstate TSS loads at this site during moderately large events which occurred in Fall.

It is important to note that the NSCE statistical measure is particularly sensitive to the errors that occur with the highest values in a data set. A preliminary model simulation for the East River Midway site contained a mistake which incidently produced results with a better statistical fit than the final results. The NSCE was 0.5 for this preliminary simulation compared to -0.17 for the final results presented here. Simply replacing the simulated value associated with the largest event (11,334 tons), with a value from the preliminary model simulation (8,429 tons), increased the NSCE to 0.45.

An example of the temporal sensitivity of the model is illustrated by the dramatic change that results when the date for plowing under the alfalfa in the fourth alfalfa year (i.e., last alfalfa crop) was temporarily changed from Oct. 1 to Oct. 5. The TSS load for the Oct. 4-6, 1985 event drops from 1,729 tons (Table 3) to 766 tons, which is much closer to the observed value.

An example of the sensitivity of the model to the spatial variability of precipitation occurred on May 10, 1985 (not shown in Table 3). Green Bay reported 24 mm of rainfall on this date; whereas, Brillion reported no precipitation on this date, and only 1.3 mm for the following day. The simulated TSS load was 1,084 metric tons for this event, based mostly on the 14 subwatersheds which were assigned Green Bay precipitation data. However, the measured daily TSS loads for that period were minor; thereby, suggesting that most of the East River did not have anywhere near the amount of precipitation that occurred in Green Bay. Temporarily substituting Brillion precipitation in place of the Green Bay data set produced simulated results which parallel the observed values for this period.

Table 3. Major simulated and observed TSS load events at East River, Monroe Street monitoring station (USGS Station #040851378): 1985-1986.

Event Period	TSS Load (metric tons)	
	observed	simulated
4/11/85-4/15/85	798	498
6/22/85 - 6/24/85	231	796
9/05/85 - 9/08/85	192	70
9/21/85 - 9/25/85	330	153
10/04/85 - 10/06/85	724	1,729
10/12/85 - 10/14/85	155	264
11/01/85 -11/05/85	5,388	11,334
11/16/85 -11/21/85[13]	1,031	1,857
7/17/86 - 7/19/86	73	175
7/25/86 - 7/28/86	117	370
8/17/86 - 8/18/86	98	24
9/10/86 - 9/13/86	584	1,283
9/21/86 - 9/30/86	977	606

[13] Prior to this event (11/13-15/1985), the observed TSS load was approximately 409 tons, compared to a simulated value of only 18 tons. The measured TSS load during this period may have been caused in part, by snow melt from a 11/09/95 snowfall of about 7.6 inches as recorded at the Green Bay NWS station, and also from rainfall of 16 mm on the 11/14/1985 at Brillion.

VII. Model Results

Table 4 summarizes simulated average annual TSS loads and flow volumes from major streams in the Lower Fox River. Point source loads are not included in these estimates, but they are assumed to be relatively small compared to sources that discharge directly to the Lower Fox. Simulated 1977-96 unit-area TSS load estimates for Duck Creek (0.26 tons/ha) and East River (0.46 tons/ha) are somewhat greater than the median value of 0.11 tons/ha (32.4 English tons/mi^2) that was estimated by Corsi et al. (1997) for rural areas of the Southeastern Wisconsin Till Plains Ecoregion.

The SWAT-modeled average annual TSS load from Duck, Apple, Ashwaubenon and Dutchman Creeks combined, was 17,700 tons, or 0.26 tons/ha (1977-96). This figure is much lower than the sediment load that was estimated for the Duck, Apple and Ashwaubenon Creeks Priority Watershed Project where the total sediment load "delivered to streams" from all sources in this watershed was 100,700 tons, or 1.46 tons/ha per year (WDNR 1997; 110,016 English tons/year in Table 3-11). The latter estimate was based in part, on WINHUSLE (Baun 1994) modeling results for upland rural loads and SLAMM modeling for urban sources. However, it is uncertain whether these estimated loads were were routed to the outlets of the watersheds.

The 1977-96 simulated average annual TSS load from all of the watersheds in the Basin was 55,000 tons (0.36 tons/ha), while the average annual stream flow was 239 mm. These figures include the Duck Creek watershed, but exclude other areas that were estimated to drain directly to Green Bay or Lake Winnebago. Point source contributions are also excluded.

The simulated loads shown in Table 4 show obvious differences in TSS yields between watersheds. However, collaborative information from actual observations which could substantiate these apparent differences may not exist. Therefore, caution should be used when interpreting these results, for the relative differences in the TSS loads shown in Table 4 may not be statistically significant.

Model segment output: Daily TSS loads and discharges were also determined by water column modeling segment, so they could be used in the PCB Fate and Transport Model. The two water column numbering sequences used for PCB transport modeling between the Lake Winnebago outlets and the DePere Dam, and between the DePere Dam and Green Bay, were utilized for this project. Where a single outlet for a subwatershed was not apparent, runoff and TSS loads were assigned to the appropriate water column segments on an area-weighted basis. Data were assigned to a total of 52 water column segments. Some water segments were allocated the same loads/flows as nearby segments. The data are provided in a spreadsheet format for five time periods: (1) 1954-56; (2) 1957-76; (3) 1977-96; (4) 1996-2016; and (5) 2017-2020.

Table 4. Simulated historical average annual stream flow and TSS loads from major streams in the Lower Fox River Basin (nonpoint TSS loads only).

Watershed	area (km^2)	Simulated Average Annual Stream Flow in million cubic meters (annual ave. in mm)		Simulated Average Annual TSS Load in metric tons (annual average metric tons/ha)	
		1956-76	1977-96	1956-76	1977-96
LF01 East River	367.8	66.0 (179)	81.1 (220)	13,000 (0.36 t/ha)	17,000 (0.46 t/ha)
LF05 Duck Creek	392.7	68.5 (174)	80.9 (206)	8,600 (0.22 t/ha)	10,000 (0.26 t/ha)
LF02 Apple Creek	139.9	36.9 (264)	37.7 (270)	4,200 (0.30 t/ha)	4,600 (0.33 t/ha)
Ashwaubenon Cr.	76.0	15.6 (205)	19.2 (252)	1,100 (0.15 t/ha)	1,300 (0.18 t/ha)
Dutchman Cr.	77.6	14.3 (184)	17.7 (229)	1,500 (0.19 t/ha)	1,700 (0.22 t/ha)
LF03 Plum Cr.	93.0	21.5 (231)	24.5 (264)	3,800 (0.41 t/ha)	4,600 (0.50 t/ha)
Kankapot Cr.	66.8	17.5 (262)	17.9 (268)	2,500 (0.37 t/ha)	2,500 (0.38 t/ha)
Garner Cr.	28.6	7.9 (277)	8.1 (283)	1,800 (0.64 t/ha)	1,900 (0.67 t/ha)
Mud Creek	67.0	18.7 (279)	19.2 (287)	2,100 (0.32)	1,900 (0.29 t/ha)
Neenah Slough	59.2	16.6 (281)	17.1 (289)	1,800 (0.30)	1,700 (0.28 t/ha)
Entire Basin, with Duck	1545[14]	329 (213)	369 (239)	50,000 (0.32)	55,000 (0.36 t/ha)

[14] Area is reduced from 1581 km^2 total Basin area due to areas that contribute directly to Green Bay or Lake Winnebago, and water area over the Fox River.

VIII. Summary

Simulated annual nonpoint TSS loads and stream flow to the Lower Fox River from 1954 to 1996 are illustrated in Figure 13. During this period, the simulated average annual TSS load to the Lower Fox River from watersheds within the Basin was 43,000 tons (0.37tons/ha).[15] The simulated average annual flow was 8.5 m^3/sec-day (300 cubic feet/sec-day, or cfs-day), which is equivalent to 234 mm on an areal basis. These figures do not include Duck Creek's contribution to Green Bay, nor flow above the Lake Winnebago outlet (total contributing watershed area is approximately 1,150 $km^{2)}$. On an annual basis, the minimum simulated TSS load was 15,000 tons in 1964, and the maximum TSS load was 100,000 tons in 1990; the standard deviation was 20,500 tons. On an annual basis, a minimum flow of 2.6 m^3/sec-day (91 cfs-day) was simulated to occur in 1977, and the maximum flow of 15.5 m^3/sec-day (550 cfs-day) was simulated to occur in 1984; the standard deviation was 3.1 m^3/sec (110 cfs-day). With some notable exceptions such as 1990, simulated TSS loads tend to follow trends in stream flow. The regulation of Fox River flow above the DePere dam is not considered in these estimates, nor are contributions from point sources.

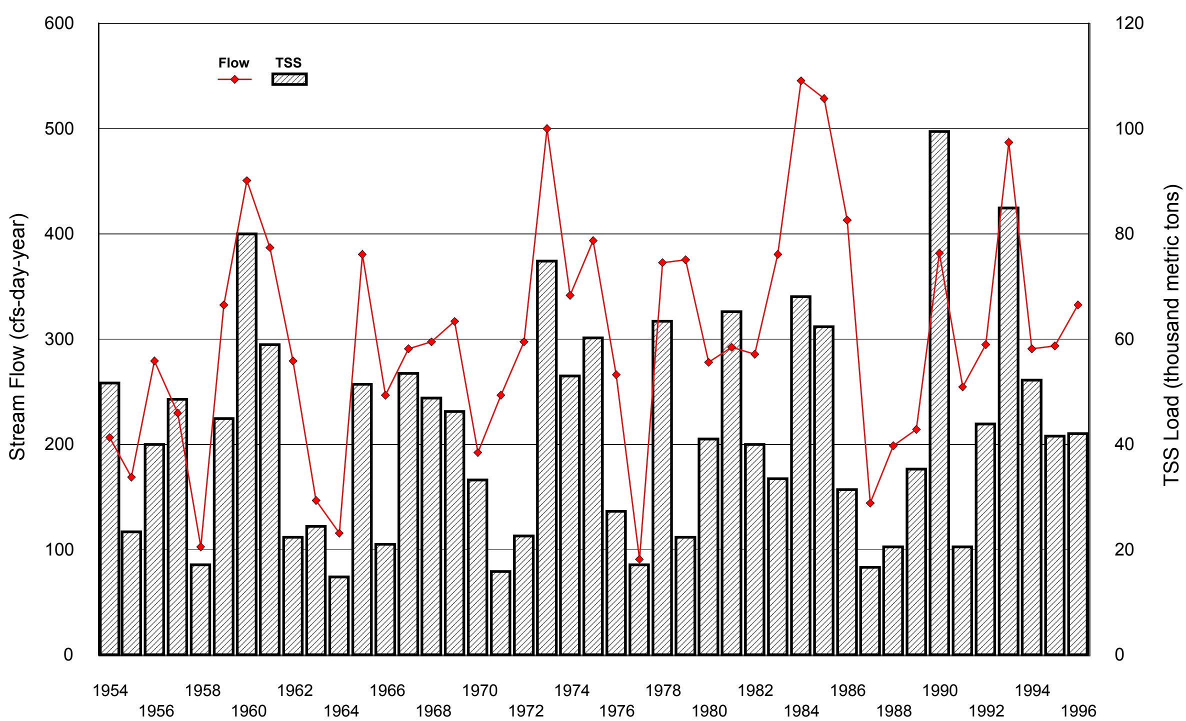

Figure 13. Simulated Annual Nonpoint TSS Loads and Stream Flow to Lower Fox River: 1954-96. Contributions Upstream of Lake Winnibago outlet are not Included.

[15] Basin totals do not include loads or flow that were estimated to drain directly to Green Bay or Lake Winnebago. Hence, the Basin area considered in this total is 1150 km^2 (Fox River water area also not included).

From 1954 to 1996, the simulated average annual TSS load to Green Bay from Duck Creek was 9,300 tons (0.24 tons/ha). The simulated average annual flow was 2.3 m3/sec-day (81 cfs-day), which is equivalent to 188 mm on an areal basis. For the same period, the simulated average annual TSS load to the Lower Fox River from watersheds between the DePere Dam and Green Bay was 23,000 tons (0.30 tons/ha). Point sources are not included in these estimates.

The maximum simulated daily flow to the Lower Fox River from watersheds in the Basin was 880 m^3/sec-day (31,000 cfs-day), and the maximum TSS load was 42,000 tons (0.36 tons/ha). Duck Creek and upstream sources are not included in these two estimates. Considering only contributions between the DePere Dam and Green Bay, the maximum simulated daily flow to the Lower Fox River was 490 m^3/sec-day (17,400 cfs-day), and the maximum TSS load was 25,000 tons (0.28 tons/ha). For Duck Creek, the maximum simulated daily flow was 210 m^3/sec-day (7,500 cfs-day), and the maximum TSS load was 8,300 tons (0.21 tons/ha). All of these maximum daily events were modeled as occurring on June 23, 1990. Note that the maximum daily TSS loads are approximately equal to the average annual loads. Again, point sources are not included in these estimates.

Overall, the modified and calibrated SWAT model performed reasonably well during the calibration and validation periods that were evaluated in this project. With some exceptions, the simulated daily hydrographs preserved the peaks and recessions of the observed hydrographs, and the total water yields were also in agreement. In general,observed TSS loads were reasonably represented by the model. The calibrated model seemed least able to estimate flows during extended dry and/or hot periods; thereby, suggesting that data inputs or the model itself might require some changes to improve the ability of the model to track soil moisture. However, these changes would not likely cause major changes in the estimated flows or TSS loads because such changes would more likely affect smaller precipitation events, which do not contribute a major portion of the TSS load. This latter point is reflected by the calibrated sediment equation (eq. 8), for which the TSS load was found to be a function of the daily simulated flow volume raised to the 1.7th power. To further assess the ability of the model to estimate TSS loads on a watershed basis, it is recommended that additional monitoring be conducted near watershed outlets within the Basin during high loading events.

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