Lake Champlain Basin SWAT Model Configuration, Calibration and Validation

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Introduction

According to the requirements of the Federal Clean Water Act, Total Maximum Daily Loads (TMDLs) are required for lakes and rivers not meeting water quality goals. A TMDL may be defined as the amount of pollutant load that a waterbody can receive without impairing vital uses such as supporting aquatic life and drinking water supplies. Phosphorus is the pollutant of concern for Lake Champlain. To reduce phosphorus loading to the lake, a TMDL was prepared for Lake Champlain in 2002. The U.S. Environmental Protection Agency (EPA) disapproved the Vermont portion of the TMDL in 2011 because of inadequate assurance that phosphorus reductions would occur and an inadequate margin of safety to account for uncertainty. EPA subsequently initiated steps to revise the original TMDL, including updating the original BATHTUB lake response model that had been used to develop the 2002 TMDL and conducting further analyses to estimate potential load reductions in Lake Champlain's tributary watersheds in Vermont and New York. The loading information will be used to support developing load and wasteload allocations for the revised Vermont TMDL, to help guide implementation of the existing New York TMDL, and to inform the development of loading capacities for the lake. Although only the Vermont portion of the TMDL is being revised, the lake and watershed modeling work encompasses the whole watershed because watershed processes do not follow jurisdictional boundaries.

A public-domain model, the Soil and Water Assessment Tool (SWAT), jointly developed by the U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS) and Texas A&M, AgriLife Research, was used to develop phosphorus loading estimates for sources in the Lake Champlain Basin. SWAT model development for the Lake Champlain Basin began in 2012 and an initial calibration was finalized and documented in November 2013 (Tetra Tech 2013). The calibrated SWAT model was subsequently subjected to a formal quality assurance (QA) review by Dr. Jon Butcher, Watershed Modeling QC Officer for the project (Tetra Tech 2014). This document describes the model setup and parameterization and presents calibration results. It reflects all changes made as a result of the formal QA review. .

The SWAT model described herein is one of three model and/or analysis tools being applied in the revision of the Lake Champlain TMDL. Each model/tool serves a unique purpose in the TMDL redevelopment process. The BATHTUB model of Lake Champlain is being used to determine whether a specified allocation scenario meets water quality criteria. In addition, SWAT models of the 13 drainage areas contributing flows and phosphorus loads to Lake Champlain are being used to estimate baseline total phosphorus loads from each source sector in each watershed. Finally, a Scenario Evaluation Tool is being used in conjunction with BMP efficiencies to evaluate whether various load reduction scenarios have reasonable potential to meet TMDL loading targets for Lake Champlain. Reduced loading scenarios from the Scenario Tool are then depicted in the BATHTUB model to test whether a given scenario can meet water quality criteria.

In this context, specific applications of the SWAT model in the TMDL revision are as follows:

- Quantify annual phosphorus loads from existing known land-use based and watershed process sources
- Support the Scenario Tool estimates of phosphorus load reductions possible from certain BMPs, relative to the base loads by supplying loading rates
- Estimate phosphorus loads from unmonitored drainage areas for input to the lake model.

SWAT is a basin-scale, continuous model that operates on a daily time step. It is designed to predict the impact of management on water, sediment and agricultural chemical yields in watersheds and is capable of predicting water quantity, water quality and sediment yields from large, complex watersheds with variable land uses, elevations and soils. The model is physically based, computationally efficient and capable of continuous simulation over long periods.

In SWAT a watershed is divided into subbasins, which are then further subdivided into hydrologic response units (HRUs) on the basis of unique combinations of land use, soil and slope class. Climatic data can be input from measured records or generated using the weather generator (or any combination of the two). Hydrology and water quality computations are performed at the level of each HRU. They are summed to the subbasin level and routed through channels, ponds, wetlands or lakes to the watershed outlet. Hydrology in SWAT is based on water balance. Overland flow runoff volume is computed using the Natural Resources Conservation Service (NRCS) curve number method. Curve numbers are a function of hydrologic soil group, vegetation, land use, cultivation practice and antecedent moisture conditions. SWAT accounts for sediment contributions from overland runoff through the Modified Universal Soil Loss Equation, which provides increased accuracy, compared to the original Universal Soil Loss Equation (USLE) method, when predicting sediment transport and yield. In-stream kinetics and transformations of nutrients, algae, carbonaceous biological oxygen demand (CBOD) and dissolved oxygen (DO) are adapted from the Enhanced Stream Water Quality Model QUAL2E, which is a steady-state model for conventional pollutants in branching streams and well-mixed lakes (Neitsch et al. 2011).

SWAT can simulate 1- to 100-year periods and links pollutant contributions to specific source areas (e.g., subbasins or land use areas). That feature is important in terms of TMDL development and allocation analysis. Details on the SWAT model and its modules are provided in *Soil and Water Assessment Tool Theoretical Documentation* (Neitsch et al. 2011).

Because phosphorus is closely associated with runoff and sediment, reliable estimation of phosphorus loading requires accurate representation of the watershed hydrology and sediment processes. SWAT version 2009 (rev. 582), with enhancement to the sediment routing algorithms, was used to develop watershed models[1] for the Lake Champlain Basin. These changes were based on modifications to the SWAT version 2009 code by Stone Environmental, Inc., for the development of the Missisquoi Critical Source Area (CSA) SWAT model (Stone Environmental 2011).

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[1] Eight separate SWAT models were developed, comprising the entire Lake Champlain Basin.

Watershed Background and Model Setup

Waterbody and Basin Overview

Lake Champlain, one of the largest lakes in North America, is shared by Vermont, New York, and the province of Quebec. Lake Champlain flows from Whitehall, New York, north to its outlet at the Richelieu River in Quebec. The lake is 120 miles long. It has a surface area of 435 square miles and a maximum depth of 400 feet. The 8,263-square-mile watershed drains nearly half the land area of Vermont and portions of northeastern New York and southern Quebec (Table 1 and Figure 1).

Table 1. Distribution of watershed area amongst Vermont, New York and the province of Quebec

State/Province	Area (sq. mi.)	Percent (%)
Vermont	4,637.5	56.1
New York	3,043.7	36.8
Quebec	581.5	7.1
Total	**8,262.5**	**100.0**

The annual average precipitation in the basin varies from approximately 30 inches near the lake and in the valleys to more than 50 inches the mountains. The population of the basin is about 571,000, and approximately 35 percent of the population depends on the lake for drinking water.

The Lake Champlain Basin is composed of eight 8-digit Hydrologic Unit Code (HUC8) watersheds. Tetra Tech developed a discrete SWAT model developed for each of these HUC8 watersheds. The watershed models were calibrated and validated for daily hydrology, as well as monthly sediment and phosphorus loadings. The following sections discuss the datasets used for the development of the SWAT models, the model setup process, and the calibration and validation process for hydrology and pollutant loads.

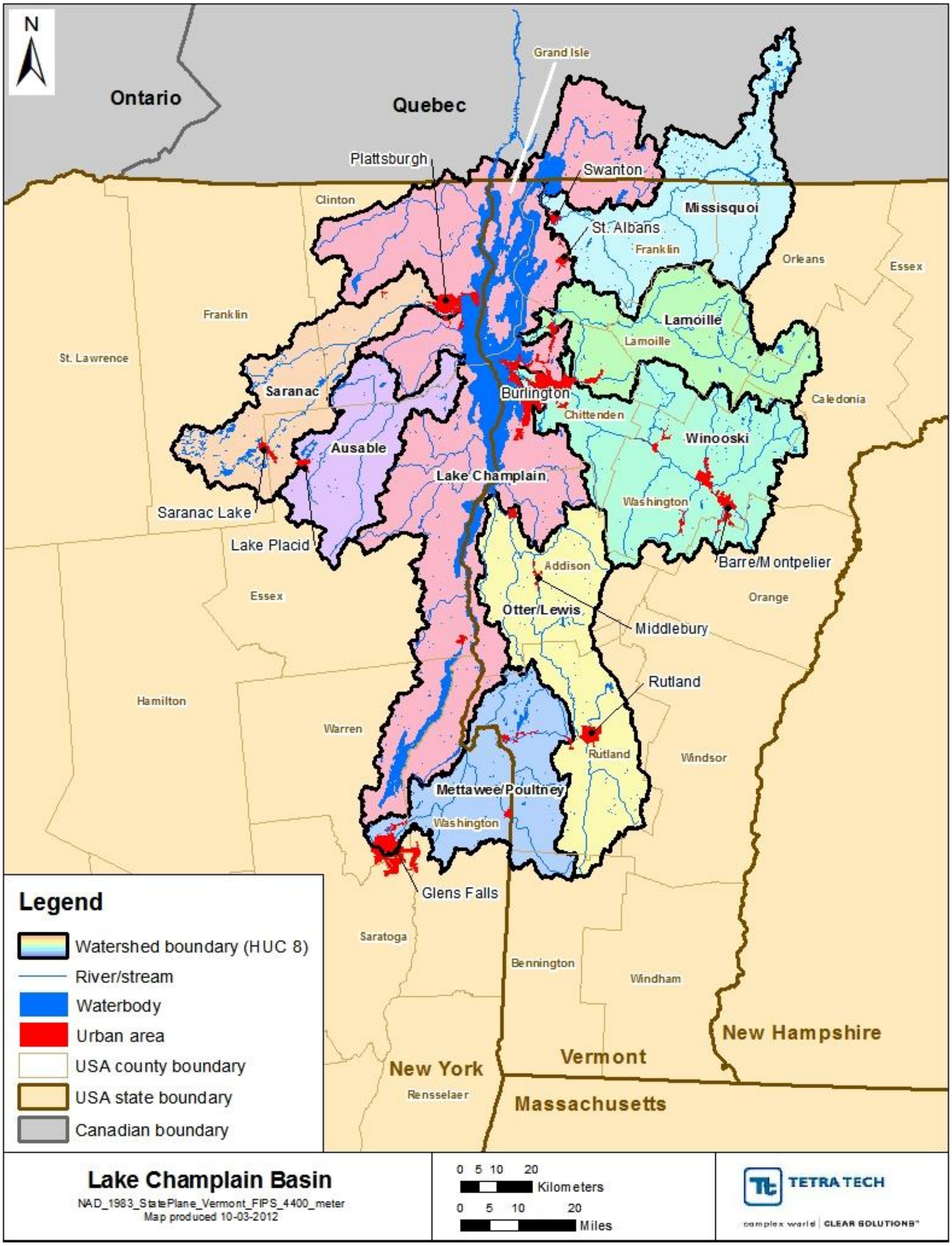

Figure 1. Location of the Lake Champlain Basin.

Elevation and Slope

Tetra Tech used a 10-meter digital elevation model (DEM) in developing the SWAT models for the Lake Champlain Basin (Figure 2). The elevation of the watershed ranges from -2 meters (a point in the bottom of the lake) to 1,626 meters in the mountains, with an average elevation of 305 meters. The datum for elevation is the North American Vertical Datum of 1988. For areas outside the continental USA, the National Geodetic Vertical Datum of 1929 and local reference datum are used. The slope of the watershed also varies highly with steeper slopes in the mountains and relatively flatter slopes near the lake.

Elevation and slope play significant roles in watershed hydrology and pollutant transport. Orographic precipitation and temperature lapse due to changes in elevation have significant impacts on total flow volume and snowmelt hydrology. Tetra Tech simulated orographic precipitation effects and temperature lapses using the precipitation and temperature lapse rates in the *.sub* files in the SWAT models during the calibration and validation processes.

The slope of the land affects the volume and timing of runoff and hence pollutant transport. The average slope of each individual HRU is calculated by the ArcSWAT interface during the SWAT model setup process.

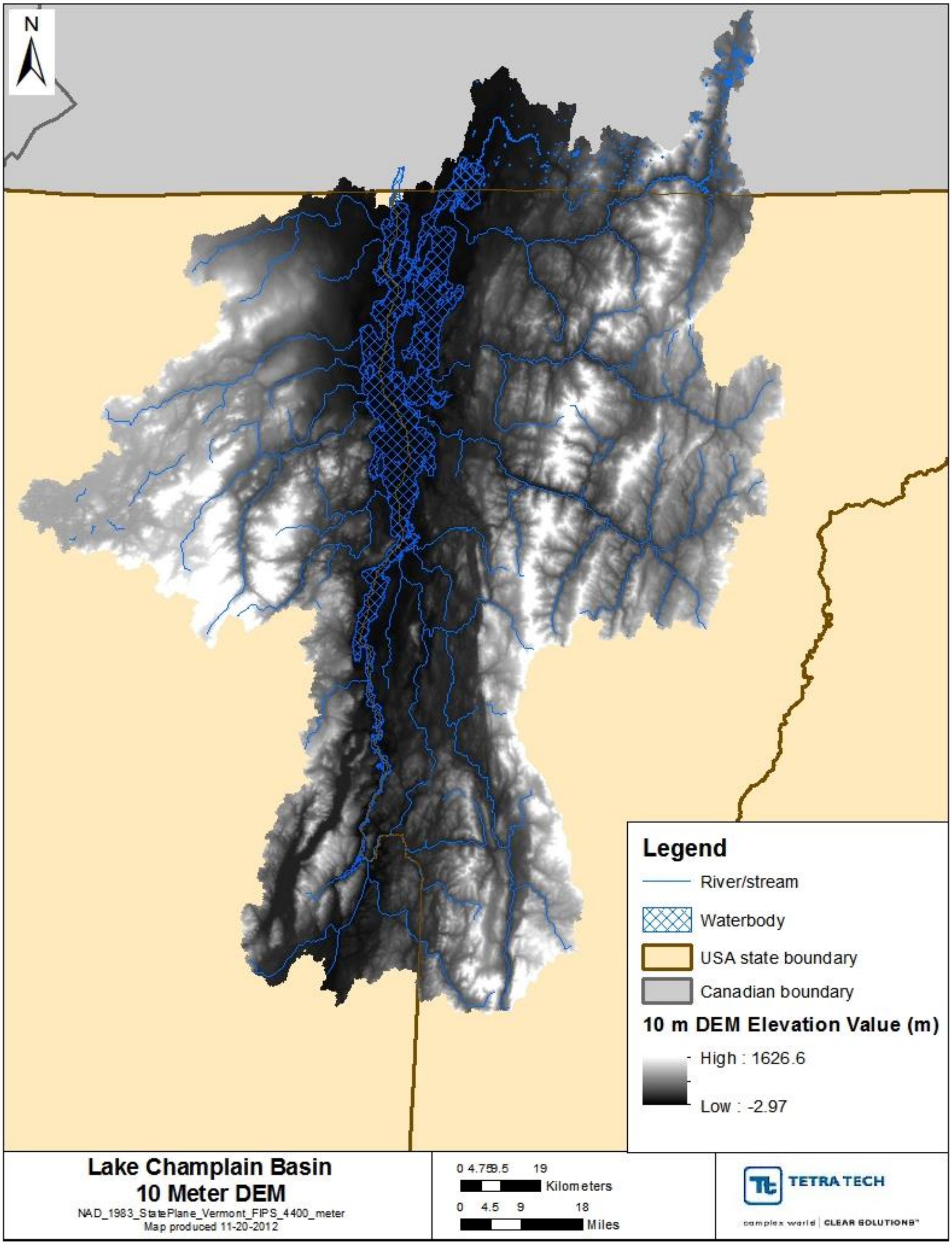

Figure 2. Elevation in the basin.

Land Cover and Land Use Representation

Land cover in the basin was based on the 2006 National Land Cover Database (NLCD) coverage (Fry et al. 2011). For the portion of the watershed in Canada, Tetra Tech used the hybrid land use layer developed by Stone Environmental for the Missisquoi CSA SWAT model. For parts of the watershed in Canada and not covered by the Missisquoi SWAT model, Tetra Tech used the Land Cover for Agricultural Regions of Canada, circa 2000 (http://open.canada.ca/data/en/dataset/16d2f828-96bb-468d-9b7d-1307c81e17b8). The NLCD base layer was enhanced using other data sources to create a custom land cover layer. This section discusses enhancement of the base NLCD layer and model representation of various land use related sources.

Agricultural Lands and Practices

Cropland, pastureland and farmstead were modeled under the broader category of agricultural lands. Cropland was further classified into different crop types and rotations.

Cropland and Crop Types

The NLCD base layer does not classify agricultural crops into different types. As a result, Tetra Tech relied on the 2008 USDA Cropland Data Layer (CDL) (USDA NASS 2010) to identify major crops types in the US portion of the watershed. Tetra Tech carried out a GIS analysis on the NLCD and CDL datasets to develop a hybrid land use layer that provided the locations of the major crops in the watershed, namely, corn, soybeans and hay.

In the Vermont portion of the basin, the major crop rotations (which consist of continuous corn, continuous hay and hay/corn rotation) were determined using the methodology adopted by Stone Environmental in the Missisquoi Bay CSA modeling project (Stone Environmental 2011). The methodology applies a set of rules based on soil properties from the Vermont TOP20 data layer, slope of land and crop type to determine crop rotation in the basin. The TOP20 data layer provides commonly used soil data for GIS application (http://www.vt.nrcs.usda.gov/Soils/index.html). Most of the information in the TOP20 table is derived from the NRCS National Soils Information System (NASIS) database. Management information including tillage, planting and harvesting dates, and commercial fertilizer and manure application rates were initially based on those developed for the Missisquoi CSA SWAT model by Stone Environmental. For the New York portion of the watershed, management information provided by the New York Extension Service were used. The limited agricultural land in the relatively small portion of the basin in Canada was represented as an unspecified generic crop in the SWAT model and is presented with other agriculture loads as *generic*.

Vermont Practices

As previously stated, the agricultural practices adopted for the Vermont portion of the basin were initially based on practices researched and developed for the Missisquoi CSA SWAT model (Stone Environmental 2011). These were further refined by Tetra Tech on the basis of inputs from NRCS, the VT AAFM, and the University of Vermont Extension Service. The major crops and associated rotations are listed below.

- Permanent hay on poorly drained soils with no reseeding
- Permanent hay on moderate/well-drained soils with no reseeding
- Permanent corn on poorly drained soils
- Permanent corn on moderate/well-drained soils
- Corn/hay rotation on poorly drained soils with 2 years of corn followed by 4 years of hay
- Corn/hay rotation on moderate/well-drained soils with 4 years of corn followed by 4 years of hay

New York Practices

Crop rotation and management data for the New York portion of the basin were developed by Tetra Tech using information from the Cornell University Agricultural Extension Service (http://www.fieldcrops.org/). The major crops and associated rotations (listed below) were found to be similar to those in Vermont.

- Permanent hay on poorly drained and moderate/well-drained soils with no reseeding
- Permanent corn on poorly and moderate/well-drained soils.

Appendix A provides a detailed description of the management practices and the rules adopted to determine areas under the various crop rotations listed above.

Tile Drains

Tile drains installed on cropland can be an important pathway of pollutant transport. Tile drains were explicitly simulated in the SWAT model for croplands on poorly drained soils (hydrologic soil groups C and D) and slope less than 5%. This was consistent with the methodology adopted by Stone Environmental for the Missisquoi CSA SWAT Model (Stone Environmental 2011).

Pastureland

Manure application on pastureland has been identified as a probable source of phosphorus in the Lake Champlain basin. The Pasture/Hay category in the NLCD layer that did not qualify as cropland were classified as pasture in the SWAT model. Manure application rates on pastureland were determined using a detailed analysis discussed in the ensuing section.

Livestock/Manure Production

The amount of manure application on pastureland was determined based on the number of animals producing manure and the estimated amount of time spent by animals on pastureland. Livestock population numbers available by county from the USDA 2007 Census of Agriculture (Table 2) were used in this analysis. Because animal numbers are not available at a SWAT subbasin level, Tetra Tech made certain assumptions to extrapolate data available at the county level to the model subbasins. Chickens were excluded from this analysis under the assumption that they do not have direct access to pastureland.

Table 2. Number of animals by type and county in Vermont

Animal type	Percent of County in Lake Champlain Basin	Beef cows	Milk cows	Calves	Hogs and pigs	Sheep and lambs	Horses and ponies	Goats
Addison	89.5	862	32,172	29,229	269	1,552	1,192	1,684
Bennington	7.1	353	1,735	1,282	33	499	790	76
Caledonia	13.9	561	6,837	6,152	326	872	926	248
Chittenden	100	666	4,851	4,952	97	1,003	1,896	71
Franklin	100	986	37,770	23,880	531	526	708	738
Grand Isle	100	160	3,041	2,656	0	84	259	52
Lamoille	99.6	288	3,589	2,488	0	431	614	327
Orange	9.7	825	9,019	8,395	514	1,571	1,013	197
Orleans	33.6	1,109	20,733	16,076	89	895	702	778
Rutland	86.9	1,508	6,765	7,400	187	2,000	1,696	566
Washington	95.8	500	3,223	3,438	106	663	963	179
Windsor	0.2	1,807	3,112	4,327	232	2,082	1,502	1,260
Total	---	**9,625**	**132,847**	**110,275**	**2,384**	**12,178**	**12,261**	**6,176**

Source: USDA NASS 2007 (Census of Agriculture).

To ensure that the number of animals reported by USDA is reasonable, the number of animals per farm operation was summarized (Table 3) and compared to the Vermont Agency of Agriculture, Food and Markets' (VAAFM) classification of medium farm operations (MFO) and large farm operations (LFO). In accordance with the rules listed below, operations listed as LFO and MFO should house at least 1000 and 300 cattle, respectively. There are 175 operations in the Lake Champlain basin that are classified as LFO or MFO.

Table 3 lists 197 and 102 cattle operations (a total of 299) with a head count of 200-499 and 500 or above, respectively. Of these 299 operations, it is not possible to determine the number of operations that house more than 300 cattle (the minimum to qualify as an MFO). At a minimum it is expected that the number of facilities housing greater than or equal to 200 cattle would be more than the number of LFO and MFO, which appears to be the case.

According to the VAAFM an LFO is a facility that is designed to house more than:

- 700 mature dairy animals, whether milked or dry; or
- 700 bulls; or
- 1000 cattle, cow/calf pairs, young stock, or heifers; or
- 1000 veal calves; or
- 2500 swine weighing over 55 pounds; or
- 10,000 swine weighing less than 55 pounds; or
- 500 horses; or
- 10,000 sheep or lambs; or
- 55,000 turkeys; or
- 30,000 laying hens with a liquid manure handling system; or
- 82,000 laying hens without a liquid manure handling system;
- 125,000 chickens other than laying hens without a liquid manure handling system; or
- 5000 ducks with a liquid manure handling system; or
- 30,000 ducks without a liquid manure handling system.

According to the VAAFM an MFO is a facility that is designed to house:

- 200 to 699 mature dairy cows, whether milked or dry;
- 300 to 999 youngstock or heifers;
- 300 to 999 veal calves;
- 300 to 999 cattle or cow/calf pairs;
- 750 to 2,499 swine weighing over 55 pounds;
- 3000 to 9,999 swine weighing less than 55 pounds;
- 150 to 499 horses;
- 3,000 to 9,999 sheep or lambs;
- 16,500 to 54,999 turkeys;
- 9,000 to 29,999 laying hens or broilers with a liquid manure system;
- 25,000 to 81,999 laying hens without a liquid manure handling system;
- 1,500 to 4,999 ducks with a liquid manure handling system;
- 10,000 to 29,999 ducks without a liquid manure handling system.

Table 3. Average number of animals per operation for all counties in Vermont as per USDA 2007 Census of Agriculture

*Head count	# animals	# operations	# animals per operation
CATTLE			
1-9 head	3373	751	4
10-19 head	4057	304	13
20-49 head	10,925	347	31
50-99 head	29,267	400	73
100-199 head	49,023	358	137
200-499 head	49,545	197	251
≥ 500 head	94,146	102	923
Not specified	264,823	2459	108
HOGS			
1-24 head	215	232	1
25-49 head	0	8	0
50-99 head	0	4	0
100-199 head	0	1	0
200-499 head	0	4	0
Not specified	2616	249	11
SHEEP			
1-24 head	2284	488	5
25-99 head	4573	126	36
100-299 head	0	7	0
300-999 head	0	5	0
Not specified	13,925	626	22

*Head count is equivalent to the number of animals

Through literature research and consultation with local experts, phosphorus excretion rates and time spent by animals on pastureland was determined during the Missisquoi CSA SWAT model development (Stone Environmental 2011). To maintain consistency, these assumptions were directly adopted to estimate the amount of manure applied to pastureland in the Lake Champlain SWAT model developed by Tetra Tech (Table 4 and Table 5).

Table 4. Excretion rate by animal type

Animal type	Average animal weight (kg)	Average excretion rate (kg-P/d-AU)[a]	Total AUs	Total excretion (kg-P/d)
Beef cows	589.7	0.050	12,513	625.7
Milk cows	589.7	0.032	172,710	5,526.7
Calves	317.5	0.018	77,189	1,389.4
Hogs and pigs	90.7	0.073	477	34.8
Sheep and lambs	81.6	0.023	2,191	50.4
Horses and ponies	498.9	0.032	13,486	431.5
Goats	81.6	0.032	1,111	35.6

Source: Stone Environmental 2011.

[a] 1 AU = 1,000 lb; AU = animal unit.

Table 5. Animal grazing assumptions

Animal type	Fraction grazed	Hours grazed per day	Fraction grazing full day (24 hours)	Cumulative grazing hours daily
Beef cows	0.90	14	0.8	22
Milk cows	0.28	14	0.0	14
Calves	0.65	14	0.4	18
Sheep and lambs	1.00	14	0.8	22
Horses and ponies	1.00	14	0.2	16
Goats	1.00	14	0.8	22

Note: This information is based on Stone Environmental 2011.

Using the above assumptions, the total mass of manure generated per day at the county level was apportioned to the Lake Champlain Basin by the fraction of the county in the basin. The total mass of manure generated per day in the Lake Champlain portion of the basin was then divided by the total pasture area to determine the unit area phosphorus loading by county. The deposition rate for each SWAT subbasin was determined using an area weighting approach on the county specific deposition rate. For example, if a SWAT subbasin was intersected by counties A and B having deposition rates of D_A and D_B, respectively, and the fraction of subbasin area under counties A and B were F_A and F_B, respectively, the net deposition rate for the subbasin would be ($F_A * D_A + F_B * D_B$). A continuous grazing period of 180 days was assumed in the SWAT model for the Lake Champlain Basin.

In a study by Iowa State University (Haan et al. 2007), about 4.6 and 8.1 percent of defecation and urination, respectively, were shown to occur directly in the stream. James et al. (2007) estimated that a similar percentage (7 percent) of manure was directly deposited to streams in a New York State watershed. On the basis of these studies, 5 percent of the total manure available for direct deposition on pastureland was applied directly to the stream as a point source. The land and stream application of manure was simulated at the model subbasin scale. Because the watershed model was configured primarily to determine sources of phosphorus and evaluate potential reductions from the Vermont portion of the watershed, land application of manure was not simulated on the New York and Quebec portions of the watershed. This disparity does not affect overall model calibration, but it does mean that for the New York and Quebec portions of the watershed the model is less capable of partitioning phosphorus loads among the agricultural sub-classes (corn, soybean, etc.) and total phosphorus from manure applications on pasture. However, it is important to note that the majority of pastureland lies in the Vermont portion of the watershed.

Farmsteads

Animal operations are an important part of the watershed's economy, and animal waste must be considered as part of the phosphorus cycle. At the time of initial model development, farmsteads in the Vermont portion of the basin were digitized into the hybrid landuse layer developed by Tetra Tech. Large and medium farmsteads were manually delineated using location information and aerial imagery. The areas associated with the barns and the visibly disturbed area around the barns were delineated as farmsteads. Small farmsteads were digitized using location information and an average area assumption.

A shapefile of all farmsteads within the Vermont portion of the watershed produced by the NRCS (Farmstead_polys.shp) became available during the later stages of this project. Since this layer provided the most up-to-date information on the area associated with each farmstead, Tetra Tech formulated a methodology to revise the areas of farmsteads in the SWAT model. The areas of farmsteads in the model were adjusted at the level of each HUC8 watershed such that the total area was equal to the area reported in the NRCS dataset. To ensure that the total area was conserved in the model, any increase in the farmstead area was accompanied by an equivalent decrease in area of pastureland. It is important to note that the delineation of farmstead areas was still in progress and had not yet been completed as of the final writing of this report (April 2015). However, EPA together with agriculture agency stakeholders agreed that it was the best available dataset to use to develop the SWAT watershed models. Farmsteads were not explicitly represented in the New York and Quebec fractions of the watershed due to lack of such data for those areas.

Developed Lands

Five categories (listed below) were modeled under the broader developed lands category.

- Developed/Open Space
- Developed/Low Intensity
- Developed/Medium Intensity
- Developed/High Intensity
- Driveways
- Paved Roads
- Unpaved Roads

Developed lands in SWAT are modeled such that a certain fraction of the area is impervious and the remaining pervious. SWAT requires the user to specify the percentage imperviousness for each developed landuse. Paved roads, unpaved roads and driveways were classified as mostly impervious areas (98% of associated areas were classified as impervious). At the time of model development, the impervious fractions associated with the remaining developed landuse categories were determined using a GIS operation on the NLCD 2006 impervious layer and the hybrid land use layer.

To ensure that the NLCD 2006 impervious dataset was appropriate for modeling, it was also compared to the NDVI Impervious Surface Layer (LandLandcov_IMPERVLCB08) for the Lake Champlain Basin (VANR 2012). The percent imperviousness associated with the developed land categories calculated using the NLCD 2006 impervious raster and the NDVI impervious layer were comparable to each other at 21.7 percent and 23.2 percent, respectively, in the Vermont portion of the basin. Thus, it was deemed appropriate to use the percentage impervious from the NLCD 2006 layer since the fractions of developed area identified as impervious are very similar and the NLCD was used as the base land use layer for the SWAT model.

To ensure that impervious areas were not double counted, paved roads, unpaved roads and driveways were *burnt* into the hybrid landuse layer before carrying out the GIS operation to determine the impervious fraction of other developed land categories. The datasets used to *burn* paved roads, unpaved roads and driveways are discussed in the ensuing sections.

During the later stages of this project, a newer impervious layer (LandLandcov_IMPERVLCB2011) was available from the University of Vermont Spatial Analysis Laboratory. The total impervious area according to this layer was found to be much lower than that reported by the NLCD 2006 impervious layer and the NDVI Impervious Surface Layer. A random quality check on the new impervious layer suggested that it was more accurate than the other layers used earlier for the impervious analysis. As a result, Tetra Tech revised the impervious fractions associated with the developed lands based on the new impervious layer. The impervious fractions associated with roads were not revised because the new impervious layer did not seem to capture the shoulder areas associated with roads. For the purpose of load allocation, actual road surfaces and their associated shoulder areas are expected to exhibit similar loading behavior.

Pervious Developed

The pervious fractions of the developed land uses were simulated as urban lawns with fertilizer application. Since fertilizer application rates can vary widely and not all lawns are fertilized, Tetra Tech conducted a literature review to estimate fertilizer application in the Lake Champlain watershed model. Literature-reported values of fertilizer application in the region range from 14.5 lb-P/ac/yr to approximately 30 lb-P/ac/yr (USGS 2002; Voorhees 2012), with an average of approximately 22 lb-P/ac/yr. A survey conducted in the Chesapeake Bay watershed found that roughly 50 percent of lawns are fertilized (Chesapeake Stormwater Network 2011). If one assumes 50 percent of lawns in the Champlain Basin of Vermont are fertilized, the average application rate would be approximately 11 lb-P/ac/yr or 12.5 kg-P/ha/yr. This rate was adopted for the SWAT model. Note that although this rate might not reflect actual application rates in Vermont, overall model calibration is not very sensitive to variations in application rates, given the small percentage of pervious developed land in the basin. However, fertilizer application rates are important to assessments of the effects of phosphorus fertilizer bans. For this reason, a supplemental analysis (Tetra Tech 2015) of the amount of phosphorus reduction anticipated from new phosphorus fertilizer restrictions in Vermont incorporated results from Vermont surveys of fertilizer application rates along with an assessment of Vermont turf area. This separate analysis was used to determine the phosphorus reduction expected from the Vermont phosphorus fertilizer ban and is detailed in the report referenced.

Impervious Developed

Tetra Tech used the buildup and washoff algorithm in SWAT to model sediment and nutrient loads from the impervious fraction of urban lands. The parameters for the buildup and washoff algorithm were based on the Missisquoi CSA SWAT model (Stone Environmental 2011) and modified during the calibration process. The calibration process for upland loads focused on adjusting the export rates from different developed categories based on published literature values for the northeastern United States (Artuso et al. 1996; Budd and Meals 1994; Stone Environmental 2011).

Paved and Unpaved Roads

The VTrans road centerline GIS dataset (TransRoad_RDS layer) developed by the VTrans mapping unit was used to *burn* unpaved roads into the hybrid land use/land cover layer. The Vermont Emergency E911_RDS roads (http://vcgi.vermont.gov/warehouse/?layer=EmergencyE911_RDS) layer was used to *burn* paved roads into the hybrid land use/land-cover layer. The SURFACE attribute in the TransRoad_RDS dataset was used to guide the classification of roads as paved or unpaved based upon the code and description associated with a given surface type. Table 6 lists the SURFACE attribute categories.

Table 6. VTrans road centerline data attributes

Code	Description	Length (km)
1	Hard surface	6,567.0
2	Gravel	4,370.0
3	Soil or graded and drained earth	1,257.0
5	Unimproved/primitive	348.0
6	Impassable or untraveled	481.0
9	Unknown surface type	2,088.0

Codes 2, 3 and 5 were classified as unpaved roads based upon communication with Jonathan Croft of the VTrans Mapping Unit and subsequent discussions with USEPA (e-mail communication August, 2012). Paved and unpaved roads were *burned* into the hybrid land use layer developed for the Lake Champlain SWAT model using an assumed width of 10 meters. Paved and unpaved roads were modeled to be generally impervious with a very small fraction (2% of road area) as pervious.

In a study to assess the effects of unpaved roads on water quality, Wemple (2013) analyzed water samples for total phosphorus at 12 roadside locations with varying grades (ranging from 1.5% to 15%) in the Winooski River watershed during 2011 and 2012. The samples collected from this study showed spatial and temporal variability in total phosphorus concentration (Table 7). The average concentration of all the samples collected was approximately 0.7 mg/L. Total phosphorus loads from unpaved roads in certain subwatersheds of the Winooski River watershed were also estimated by the study. Table 13 from Wemple (2013) estimates that 15,380 kg of total phosphorus are eroded from 2,509.7 km of unpaved roads in some subwatersheds of the Winooski River watershed. Assuming a road width of 10 meters, this equates to an approximate loading of 6 kg-P/km/yr.

Table 7. Range of TP concentration from unpaved road sites

Site	Grade (%)	# samples	TP (mg/L)	
			Mean	Range
Senor	1.5	64	0.2	0 to 1.8
Common	1.5	19	0.1	0 to 0.3
North Fayston	2.5	18	0.6	0.1 to 2.6
3 Way	8	71	1.2	0 to 11.9
Barton	8	15	0.8	0 to 7.3
Bragg Hill	9	25	1.0	0.1 to 3
Sharpshooter	9	16	0.4	0 to 3.4
Ski Valley	10	42	0.4	0 to 2.4
Rolston	12	12	3.8	1.3 to 14.2
Mansfield	12	17	0.5	0 to 3.7
Cider Hill	13	26	0.1	0 to 0.3
Randell	15	4	0.5	0.2 to 1

Based on the analyses conducted by Wemple (2013), unpaved roads were parameterized in the SWAT model to produce an average total phosphorus concentration of 0.7 mg/L and loads of 6 kg-P/km/yr, respectively.

Driveways

Tetra Tech *burned* driveways into the hybrid land use layer using the EmergencyE911_DW driveways (http://vcgi.vermont.gov/warehouse/?layer=EmergencyE911_DW) layer and an assumed width of 10 meters. Although driveways were categorized as a separate land use category in the hybrid land use layer, the phosphorus loads generated by driveways are lumped with the residential category in the SWAT model results. Similar details were not available for New York and Quebec. The areas associated with driveways were modeled as 98% impervious in the SWAT model. Table 8 summarizes the sources of roads and driveways data.

Table 8. Summary of Road and Driveway Source Data

Impervious Source Category	Data Source
Paved Roads	EmergencyE911_RDS layer
Unpaved Roads	VTrans TransRoad_RDS layer
Driveways	EmergencyE911_DW driveways layer

Table 9 shows modeled landuses as a percentage of major drainages in the basin. Figure 3 illustrates the landuse/landcover in the basin.

Table 9. Modeled land use as a percentage of major drainages in the Lake Champlain Basin

Code	Land use	Mettawee-Poultney	Otter-Lewis	Winooski	Lamoille	Missisquoi	Ausable	Saranac	Lake Champlain Direct Drainage	Total	
										Percent (%)	Area (ha)
11	Open Water	1.95	1.02	0.89	1.10	0.89	1.97	6.47	17.86	7.35	156,864
19	Paved Roads	0.40	0.80	1.01	0.72	0.48	0.00	0.00	0.33	0.48	10,290
20	Driveways	0.29	0.55	0.84	0.62	0.35	0.00	0.00	0.25	0.37	7,964
21	Developed/Open Space	4.16	2.54	3.67	2.85	1.91	2.76	2.80	3.09	3.01	64,133
22	Developed/Low Intensity	2.10	1.21	1.72	1.21	1.90	0.70	0.76	1.77	1.55	33,082
23	Developed/Med Intensity	0.67	0.59	0.76	0.28	0.28	0.11	0.34	0.43	0.46	9,746
24	Developed/High Intensity	0.18	0.13	0.27	0.07	0.13	0.02	0.15	0.12	0.14	2,976
25	Unpaved Roads	0.32	0.53	0.74	0.70	0.72	0.00	0.00	0.16	0.37	7,959
28	Medium/Large Farmstead	0.00	0.05	0.01	0.01	0.04	0.00	0.00	0.02	0.02	415
29	Small Farmstead	0.06	0.11	0.06	0.08	0.10	0.00	0.00	0.04	0.06	1,205
31	Barren	0.15	0.11	0.22	0.15	0.18	0.13	0.08	0.12	0.14	2,985
41	Deciduous Forest	38.04	37.53	38.43	40.03	28.08	34.72	35.06	23.92	31.88	680,138
42	Evergreen Forest	13.58	11.37	13.07	15.42	8.16	32.16	29.57	13.56	15.21	324,462
43	Mixed Forest	7.05	12.14	26.82	21.84	36.67	19.66	9.65	10.41	16.69	356,018
52	Shrubland	7.00	3.27	2.12	2.13	2.32	1.06	2.22	2.18	2.64	56,370
71	Grassland Herbaceous	0.23	0.20	0.43	0.31	0.14	1.11	1.47	1.21	0.73	15,681
81	Pasture/Grass	0.78	1.31	0.87	1.26	1.33	0.03	0.03	2.89	1.58	33,608
82	Cultivated Crop	0.15	0.21	0.02	0.02	2.28	0.05	0.02	2.99	1.31	28,007
83	Corn	2.00	0.44	0.27	0.51	0.80	0.25	0.10	1.68	0.98	20,981
84	Soybeans	0.02	0.03	0.01	0.00	0.03	0.00	0.00	0.12	0.05	1,077
85	Fallow/Idle Cropland	0.72	0.65	0.33	0.46	0.43	0.03	0.01	0.26	0.35	7,557
87	Hay	10.10	10.21	3.86	4.45	6.25	0.69	0.34	5.56	5.53	118,081
89	Corn/Hay	1.70	2.34	1.67	3.01	3.29	0.00	0.00	1.49	1.74	37,194
90	Woody Wetlands	7.36	5.90	1.22	2.05	2.14	4.11	9.91	6.38	5.04	107,568
95	Herbaceous Wetlands	0.57	0.64	0.22	0.31	0.22	0.43	1.03	0.65	0.53	11,226
831	Corn-Clay[a]	0.02	0.66	0.04	0.04	0.13	0.00	0.00	0.49	0.27	5,672
841	Soybean-Clay[a]	0.00	0.23	0.00	0.00	0.01	0.00	0.00	0.04	0.04	876
891	Corn/Hay-Clay[a]	0.41	5.23	0.43	0.37	0.74	0.00	0.00	1.98	1.48	31,621
Total	Percent (%)	1.95	1.02	0.89	1.10	0.89	1.97	6.47	17.86	7.35	---
	Area (ha)	178,053	244,280	275,359	186,948	220,718	133,379	158,872	736,146	---	2,133,756

[a] Not simulated on the New York side of the basin. This distinction was required because management practices implemented on clayey soils differ from those implemented on non-clayey soils.

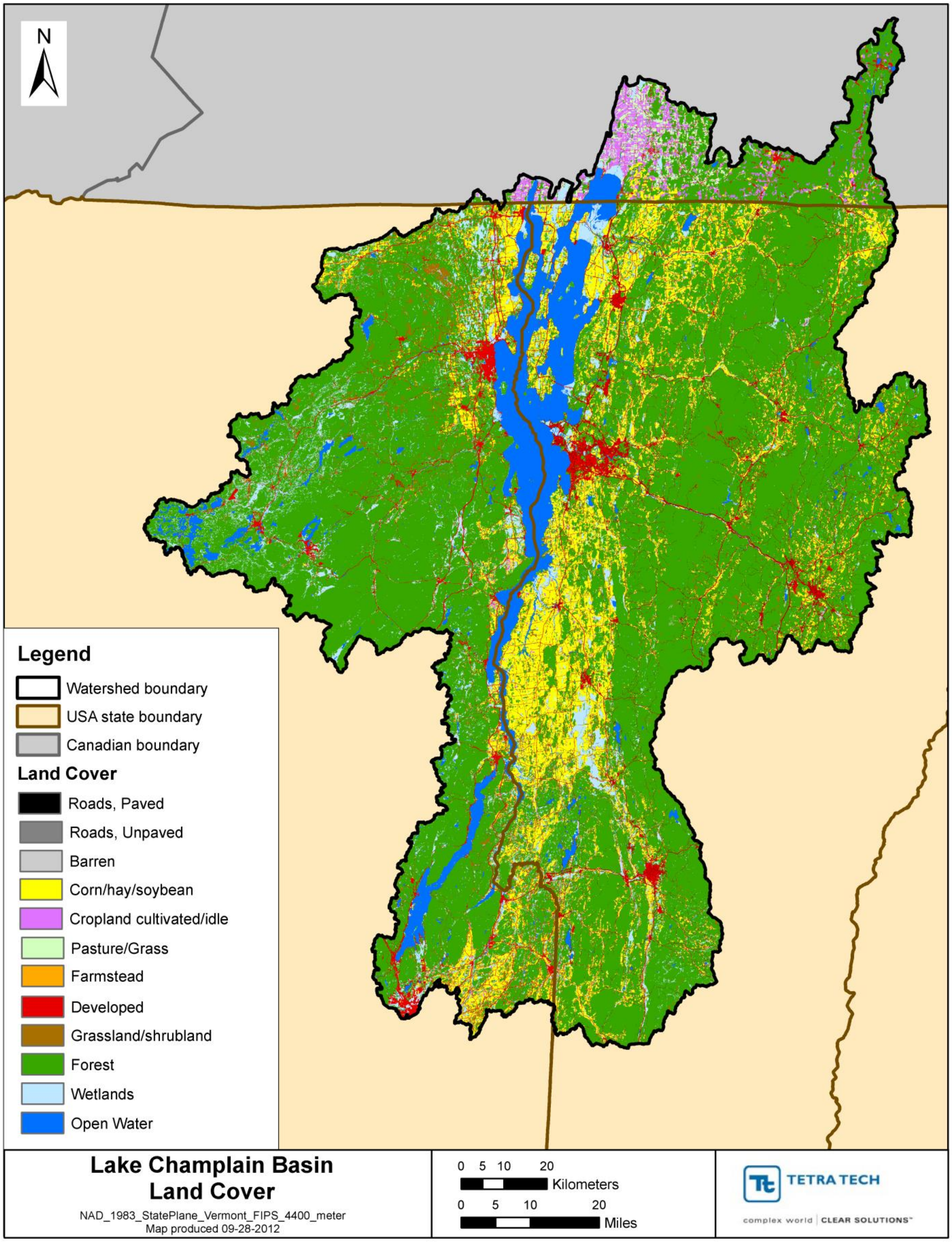

Figure 3. Land use/land cover in the Lake Champlain Basin.

Soil Characteristics

The SWAT model requires the following soil properties for each HRU:

- Number of horizons
- Hydrologic soil group
- Maximum rooting depth
- Anion exchange capacity
- Soil cracking potential.

For each soil horizon, the following properties are required:

- Depth of horizon
- Bulk density
- Available water capacity
- Hydraulic conductivity
- Percent organic carbon
- Percent sand, silt and clay
- Percent rock
- Albedo
- USLE erosivity factor
- Electrical conductivity.

The USDA's detailed Soil Survey Geographic Database (SSURGO) soil data were used in the SWAT model for the majority of the Lake Champlain Basin. The less detailed State Soils Geographic Database (STATSGO), which classifies areas according to dominant soil components, was used for certain parts of the basin in the Saranac River and Ausable River HUC8 watersheds in Franklin County, New York, that lacked SSURGO data. For the Canadian portion of the basin, soil properties were determined from the Soil Landscapes of Canada (version 3.2) dataset (http://sis.agr.gc.ca/cansis/nsdb/slc/intro.html) and the soils data layer developed for the Missisquoi CSA model by Stone Environmental (Stone Environmental 2011). Figure 4 illustrates the primary soil data sources used for different portions of the basin.

All the parameters listed above were available from the cited databases. A small fraction of required data were missing. The approach adopted by Tetra Tech to address missing data is outlined below.

- If values for parameters associated with a given horizon were missing then these were filled using data from an adjacent horizon of the same soil.
- If data for all horizons were missing then the SWAT soils database was used to fill data based upon the name of the soil.

In addition, Official Series Descriptions from USDA (http://soils.usda.gov/technical/classification/osd/index.html) were used to guide the gap filling process.

Hydrologic soil group (HSG) governs the infiltration capacity of the soil. A soils have the highest infiltration capacity and D the least. As a result, A soils have the least runoff potential and D have the highest runoff potential. The percentages of land area in the Lake Champlain Basin falling into the A, B, C and D soil groups are 11.0 percent, 19.9 percent, 34.5 percent and 34.6 percent, respectively.

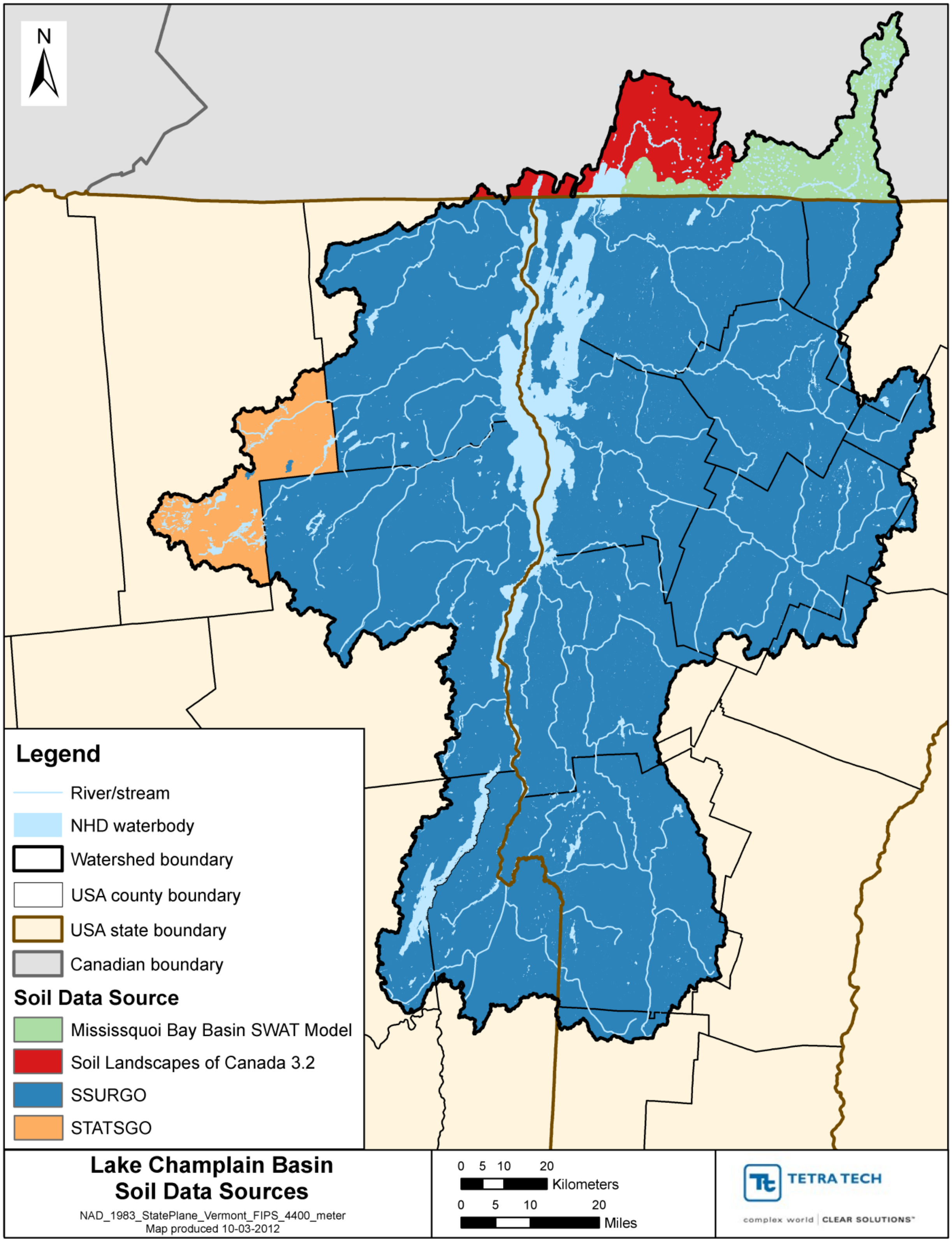

Figure 4. Soil data by source used in the Lake Champlain Basin SWAT model.

Highly Erosive Lands (HELs)

HELs were determined using the HEL attribute in the Vermont TOP20 layer provided by USDA-NRCS in conjunction with slope determined from the DEM of the watershed. Tetra Tech used this information to set specific slope thresholds in developing HRUs to account for HELs. The same assumptions were applied to identify HELs on the New York side of the basin.

The VTSoils layer includes a specific designation for HEL with five possible categories:

- Highly erodible
- Potentially highly erodible - designates soil polygons where further investigation is needed
- Not highly erodible
- Not rated - used for non-soil polygons (e.g., muck [wetlands], gravel pits, bedrock)
- Water.

In addition to the highly erodible category, Tetra Tech considered soil polygons with a designation of potentially highly erodible and a slope greater than 5 percent to be likely highly erodible as well. Highly erosive lands were used in the determination of crop rotations in the basin.

HRU Development

The SWAT model representation of the upland watershed area is set up using HRUs. SWAT provides a built-in HRU overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use, SSURGO major soils and user-defined slope classes. HRU development for the Lake Champlain Basin was also implemented to facilitate the phosphorus loading reduction analysis phase of the project. As a result, model setup required creating HRUs specific to potential future implementation activities. The following steps describe how Tetra Tech developed HRUs for phosphorus sources in the ArcSWAT interface:

1. Import hybrid land use and soil data layers developed by Tetra Tech.
2. Specify three broad slope classes, namely, 0–5 percent, 5–10 percent and above 10 percent. Slope was calculated by the ArcSWAT interface using a 10-meter DEM of the basin. HRUs with slope greater than 5 percent could fall in the highly erodible land category.
3. Overlay land use, soil and slope layers.

With some exceptions (described below), specify a threshold of 5 percent for land use, 10 percent for soil and 5 percent for slope while defining HRUs. Only land uses, soil types, and slope classes that exceed these percentages in a watershed were used to generate HRUs. This avoided creating an excessive number of HRUs, which would significantly increase model run time. However, developed lands, farmsteads, unpaved roads, paved roads, driveways, pastureland and agricultural land identified as hay or corn were exempt from the 5 percent threshold so that pollutant loads from these land use categories could be accurately modeled and quantified. Table 10 shows areas by land use category before and after implementing thresholds on land use, soil and slope classes.

Table 10. Land use areas before and after implementing thresholds

Land use	Original area (ha)	SWAT model area (ha)
Agriculture	252,294	239,557
Pasture	33,557	33,557
Urban	137,682	137,682
Forest	1,359,649	1,434,083
Grass/Shrub	71,957	36,293

Land use	Original area (ha)	SWAT model area (ha)
Wetlands	118,752	95,069
Water	156,851	157,483
Barren	2,981	0
Total	**2,133,723**	**2,133,723**

To reduce the number of HRUs and computational time, thresholds were imposed on landuse, soil and slope when setting up the SWAT models[2]. However, certain landuses deemed as critical sources of phosphorus were exempt from the threshold. A threshold was enforced for all soils and slope classes. There is no clear guidance or consensus in the scientific community on the appropriate choice of thresholds for landuse, soil and slope. The thresholds for this model were set such that:

1) areas associated with critical landuses areas were not lost or reapportioned to other landuses, and
2) the total number of HRUs for a model were not too many to significantly increase model run times.

The re-apportioning of landuse, soil and slope as implemented by the SWAT is described below. A 5% threshold on landuse implies that in a subbasin if a certain landuse occupies less than 5% of subbasin area then that landuse is dropped and the areas of the other landuses are proportionately increased such that they make up 100% of the subbasin area. A 10% threshold on soil implies that within a subbasin and for a given landuse, soils that occupy less than 10% of the landuse area are dropped and areas associated with the other soils are proportionately increased such that they make up 100% of the landuse area within the subbasin. This process is repeated for all landuses within a subbasin. A threshold of 5% on slope implies than within a subbasin for a given landuse and soil, slope categories that occupy less than 5% of a soil area are dropped and the areas associated with the other slope categories are increased proportionately such that they make 100% of the soil area within a landuse in a subbasin.

The ArcSWAT documentation provides a detailed example of the process. The ArcSWAT documentation states that the setting of thresholds is a function of project goal and desired level of detail. The documentation also states that landuse, soil and slope thresholds of 20%, 10% and 20%, respectively, are adequate for most applications. Table 11 shows the area in each watershed redefined for landuse, soil and slope.

Table 11. Landuse, soil and slope areas redefined for each watershed in the SWAT model

Re-apportioned	Mettawee/Poultney	Otter	Lamoille	Winooski	Missisquoi	Ausable	Saranac	Lake Champlain
Watershed area (ha)	178,052	244,281	206,517	275,355	229,816	152,643	176,340	670,368
Landuse area (ha)	7,965	13,358	12,058	13,328	12,639	8,885	8,205	27,807
Landuse area (%)	4.47%	5.47%	5.84%	4.84%	5.50%	5.82%	4.65%	4.15%
Soil area (ha)	12,647	14,803	53,400	32,083	24,796	11,215	11,783	50,112
Soil area (%)	7.10%	6.06%	25.86%	11.65%	10.79%	7.35%	6.68%	7.48%
Slope area (ha)	10,323	15,835	9,921	14,565	9,906	10,438	2,843	23,289
Slope area (%)	5.80%	6.48%	4.80%	5.29%	4.31%	6.84%	1.61%	3.47%

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[2] The model was run watershed-by-watershed. For each watershed, the model runtime was approximately 10 minutes. The total run time for the entire watershed is approximately 1 hour. If thresholds are not imposed, the number of HRUs increase greatly. For example, the Lamoille River watershed currently has 2,472 HRUs. If no thresholds are imposed, the number of HRUs would be 79,012 for this HUC8 watershed alone. The model run time and number of HRUs are not related linearly. So if running a model with 2,472 HRUs takes minutes, running the same with 79,012 HRUs would likely take hours

As evident from the table above, the reapportionment was generally around 5% of the watershed area for landuse and slope, and around 10% for soils with the exception of Lamoille River. A closer examination revealed that the re-apportionment was generally between C and D soils, and A and B soils, respectively, and is expected to have marginal impact on simulated flow, and sediment and phosphorus loads.

It is important to note that the models setup for this project are not expected to provide loading at the field scale but for average annual loads by landuse at the HUC8 level. To ensure that the imposition of threshold values did not introduce artificially low estimates of loads due to threshold values selected, basin-scale loads were compared to the loads reported in the Missisquoi CSA SWAT model (Stone Environmental 2011). The comparison verified that despite the thresholds, the unit area sediment and phosphorus loads by landuse were similar for both modeling efforts.

Point Sources

Information on permitted point source dischargers in the Lake Champlain basin was provided by the Vermont Department of Environmental Conservation including actual flows, and total phosphorus concentrations and loads for all facilities in the basin including New York, Vermont and Quebec. Monthly data were available for Vermont while yearly data were available for New York and Quebec. In addition, the point source data indicate whether the facility discharges directly to the Lake or to upstream tributaries. This information was used to determine whether a facility was simulated in the SWAT model or in the BATHTUB model. Facilities listed as discharging directly to the Lake were represented in the Bathtub model, while facilities listed as discharging to upstream tributaries were represented in the SWAT model. The SWAT point source representation employed monthly time-series for Vermont facilities. New York facilities were represented using a yearly time series. Point sources discharging directly into the Lake were not modeled in SWAT. Appendix B lists all National Pollutant Discharge Elimination System facilities in the Champlain basin, and whether the facility is included in the SWAT or Bathtub model. If the facility is included in the SWAT model, the HUC12 location is also indicated.

Water Withdrawals

Surface water withdrawals were explicitly represented in the SWAT models. Water withdrawal data for commercial, municipal and domestic use were available from the U.S. Geological Survey (USGS) for Vermont and New York. Vermont data were available by town/city (Table 12); New York water withdrawal data were available only by county (Table 13). As per requirements of the SWAT model, an average daily withdrawal rate from modeled streams has been specified for each month of the year. In the Vermont portion of the basin, depending on the location of the city or town, daily surface water withdrawal was simulated for the respective reach in the SWAT model. For New York, the surface water withdrawal for a reach was determined using the fraction of the subbasin in the county.

Table 12. Vermont water withdrawals in Lake Champlain Basin SWAT Models (mgd)

Town/city	Ground water	Surface water	Total
Barre City	0.053	2.809	2.862
Barre Town	0.545	0.034	0.580
Cambridge	0.782	0.536	1.318
Fair Haven	0.100	0.438	0.539
Georgia	0.809	0.236	1.045
Montpelier	0.078	1.945	2.023
Pittsford	0.665	0.212	0.877
Proctor	0.050	0.248	0.299
Richford	0.148	0.413	0.562
Rutland City	0.003	5.590	5.594
St. Albans City	0.000	0.388	0.388
St. Albans Town	0.577	4.430	5.007
Stowe	1.371	1.401	2.771
Warren	1.543	0.482	2.025
Waterbury	0.596	0.374	0.970

SOURCE: Medalie and Horn 2010.

Table 13. New York water withdrawals in the Lake Champlain Basin SWAT Models (mgd)

County name	Ground water	Surface water	Total
Clinton	3.69	9.89	13.58
Essex	1.78	6.53	8.31
Franklin	3.55	5.22	8.77
Warren	1.97	9.75	11.72
Washington	5.00	3.46	8.46

SOURCE: USGS National Water Use Information Program. (http://water.usgs.gov/watuse/data/2000/datadict.html)

Meteorological Data

The required meteorological time series for SWAT include daily precipitation, daily maximum and minimum air temperature, and either calculated potential evapotranspiration (PET) or time series required to generate PET. For the Lake Champlain watershed model, precipitation and temperature time-series obtained from the Summary of the Day dataset (National Oceanic and Atmospheric Administration) were used. In SWAT, the full Penman-Monteith method (Allen et al., 2005) is implemented as an internal option in the model and includes feedback from crop height simulated by the plant growth model. The additional inputs to the energy balance (solar radiation, wind movement, cloud cover, and relative humidity) for internal calculation of PET were provided by the SWAT weather generator, which relies on monthly conditional probability statistics for each of these inputs. An evaluation of the Summary of the Day indicated substantial amounts of missing data for these inputs (especially for solar radiation and cloud cover); hence, the SWAT weather generator was preferred to enable consistent 30-year simulations.

Precipitation and temperature data were patched using MetADAPT software to fill data gaps and allocate accumulated data. A total of 36 precipitation stations were identified for use in the Lake Champlain watershed model with a common period of record of January 1, 1980, to December 31, 2010 (Table 14 and Figure 5).

Temperature records are sparser; where these were missing, the temperature was taken from nearby stations with an elevation correction.

Table 14. Precipitation stations for the Lake Champlain Basin SWAT model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (meters)
301387	CHASM FALLS	44.75000	-74.21667	x	323
301401	CHAZY	44.88000	-73.43306	x	52
301966	DANNEMORA	44.72056	-73.72361	x	408
302554	ELIZABETHTOWN	44.25222	-73.57722	x	189
302574	ELLENBURG DEPOT	44.90944	-73.79444		262
303284	GLENS FALLS FARM	43.33333	-73.73333	x	154
303294	GLENS FALLS AP	43.34111	-73.61028	x	98
304555	LAKE PLACID 2 S	44.24667	-73.99083	x	591
306538	PERU 2 WSW	44.56667	-73.57306	x	155
306957	RAY BROOK	44.29611	-74.10278	x	494
307818	SMITHS BASIN	43.35194	-73.49611		43
308631	TUPPER LAKE SUNMOUNT	44.23333	-74.44194	x	512
309389	WHITEHALL	43.55000	-73.40000	x	36
430940	BROOKFIELD 2 SW	44.02833	-72.64694		396
431081	BURLINGTON WSO AP	44.46806	-73.15028	x	101
431433	CHITTENDEN	43.70778	-72.96639		323
431580	CORNWALL	43.97056	-73.23111	x	122
432698	EDEN 2 S	44.67556	-72.56139	x	444
432769	ENOSBURG FALLS	44.86472	-72.80889	x	128
432773	ENOSBURG FALLS 2	44.93194	-72.79972	x	130
434189	JAY PEAK	44.94111	-72.50944	x	572
434747	LUDLOW	43.39750	-72.71667		386
435278	MONTPELIER AP	44.20333	-72.57944	x	343
435376	MORRISVILLE 4 SSW	44.51667	-72.62944	x	232
435416	MOUNT MANSFIELD	44.53139	-72.81500	x	1,204
435542	NEWPORT	44.93333	-72.20000	x	235
436335	PERU	43.26667	-72.90000	x	518
436391	PLAINFIELD	44.27611	-72.41583	x	244
436995	RUTLAND	43.61667	-72.96667	x	189
437032	ST ALBANS RADIO	44.81111	-73.07917	x	140
437098	SALISBURY 2 N	43.93111	-73.10000	x	128
437607	SOUTH HERO	44.63306	-73.30639	x	34
437612	SOUTH LINCOLN	44.07806	-72.96861	x	418
438160	SUNDERLAND 2	43.09083	-73.12444	x	274
438172	SUTTON 2 NE	44.66472	-72.02194	x	305
438637	WAITSFIELD 2 W	44.18333	-72.88333	x	313

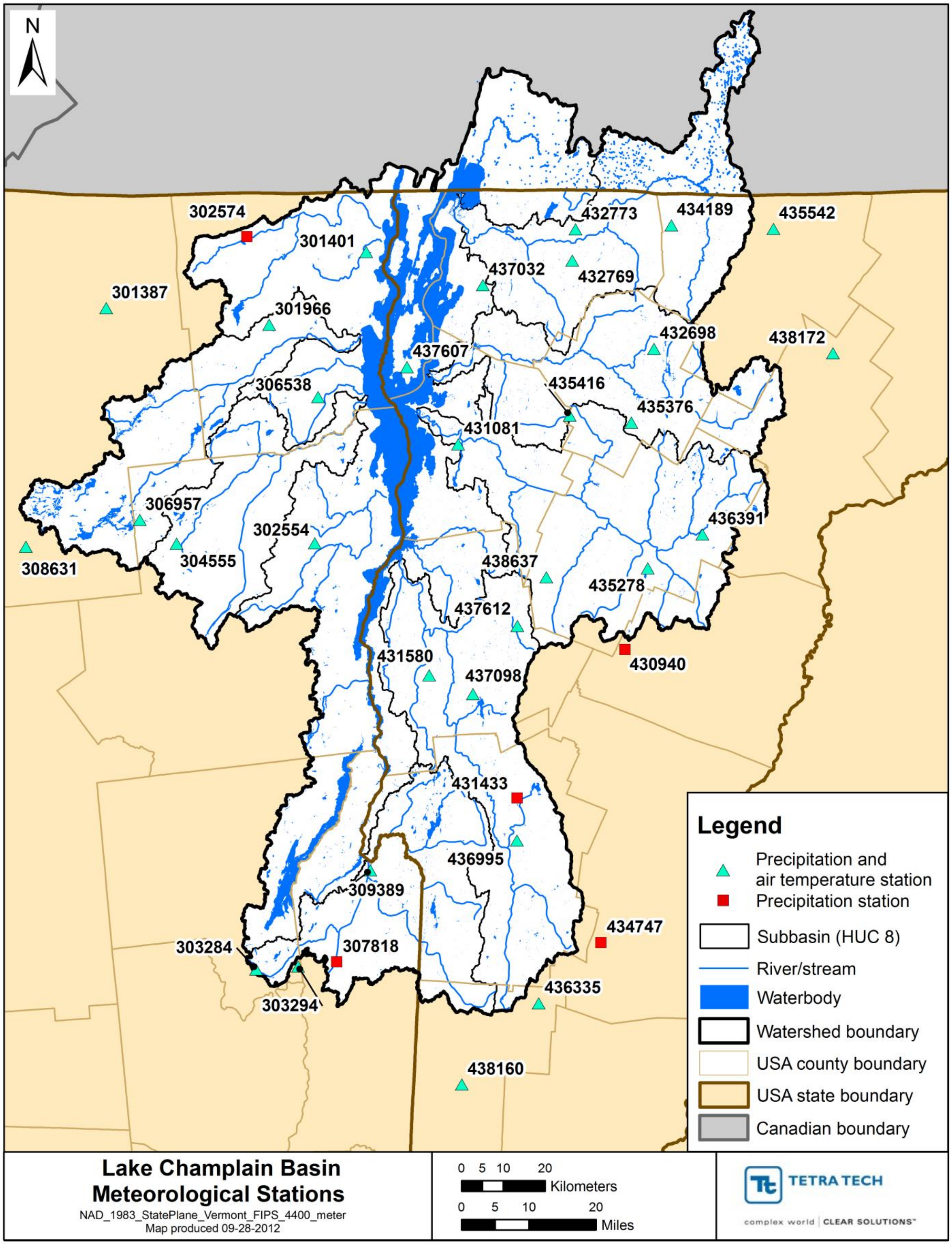

Figure 5. Meteorological stations used in the SWAT model.

Model Segmentation

The Lake Champlain Basin was delineated into subbasins using HUC12 watersheds with some alterations to account for critical watershed features or locations with important flow or water quality calibration data. The resulting model segments are shown in Figure 6.

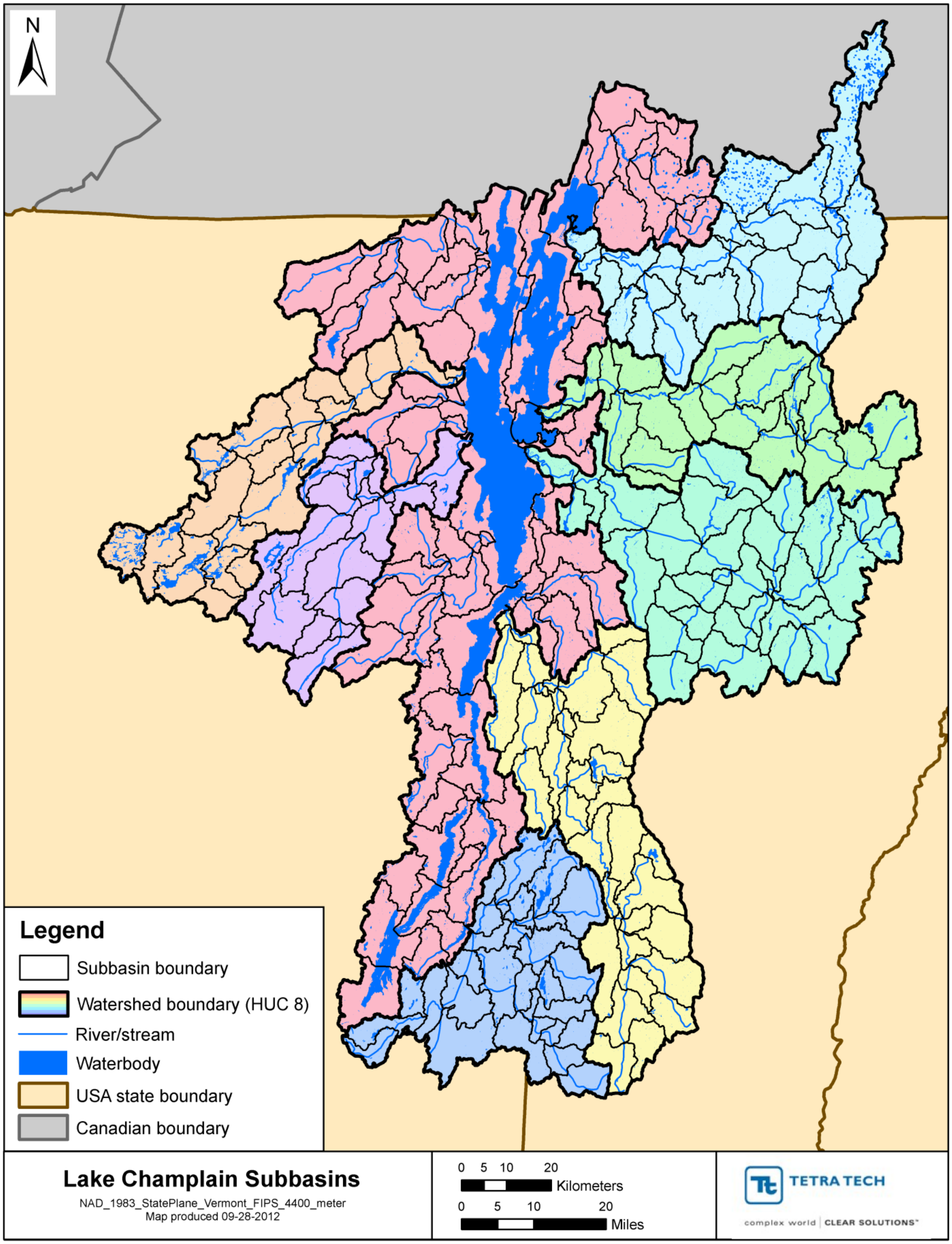

Figure 6. Delineated subbasins (by HUC12 watershed) for the Lake Champlain Basin SWAT model.

Reservoirs

Reservoirs can significantly affect the timing and magnitude of flow in a stream or river. There are a number of reservoirs in the Lake Champlain watershed; however, only a few of them are located on the modeled reach or are large enough to affect the flow. Reservoirs located on modeled reaches and having significant storage were modeled explicitly. In addition, smaller flow-through reservoirs were explicitly modeled when they were found to affect the downstream flow during baseflow periods. Reservoirs were modeled using the average annual release option in SWAT. During the model calibration/validation and subsequent revisions of the models, it was ensured that the reservoirs generally acted as sinks and not as sources of sediment and phosphorus. The reservoirs explicitly modeled in the SWAT model are shown in Table 15.

Table 15. Reservoirs represented explicitly in the SWAT model

Dam name	State	County	River	Normal storage (acre-feet)	Surface area (acres)
Waterbury	VT	Washington	Little River	37,000	850
Wrightsville	VT	Washington	North Branch Winooski River	2,800	190
East Barre	VT	Washington	Jail Branch	23,550	0
Marshfield No. 6	VT	Washington	Mollys Brook	9,259	411
Essex No. 19	VT	Chittenden	Winooski River	1,950	352
Green River Dam	VT	Lamoille	Green River	16,900	625
Cadys Falls (Lake Lamoille)	VT	Lamoille	Lamoille River	700	130
Clark Falls (Arrowhead Mountain Lake)	VT	Chittenden	Lamoille River	6,000	740
Peterson	VT	Chittenden	Lamoille River	2,840	136
Lake Bomoseen	VT	Rutland	Castleton River	7,046	2,360
Lake Dunmore	VT	Addison	Leicester River	4,900	985
Chittenden Reservoir	VT	Rutland	East Creek	17,200	693
Union Falls	NY	Clinton	Saranac River	8,900	1,630
Lake George	NY	Essex	La Chute River	2,250,000	28,160
Bartlett Carry Dam	NY	Franklin	Saranac River	70,924	5,066
Lake Flower	NY	Franklin	Saranac River	6,200	1,360

Parameter Simulations

Hydrology Simulation

The hydrologic cycle in SWAT consists of the land phase and the routing phase. The land phase consists of precipitation, interception by plant canopy, infiltration and redistribution in soil profile, evapotranspiration, and surface runoff, interflow and baseflow generation at each individual HRU at a daily-time step. SWAT allows the user to choose from the Curve Number method or the Green and Ampt method to model runoff and infiltration. The flows generated at the HRU level are aggregated at the subbasin level and routed through the stream network using the variable storage method or the Muskingum routing method. SWAT also allows for losses to deep groundwater at the HRU level and through stream beds. The Curve Number method and the variable storage method were used for the Lake Champlain SWAT model.

Sediment Simulation and Channel Erosion

The SWAT model for the Lake Champlain Basin was set up to simulate daily flow and total suspended solids (TSS) and phosphorus loads from all the major rivers and tributaries draining into Lake Champlain. Although the SWAT model simulates sediment and phosphorus loads from upland and channel sources, additional information is required to parameterize the model to constrain the loads generated from these sources. Tetra Tech used information available from different sources to develop predictions of the proportion of sediment load from upland sources and channel sources.

Upland sediment generation is simulated in SWAT using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975).

$$sed = 11.8\left(Q_{surf}q_{peak}area_{hru}\right)^{0.56}K_{USLE}.C_{USLE}.P_{USLE}.LS_{USLE}.CFRG$$

where *sed* is the sediment yield from an HRU on a given day (metric tons), Q_{surf} is the surface runoff volume (mm/ha), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of the HRU (ha), K_{USLE} is the soil erodibility factor, C_{USLE} is the cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is USLE topographic factor and *CFRG* is the coarse fragment factor.

Q_{surf} and q_{peak} are simulated by the model, and K_{USLE} and *CFRG* are determined from the soil data input to the model. Default values of C_{USLE}, P_{USLE} and LS_{USLE} were generally used.

Channel processes are an important aspect of the sediment budget in a watershed. Past studies in the basin have attributed a significant fraction of the total sediment load to channel sources (Langendoen et al. 2012, Stone Environmental 2011). Tetra Tech used Bagnold's equation with the particle tracking option to simulate sediment routing and channel erosion during the calibration and validation process.

In this approach, the transport capacity of a stream is controlled by Bagnold's stream power equation but channel erosion is simulated based on the shear stresses acting on the bank and bed. Channel erosion occurs when the excess shear stress exceeds the critical shear stress. The SWAT code, regardless of the availability of excess shear stress, does not simulate bank erosion unless the sediment transport capacity is high enough to transport additional sediment. Stone Environmental modified the SWAT code to allow bank erosion to occur regardless of the availability of excess transport capacity in the Missisquoi CSA SWAT model. The same modifications employed for the Missisquoi CSA SWAT model were used for the Lake Champlain SWAT model. A closer examination of the SWAT code also revealed that although deposition of sediment scoured from channel is accounted for, the same does not hold true for phosphorus. That is, phosphorus is scoured from the channel with sediment but no deposition occurs when a fraction of the scoured sediment settles in the channel. The code was further modified to address this issue which ensured that the phosphorus and sediment dynamics were reasonably represented in the stream systems.

Estimates of the proportion of channel erosion sediment load to total sediment load were available from the Missisquoi CSA model (Stone Environmental 2011) and the Missisquoi BSTEM model (Langendoen et al. 2012). Additionally, quantitative geomorphology data from Vermont's Phase II stream geomorphic assessment program (Phase II data) were available only for certain reaches in the basin. The remainder of this section describes how the SWAT modeling incorporated the above data with respect to stream channel load estimation.

Tetra Tech used available Phase II data to calculate the ratio of eroding area to channel length (erosion indicator ratio) as a quantitative indicator of reaches undergoing erosion. Eroding area is defined as the surface area of the channel eroding per unit length of the channel. Because Phase II data are not available for all reaches in the basin, there was a need to relate the erosion indicator ratio to other quantitative data that are available across the basin (e.g., SSURGO parameters). Based on that relationship, EPA would have a data-driven basis for identifying eroding reaches across the basin without having to rely solely on SWAT model results to predict stream channel loads.

NRCS staff developed the Streambank Scour Erosion Susceptibility methodology for the Missisquoi Areawide Plan as a way to predict the susceptibility of streambanks to scour erosion by floodwaters. The methodology uses detailed digital soil data to map susceptible soils and ranks them on a scale of 0-1 based on how they compare to a set of criteria. Tetra Tech calculated the streambank scour susceptibility rating (susceptibility rating) for all soils in the Vermont portion of the Lake Champlain Basin using these criteria (Table 16). The resulting rating allows for inferring susceptibility to erosion.

Table 16. Streambank scour susceptibility ratings for soils

FUZZY RATING	SOIL TYPE	CRITERIA
1	alluvial parent material EXCEPT very poorly drained OR poorly drained	PARENT = A AND (HYDROGROUP <> C or HYDROGROUP <> D)
0.85	particle size class = sandy or sandy-skeletal OR loamy-skeletal OR anything over sandy-skeletal	TAXPARTSIZE = sandy or sand-skeletal OR TAXPARTSIZE = loamy-skeletal OR TAXPARTSIZE = anything over sandy-skeletal
0.6	particle size class = coarse-silty OR sandy over loamy OR loamy over clayey	TAXPARTSIZE = coarse-silty OR TAXPARTSIZE = sandy over loam OR TAXPARTSIZE = loamy over clayey
0.5	E slope with densic contact OR E slope with clay soils	HYDROGROUP = C OR D WITH SLOPELOW > 25%
0.4	particle size class = coarse-loamy NOT alluvial parent material NOT with a densic contact	TAXPARTSIZE = coarse-loamy AND PARENT <> A
0.4	densic contact OR clay soils, NOT E slope	HYDROGROUP = C OR HYDROGROUP = D AND SLOPELOW < 25%
0.2	shallow OR moderately deep to bedrock (would include moderately deep to deep)	ROCKSHALLOW < 60
0.05	very poorly drained mineral or organic soil OR very shallow to bedrock	HYDROGROUP = D OR ROCKSHALLOW < 40
0	rock outcrop (water would get 0.000, too)	WATER OR ROCK OUTCROP

Notes:

- If a soil had more than one fuzzy rating, depending upon the criteria set above, the maximum value of fuzzy rating was chosen.
- If a soil was classified as water or rock outcrop, it was always a given a fuzzy rating of 0.
- Ideally densic contact would be determined using the *featkind* attribute in the *codiagfeatures* table of the SSURGO database. Since the codiagfeatures table was blank for all SSURGO areas in Vermont, it was assumed that no soils in the Vermont portion of the Lake Champlain Basin have a densic contact.

For the streams having Phase II data, all soils within a 100-foot buffer of the streams were selected. The susceptibility ratings of these soils were then compared to the ratio of eroding area to channel length. The relation between the two datasets is best described using a second-order polynomial, as depicted in Figure 7.

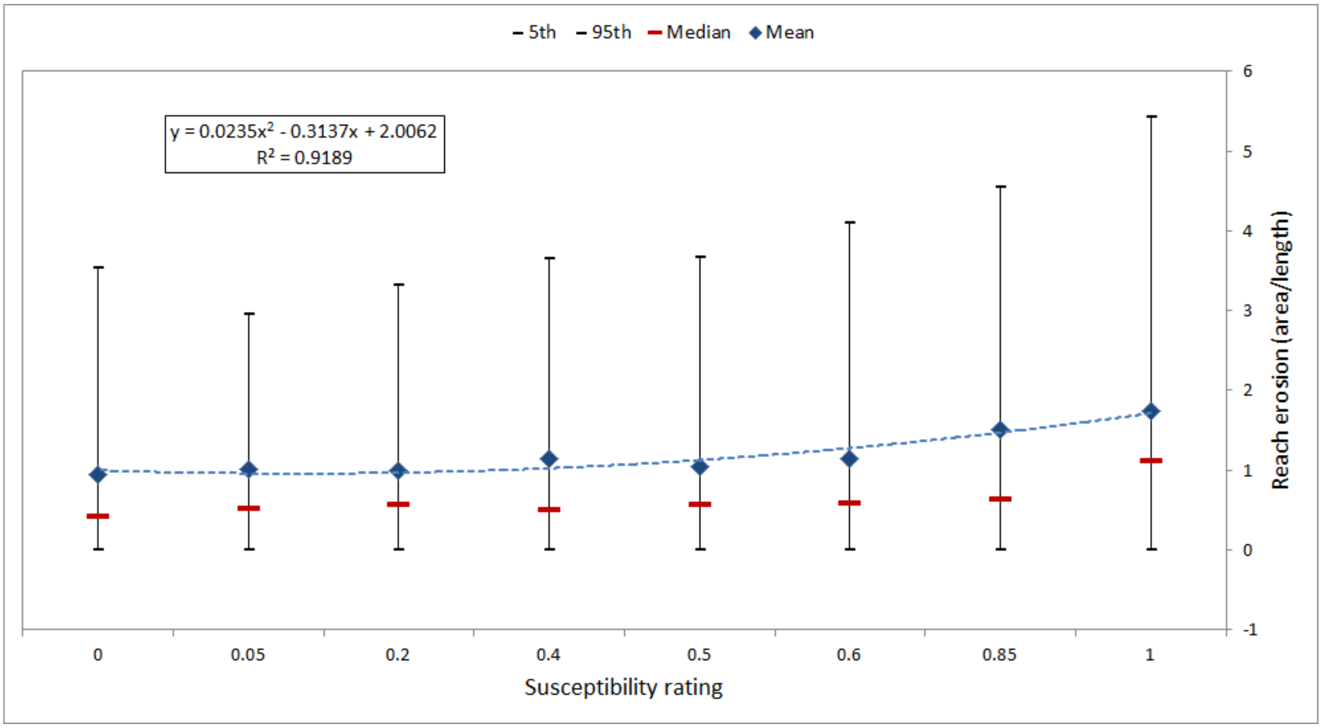

Figure 7. Mean, median, 5th and 95th percentile erosion indicator ratio for susceptibility rating classes, and relationship between erosion indicator ratio and susceptibility rating.

The next step involved establishing the upland erosion-to-channel erosion relationships across the basin using predicted channel sediment proportions from the Missisquoi CSA model and the calculated susceptibility rating. A susceptibility rating of 0.6 was calculated for the Missisquoi Basin. On the basis of the CSA model prediction that 41 percent of total loading is from channel sources, it was assumed that a susceptibility rating of 0.6 should correspond to a channel erosion proportion of 41 percent in the Missisquoi Basin. Next, upland and channel erosion proportions for the rest of the basins were determined by applying this relationship to the calculated susceptibility ratings and predicted SWAT loads.

An area weighted net susceptibility rating was determined for all the major drainages in the Vermont portion of the Lake Champlain Basin (Table 17).

Table 17. Susceptibility rating for the major drainages flowing into Lake Champlain

Drainage	Susceptibility rating
Missisquoi River	0.602
Winooski River	0.577
Lamoille River	0.627
Otter Creek	0.588
Poultney River	0.707

Note: The Mettawee River was not included in the susceptibility analysis because a very small fraction of the watershed lies in Vermont.

The area-weighted susceptibility ratings for all the drainages are fairly similar, suggesting that similar *potential* for bank erosion exists in all the major drainages in the Lake Champlain Basin. If the above relationship applied, these results would suggest that all the basins could be expected to have similar fractions of upland and channel sediment loads. This is not likely. For example, given the presence of known wetlands in the Otter Creek watershed, it is highly improbable that the amount of sediment coming from the channel sources is comparable to that of the Missisquoi River. Although susceptibility is an important predictor of erosion, the actual amount of channel erosion is largely governed by the excess shear stresses acting on the bank and bed. Therefore, susceptibility rating alone is not adequate for estimating erosion.

In the absence of any observed data on the proportion of sediment and phosphorus loads from upland and channel sources, Tetra Tech relied exclusively on the calibrated SWAT model for estimates of upland and channel load. The total SWAT estimated channel erosion load generated at the HUC8 level was distributed to its HUC12 subbasins based on their relative susceptibility rating. This ensures that a HUC12 subbasin having a high susceptibility rating has a higher channel erosion per unit length than one having a lower rating. Figure 8 shows the results of this procedure conducted for the Missisquoi River SWAT model developed by Tetra Tech.

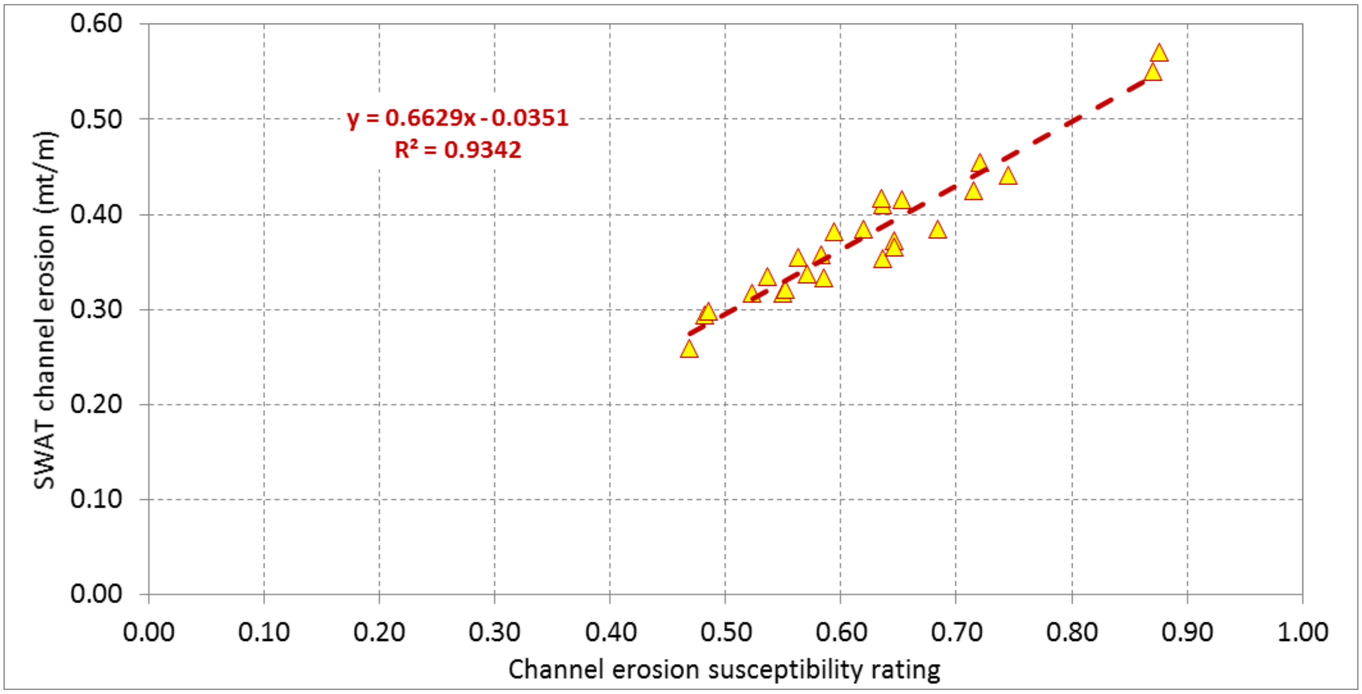

Figure 8. Adjustment of SWAT-simulated channel erosion relative to the channel erosion susceptibility rating (Missisquoi River watershed).

The proportion of sediment and phosphorus by upland and channel sources as simulated by the SWAT models are provided in Appendices C–K by major basin.

Water Quality Simulation

Phosphorus is the constituent of interest in this modeling effort. While nitrogen was also simulated, calibration/validation was only performed for phosphorus. The different processes associated with phosphorus cycle modeled by SWAT at the HRU are depicted in Figure 9.

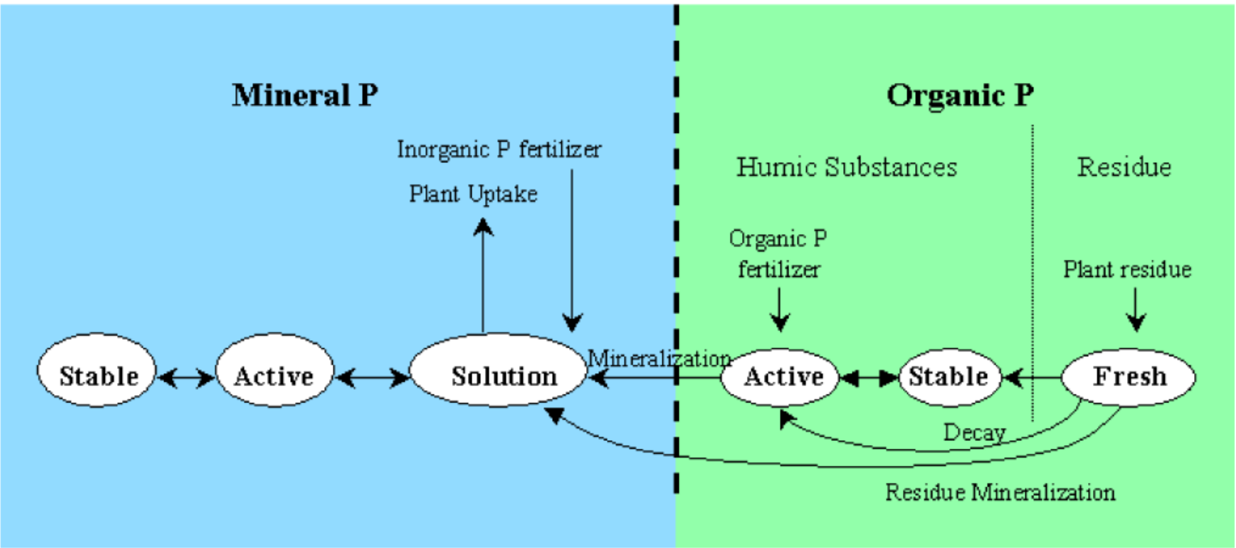

Figure 9. Phosphorus cycle processes simulated by the Lake Champlain SWAT models

Phosphorus is added to the system via residue decomposition and fertilizer application. Phosphorus is lost from the system by plant uptake, in water flow (in soluble and organic forms) from soil matrix, and by association with sediment.

In the channel, phosphorus is generated by algal death and lost via settling in reaches and consumption by algae. Sediment bound phosphorus may be generated in the channel system due to erosive processes associated with stream bed and bank.

SWAT Model Calibration and Validation

A separate SWAT model was configured for each of the HUC8 watersheds to facilitate the calibration and validation process. Calibration refers to the adjustment or fine-tuning of model parameters to reproduce observations within acceptable levels of agreement. Following calibration, a validation test is conducted by applying the calibrated model to a second period of data not used in the calibration. This section of the report presents the process used to calibrate the model for both hydrology and water quality. Results are provided for individual HUC8 watersheds in Appendices C–K.

Hydrology Calibration and Validation

Hydrologic calibration and validation focused on the periods of 2000–2010 and 1990–2000, respectively. Calibration and validation were completed by comparing time-series model results to gaged daily average flow. Key considerations in the hydrology calibration were the overall water balance, the high-flow to low-flow distribution, storm flows and seasonal variation. Two criteria for goodness of fit—graphical comparison and the relative error method—were used for calibration. Graphical comparisons are extremely useful for judging the results of model calibration; time-variable plots of observed versus modeled flow provide insight into the model's representation of storm hydrographs, baseflow recession, time distributions and other pertinent factors often overlooked by statistical comparisons. The model's accuracy was assessed primarily by interpreting the time-variable plots. The relative error method was used to support the goodness-of-fit evaluation through a quantitative comparison. A small relative error indicates a better goodness of fit for calibration.

Models are deemed acceptable when they can simulate field data within predetermined statistical measures. Tetra Tech used a hydrologic calibration spreadsheet to determine the acceptability of modeling results on the basis of statistical criteria set out in the Quality Assurance Project Plan (Tetra Tech 2012). The spreadsheet computes the relative error for various aspects of the hydrologic system. Statistical targets developed and implemented in previous studies (Lumb et al. 1994) are defined and met for each aspect of the system before accepting the model. The following criteria were used to judge the quality of calibration (Table 18). These criteria have subsequently been widely adopted as targets for modeling (see Duda et al. 2012).

Table 18. Target calibration criteria

Statistic	Criteria
Error in total volume	≤ 10%
Error in 50% lowest flows	≤ 10%
Error in 10% highest flows	≤ 15%
Seasonal volume error (summer)	≤ 30%
Seasonal volume error (fall)	≤ 30%
Seasonal volume error (winter)	≤ 30%
Seasonal volume error (spring)	≤ 30%
Error in storm volumes	≤ 20%
Error in summer storm volumes	≤ 50%

In addition, the Nash-Sutcliffe efficiency (NSE) coefficient (Nash and Sutcliffe 1970) was calculated at each calibration location. The NSE is an indicator of a model's ability to predict about the 1:1 line. Values may vary from $-\infty$ to 1.0. A value of $E = 1.0$ indicates a perfect fit between modeled and observed data; values equal to or less than 0 indicate the model's predictions are no better than using the average of observed data. The closer the value is to 1.0, the more accurate the model.

An overall assessment of the success of the calibration can be expressed using calibration levels:

- Level 1: Simulated values fall within the target range (highest degree of calibration).
- Level 2: Simulated values fall within two times the desired range of the calibration target.
- Level 3: Simulated values fall within three times the desired range of the calibration target.
- Level 4: Simulated values are greater than four times the desired range of the calibration target (lowest degree of calibration).

Figure 10 shows the location of USGS flow stations used for hydrology calibration and validation in the Lake Champlain Basin.

The calibration and validation at each flow monitoring location consisted of three broad steps:

1. Total flow balance
2. Surface runoff and baseflow balance
3. Seasonal flow balance.

The above steps were repeated unless the calibration was deemed satisfactory.

Total flow balance consisted of minimizing the error between observed and simulated flow for the calibration period. This was achieved by changing the soil evaporation compensation factor (ESCO) and the curve number for moisture condition II (CN2) from their default values. The calibrated values of ESCO ranged between 0.8 and 1.0 for the SWAT models. The final values of CN2 were within a range of ± 4 of their default values. Changes made to CN2 affect the surface runoff volume as well. The total flow volume was also adjusted by introducing a precipitation lapse rate (PLAPS) for subbasins with significant elevation changes.

Once the total flow balance was acceptable, the surface runoff and baseflow components were calibrated. Surface runoff was calibrated by varying the surface runoff lag factor (SURLAG), Manning’s n value for tributary channels (CH_N1), and Manning’s n value for the main channel (CH_N2). SURLAG was set at a value of 0.5 for the watershed models. The final value of CH_N1 varied between 0.1 and 0.3, and that of CH_N2 between 0.01 and 0.1. It should be noted that a value of 0.01 is unreasonably low for natural channels and was used only for the Little Ausable River. This value, although low, was necessary to reproduce the observed high flow characteristics at the USGS gage.

Baseflow was calibrated by modifying the values of ground water delay (GW_DELAY) and baseflow alpha factor (ALPHA_BF). The calibrated value of GW_DELAY varied between 1 and 40 days. The final value of ALPHA_BF was 0.9. The parameter GW_DELAY impacts the timing and magnitude of baseflow. The large variability in the final values of GW_DELAY were required to address the large variability in low flow characteristics observed across the HUC8 watersheds in the Lake Champlain basin. The lateral flow volume was adjusted by changing the values of lateral flow travel time (LAT_TTIME) and hillslope length (SLSOIL). Calibrated values of LAT_TTIME and SLSOIL varied between 30 and 90 days and between 100 and 150 meters, respectively. Ground water and lateral flow magnitudes and timing were also informed by visual inspection of the observed hydrograph.

The final step consisted of ensuring that the seasonal flow balances were within acceptable error ranges. Adjustments for total flow, runoff and baseflow volumes, and timing generally ensured that the seasonal flow errors were acceptable. Further adjustments were required for winter and spring volumes because of the significant impacts of snow in the basin. Calibration during the winter and spring months consisted of matching the timing and magnitude of snowmelt peaks. The temperature lapse rate (TLAPS) had significant impacts on the timing and magnitude of snowmelt. The calibrated value of TLAPS varied between 0 and 5 deg C/km. The lapse rate is largely a function of atmospheric conditions and is not expected to vary dramatically between watersheds although some variation is expected with aspect that may affect the relationship between individual observation point and the surrounding watershed. A summary of the parameters used in the hydrology calibration and their final values are summarized in Table 19 and Table 20.

Table 19. Hydrology calibration - parameter values

Watershed	ESCO	CH_N2	CH_N1	TLAPS	GW_DELAY	LAT_TTIME	SLSOIL
Mettawee/Poultney	1.65	0.045	0.250	-3	23	53	100
Otter	0.95	0.051	0.250	-1	25	30	100
Lamoille	1	0.046	0.200	0	20	30	50
Winooski	1	0.031	0.200	0	24	75	50
Missisquoi	1	0.036	0.100	-2	5	60	100
Ausable	0.9	0.018	0.093	0	5	65	100
Saranac	0.9	0.080	0.267	0	37	64	93
Lake Champlain	4.8	0.038	0.144	-1	6	54	111

Table 20. Summary of calibrated values of initial moisture condition II curve numbers* by landuse and hydrologic soil group

Landuse	A	B	C	D
Generic Agriculture	67	78	85	89
Corn	67	77	83	87
Corn-Hay	49	68	78	83
Farmstead, Medium/Large	49	69	79	84
Farmstead, Small	49	69	79	84
Hay	31	59	72	79
Pasture	49	69	79	84
Residential (including driveways)	48	67	78	83
Commercial/Industrial	49	67	77	82
Road, Paved	49	69	79	84
Road, Unpaved	49	69	79	84
Forest	34	61	74	80
Grass/Shrub	42	65	74	80
Wetland	45	66	77	83

*Impervious fractions of residential, commercial/industrial, paved roads and unpaved roads have curve number of 98

In addition to applying these criteria, the goodness of fit of the models was also evaluated using the daily Nash-Sutcliffe Model Efficiency values, as noted above. Although the values varied some from basin to basin (as depicted in appendices C–K), the E value was between 0.5 and 1.0 for the vast majority of basins, indicating a fairly high level of model accuracy. The basins with E values below 0.5 were only slightly below 0.5, indicating a reasonably good fit for those basins as well. Table 21 shows the daily and monthly NSE values for the flow gages used for calibration and validation in the Vermont portion of the watershed.

Table 21. Daily and Monthly NSE values for flow gages in the Vermont portion of the watershed

Location	Calibration		Validation	
	Daily - NSE	Monthly - NSE	Daily - NSE	Monthly - NSE
USGS 04282795 LaPlatte River at Shelburne Falls, VT	0.496	0.653	0.430	0.550
USGS 04282780 Lewis Creek at North Ferrisburg, VT	0.547	0.672	0.522	0.599
USGS 04282650 Little Otter Creek at Ferrisburg, VT	0.521	0.631	0.468	0.563
USGS 04280350 Mettawee River near Pawlet, VT	0.459	0.546	0.568	0.731
USGS 04287000 Dog River at Northfield Falls, VT	0.623	0.789	0.503	0.624
USGS 04286000 Winooski River at Montpelier, VT	0.644	0.848	0.536	0.704
USGS 04288000 Mad River near Moretown, VT	0.571	0.638	0.576	0.723
USGS 04290500 Winooski River near Essex Junction, VT	0.688	0.856	0.603	0.820
USGS 04282000 Otter Creek at Center Rutland, VT	0.577	0.601	0.724	0.844
USGS 04282525 New Haven River @ Brooksville near Middlebury, VT	0.500	0.652	0.426	0.459
USGS 04282500 Otter Creek at Middlebury, VT	0.610	0.726	0.714	0.838
USGS 04280000 Poultney River below Fair Haven, VT	0.525	0.634	0.500	0.680
USGS 04293000 Missisquoi River near Troy, VT	0.491	0.627	0.460	0.696
USGS 04293500 Missisquoi River near East Berkshire, VT	0.577	0.665	0.556	0.735
USGS 04294000 Missisquoi River at Swanton, VT	0.675	0.782	0.564	0.747
USGS 04292000 Lamoille River at Johnson, VT	0.620	0.747	0.610	0.798
USGS 04292500 Lamoille River at East Georgia, VT	0.618	0.726	0.596	0.690

Overall, the calibration and validation process met most of the criteria set out. Some criteria, however, were exceeded, which generally puts the assessed quality of calibration and validation between levels 1 and 2. The most frequent exceedances were for the summer seasonal volume error. For purposes of this project, which is focused on annual load estimates, these seasonal exceedances are not a significant concern given that the criteria for error in total volume and storm volumes are never exceeded in any of the watersheds. Appendices C–K provide error statistics for each calibration gage for both the calibration and validation periods.

It is evident from the calibration and validation results that the summer flow volumes are consistently over-represented in the SWAT models. A closer investigation into the observed and simulated flows revealed that the bulk of the over-representation is due to a higher-than-observed baseflow (Table 22).

Table 22. Average observed and simulated seasonal baseflow, runoff and total flow volumes (cfs) at USGS 04294000 Missisquoi River at Swanton, VT, from 10/1/2000 to 9/30/2010

Season	Baseflow (obs)	Baseflow (sim)	Error	Runoff (obs)	Runoff (sim)	Error	Total (obs)	Total (sim)	Error
Summer	440	739	**68.0%**	532	549	**3.0%**	972	1288	**32.4%**
Fall	992	966	**-2.7%**	951	674	**-29.1%**	1943	1640	**-15.6%**
Winter	1061	702	**-33.9%**	652	643	**-1.5%**	1713	1344	**-21.5%**
Spring	1661	1999	**20.4%**	1297	939	**-27.6%**	2958	2939	**-0.7%**

SWAT is primarily a rainfall-runoff model; it does not have a robust representation of ground water processes. However, the pollutant of concern in this modeling study is phosphorus. The fate and transport of phosphorus are largely dominated by the runoff component of watershed hydrology, and over-representation of the baseflow component is not necessarily a significant issue. Moreover, because the effectiveness of a best management practice (BMP) is calculated as the relative change in pollutant load with respect to the calibration condition, biases in seasonal flows are not expected to have minimal impacts on the efficiencies of the modeled BMPs.

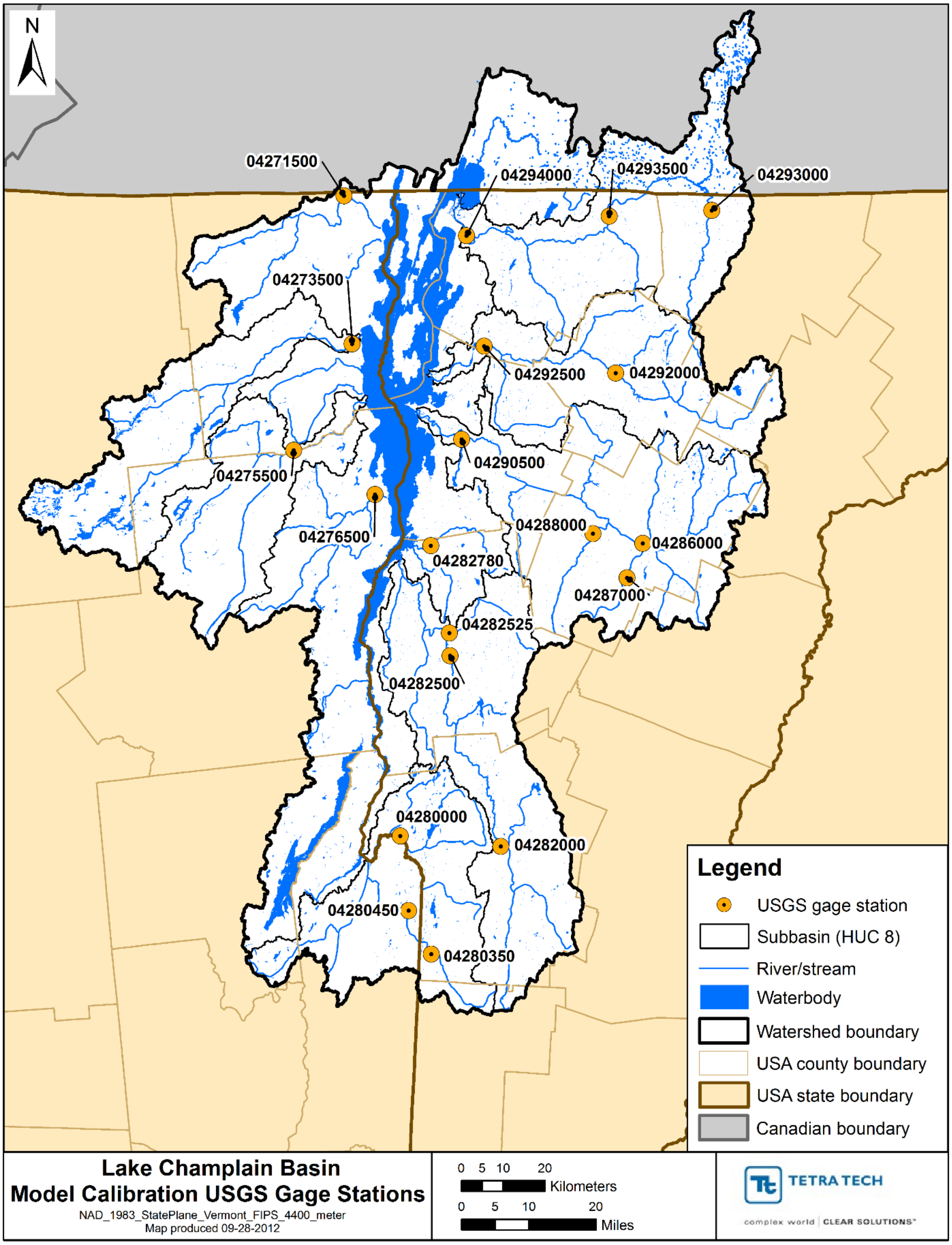

Figure 10. USGS hydrology calibration/validation locations.

Water Quality Calibration and Validation

Water quality calibration and validation focused on the periods of 2000–2010 and 1990–2000, respectively. Tetra Tech adopted a monthly regression approach for water quality calibration and validation. Simulated total suspended solids (TSS) and total phosphorus (TP) loads were compared to regression loads.

Consistent with the recommendations of Moriasi et al. (2007) and with the approach outlined in the project quality assurance project plan (Tetra Tech 2012), SWAT water quality calibration focused on replicating monthly loads. Comparison of model results to monthly loads presents challenges because monthly loads are not observed. Instead, monthly loads must be estimated from scattered concentration grab samples and continuous flow records. As a result, the monthly load calibration is inevitably based on comparing two uncertain numbers.

The Lake Champlain Basin Program has operated water quality monitoring stations for major tributaries draining into the lake since 1990 (Table 23 and Figure 11). The frequency of data collection for TSS and TP at these locations is one or two observations per month. TSS and TP loads usually exhibit a strong positive correlation to flow (and associated erosive processes). Accordingly, Tetra Tech estimated TSS and TP loads from observations using a flow-stratified log-log regression approach, consistent with the discussion by Preston et al. (1989), and compared to modeled loads.

Table 23. Tributary monitoring stations

Tributary stations	Latitude	Longitude
Winooski (WINO01)	44° 31.52'	73° 15.41'
Otter (OTTE01)	44° 09.94'	73° 15.40'
Missisquoi (MISS01)	44° 55.23'	73° 07.63'
Lamoille (LAMO01)	44° 37.96'	73° 10.39'
Poultney (POUL01)	43° 34.24'	73° 23.53'
Pike (PIKE01)	45° 07.38'	73° 04.18'
Lewis (LEWI01)	44° 14.80'	73° 14.77'
Little Otter (LOTT01)	44° 12.24'	73° 15.11'
LaPlatte (LAPL01)	44° 22.21'	73° 13.01'
Saranac (SARA01)	44° 41.52'	73° 27.19'
Ausable (AUSA01)	44° 33.63'	73° 26.95'
Mettawee (METT01)	43° 33.33'	73° 24.10'
Great Chazy (GCHA01)	44° 58.81'	73° 25.96'
Bouquet (BOUQ01)	44° 21.84'	73° 23.41'
Little Ausable (LAUS01)	44° 35.65'	73° 29.79'
Salmon (SALM01)	44° 38.40'	73° 29.70'
Putnam (PUTN01)	43° 57.35'	73° 25.99'
Little Chazy (LCHA01)	44° 54.12'	73° 24.88'
Rock River (ROCK02)	44° 59.49'	73° 04.22'
Stevens Brook (STEV01)	44° 50.95'	73° 07.15'
Jewett Brook (JEWE02)	44° 51.37'	73° 09.06'
Mill River (MILL01)	44° 46.46'	73° 08.39'

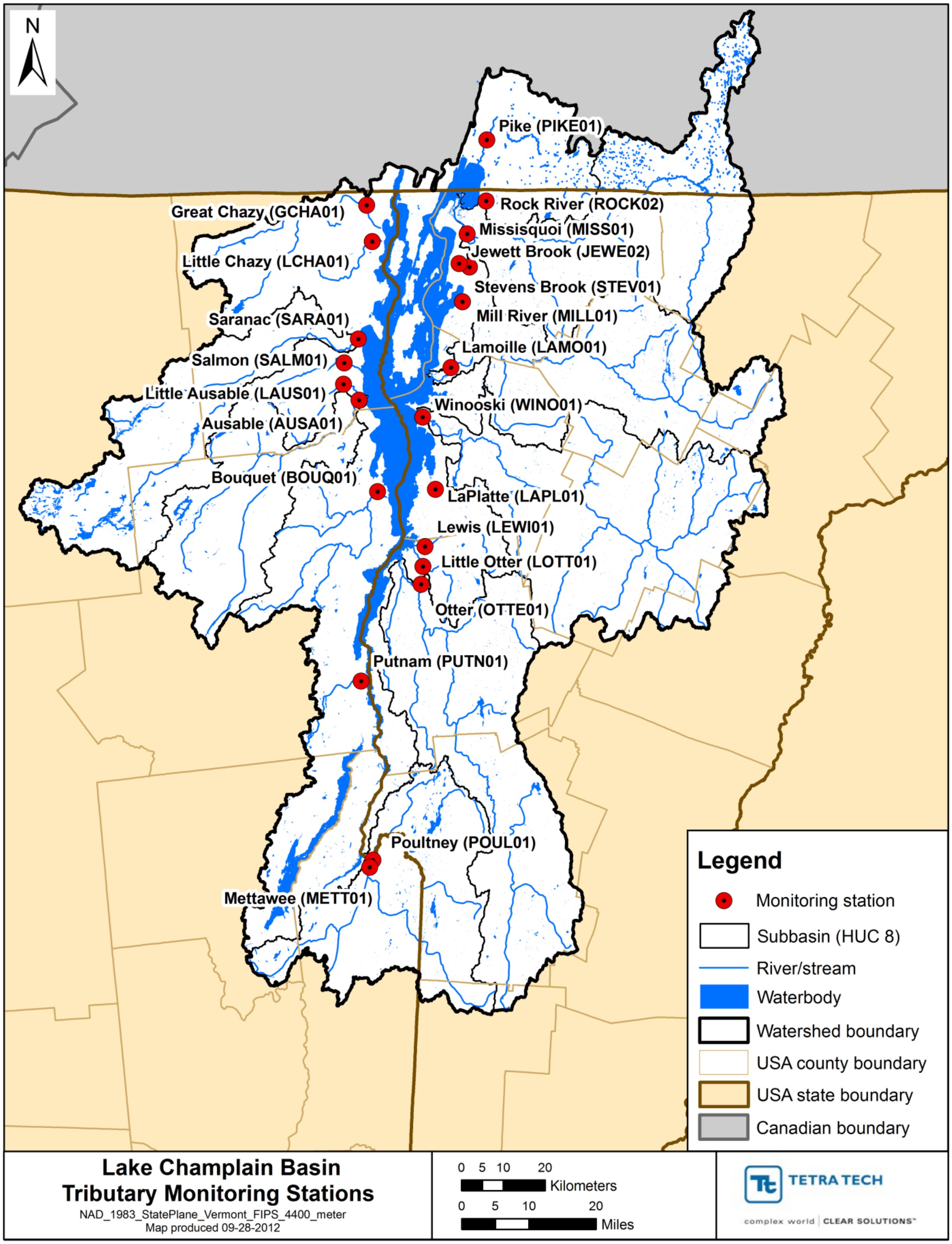

Figure 11. Lake Champlain Basin Program tributary monitoring locations used in water quality calibration/validation.

The flow-stratified segmented regression approach uses different functions to fit TSS and TP data over varying ranges of flow. The change from low rates to high rates of sediment transport occurs at a *breakpoint*, which is defined as the flow where the fitted functions intersect. The model used here fits linear segments on a log-log scale. The transition phase is identified by visually inspecting the plot of TSS or TP load against flow on a log-log scale.

The regression method of load estimation is discussed in further detail for TP for the Missisquoi River. Figure 12 shows the regression model for TP for the Missisquoi River.

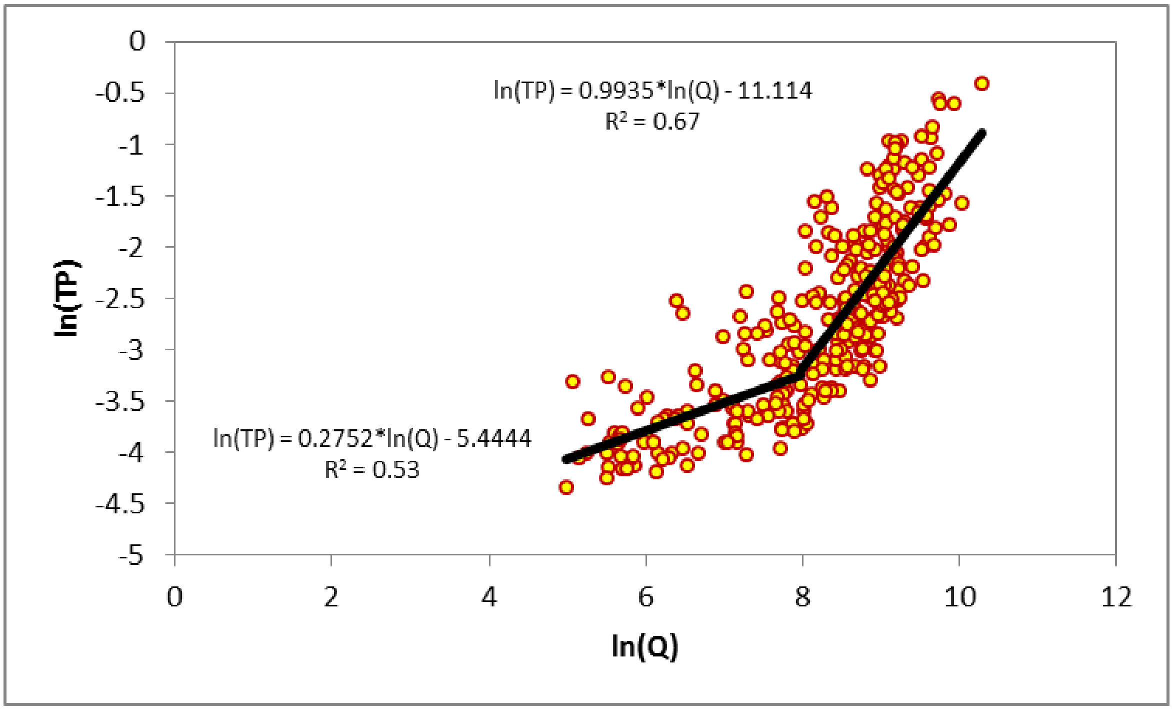

Figure 12. Flow-stratified log-log regression of TP vs. flow.

The breakpoint flow for the stratified regression model above is 2882 cfs. Below 2882 cfs, TP concentration in mg/L is calculated using the equation ln (TP) = 0.2752 * ln (Q) – 5.4444. Above 2882 cfs, TP concentration is calculated using the equation ln (TP) = 0.9935 * ln (Q) – 11.114. Daily concentration and loads were calculated using the regression models and summed to a monthly time-step. The monthly loads were then compared to SWAT-simulated loads. Similar regression models were constructed for TSS and TP for all the water quality calibration and validation locations.

Figure 13 shows the regression residuals versus flow and time, respectively. As evident, the residuals do not exhibit a significant bias, and hence the same regression model was deemed applicable for the entire modeling time period. It is important to note that Figure 13 is intended to point out that the regression model itself does not have a flow or seasonal bias and is not intended to show the uncertainty or biases associated with the observed and simulated phosphorus loads.

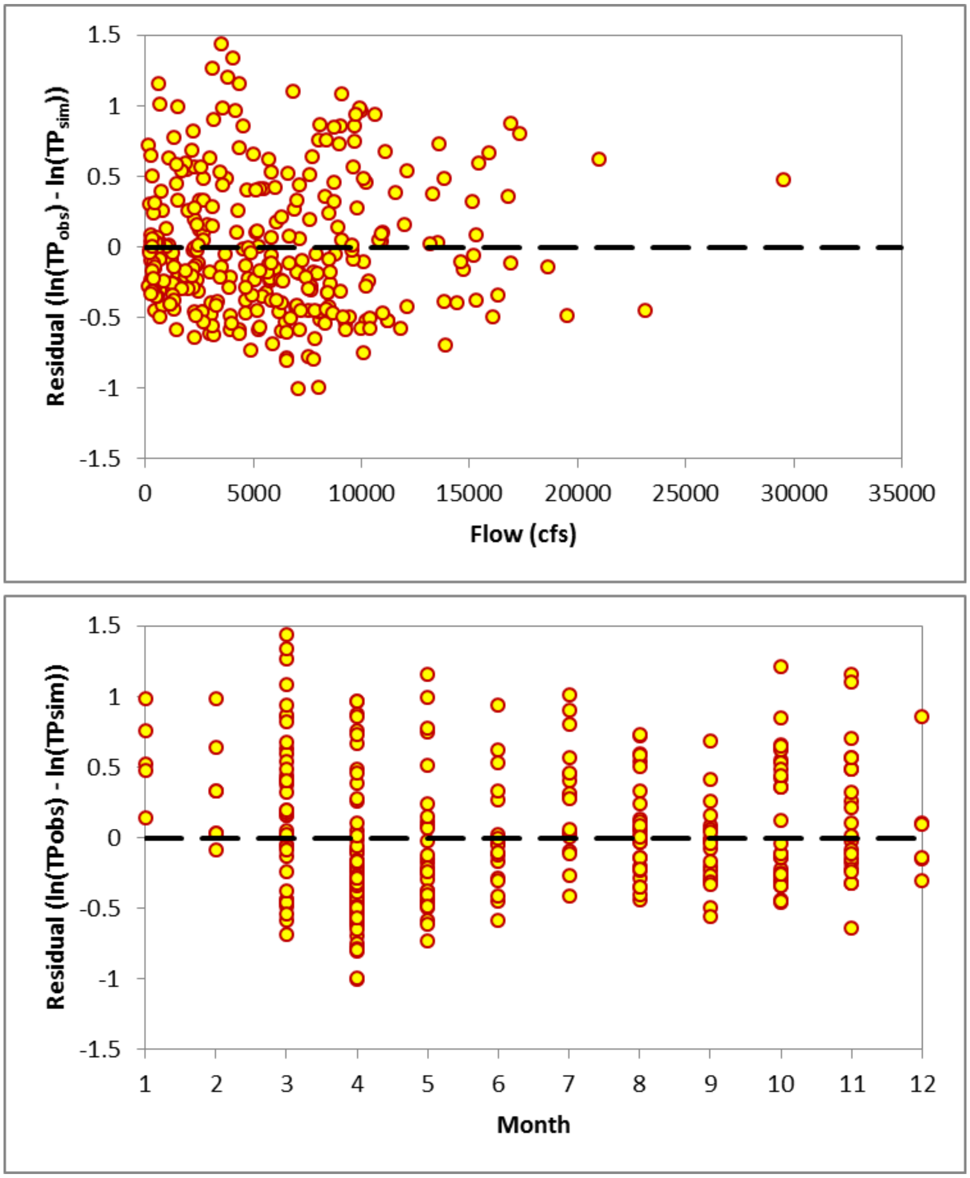

Figure 13. a) Regression residuals vs. flow; b) Regression residuals vs. time.

The load comparisons were supported by detailed examinations of the relationships of flows to loads and concentrations and the distribution of concentration prediction errors versus flow, time and season, as well as standard time-series plots. The key statistic is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions, was also calculated. That number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which could as easily be from uncertainty in the estimated load because of limited data as from problems with the model). The third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

In addition to comparing SWAT-simulated loads to regression loads as discussed above, comparisons were made with FLUX estimates of TP loads (Smeltzer et al. 2009; Medalie 2013). Smeltzer et al. (2009) carried out a detailed FLUX analysis to determine biannual (on a water year basis) TP loads to the lake from each tributary at the mouth and at the upstream USGS gage. The SWAT model daily TP loads were summed to biannual water years and directly compared to the FLUX estimates. The comparison was done by visually analyzing SWAT-predicted loads to FLUX loads using graphs and the percent difference between SWAT-simulated and FLUX-estimated loads. A similar comparison of SWAT-simulated loads was made with the recent FLUX-based estimates of TP loads (Medalie 2013). Results for each major tributary basin are presented in the calibration appendix for that basin (Appendices C–K).

The calibration and validation show reasonable agreement. The relative percent errors for TSS and TP were generally within 25 percent, which puts the calibration/validation success levels between good and very good.

A review of sediment loads by HRU revealed some HRUs with large values. These high HRU loads were generally produced because of very high slopes on some HRUs. For HRUs producing the highest unit area loads (generally greater than 50 mt/ha/yr and flagged by the SWAT Error Checker as excessive sediment load), the slope lengths were reduced to bring down the LS factor. Slope length is a suggested calibration parameter for sediment in SWAT. This approach did bring down the unit area sediment loads but had very little impact on the total load at the watershed scale. This is appropriate given that the objective of this modeling exercise is to have a reasonable estimate of watershed scale average annual loads by landuse. The model was not designed for accurate estimation of loads at the field scale.

In addition to calibrating at the Lake Champlain Basin Program water quality stations, Tetra Tech calibrated the average annual phosphorus export rates from upland areas by land use categories to literature values from studies in the general region (Artuso et al. 1996; Budd and Meals 1994; Stone Environmental 2011).

Table 24. Literature reported phosphorus export rate by landuse

Landuse	Mean Phosphorus Export rate (kg/ha/yr)
Forest	0.15
Urban	1.50
Unpaved Roads	6.0 (Beverly Wemple)
Agriculture	Table 3.4 of Missisquoi CSA SWAT Model Report (Stone Environmental 2010)

Forest and urban export rates are in general agreement across the literature. However, the export rates reported for agricultural land vary significantly across different studies. Artuso and Walker (1996) report mean export rates of 4.9 kg/ha and 5.5 kg/ha for manured row crops and manured pasture/hay, respectively. Budd and Meals (1994) report a mean export rate of 0.5 kg/ha/yr with a most common range of 0.25 to 0.81. Stone Environmental (2010) report export rates of 1.99, 2.10, 3.78 and 0.88 kg/ha for corn-hay, corn, soybean-corn and hay crops, respectively. In light of the variability in published data, it is difficult to enforce a mean export rate for the model for agricultural land. Tetra Tech adopted export rates developed by Stone Environmental (2010) since the Tetra Tech effort to model the Lake Champlain basin used SWAT and similar assumptions as used in the Missisquoi CSA SWAT model.

The water quality calibration first focused on calibration for sediment and then on phosphorus. The values associated with parameters listed below were adjusted during sediment calibration. Table 24 summarizes the calibrated values of these parameters by each HUC8 watershed.

- PRF - Peak rate adjustment factor for sediment routing in the main channel
- SPCON - Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing
- SPEXP - Exponential parameter for calculating sediment re-entrained in channel sediment routing
- CH_COV1 - Channel erodibility factor
- CH_COV2 - Channel cover factor

Table 25. Sediment calibration - parameter values

Watershed	PRF	SPCON	SPEXP	CH_COV1	CH_COV2	CH_OPCO
Mettawee/Poultney	2.9	0.0002	3.5	2.264	1.000	1014
Otter	1.05	0.0001	2	3.016	3.029	950
Lamoille	0.65	0.0001	2	2.051	2.077	775
Winooski	1.35	0.0002	2	1.935	2.875	740
Missisquoi	1.3	0.0001	2	2.490	5.160	479
Ausable	0.43	0.0001	2	1.642	3.913	404
Saranac	0.6	0.0001	2	4.888	18.000	157
Lake Champlain	4.67	0.0006	9	2.593	2.471	546

The SWAT input variables associated with the phosphorus cycle are listed below. The default values associated with several of these parameters were adjusted during the calibration process.

- SOL_SOLP: Initial soluble P concentration in the soil layer (mg/kg)
- SOL_ORGP: Initial organic P in the soil layer (mg/kg)
- PSP: phosphorus availability index
- RSDIN: Material in the residue pool for the top 10mm of soil (kg/ha)
- SOL_BD: Soil bulk density (Mg/m^3)
- CMN: Rate coefficient for mineralization of the humus active organic nutrients
- RSDCO/ RSDCO_PL: Rate coefficient for mineralization of the residue fresh organic nutrients
- PPERCO: Phosphorus percolation coefficient (m^3/Mg)
- PHOSKD: Phosphorus soil partitioning coefficient (m^3/Mg)
- ERORGP: Phosphorus enrichment ratio

SWAT was allowed to initialize the soil phosphorus levels (SOL_SOLP and SOL_ORGP) in the model. The Lake Champlain SWAT model was run with an equilibration period of 1 year. According to the SWAT theoretical documentation, an equilibration period is recommended to get the hydrologic cycle fully operational. The equilibration period also allows the nutrient levels in soils to equilibrate making it unnecessary to initialize the soil nutrient levels.

RSDIN, CMN and RSDCO were left at their default values in the absence of better data for these parameters. The values of PSP, PPERCO and PHOSKD were treated as calibration parameters for the models at the watershed scale. Table 26 shows the calibrated values of these parameter in the watershed models.

Table 26. Phosphorus calibration - parameter values

Watershed	PSP	PPERCO	PHOSKD
Mettawee/Poultney	0.55	10	150
Otter	0.70	10	200
Lamoille	0.40	10	200
Winooski	0.70	10	200
Missisquoi	0.40	10	200
Ausable	0.40	10	200
Saranac	0.40	10	200
Lake Champlain	0.46	10	190

ERORGP was varied at the HRU level to calibrate landuse phosphorus generation rates. Table 27 shows calibrated average values of ERORGP by landuse in the watershed models.

Table 27. Average value of ERORGP by landuse

Landuse	ERORGP
Generic Agriculture	1.05
Corn	0.68
Corn-Hay	0.59
Hay	1.02
Pasture	0.64
Farmstead, Medium/Large	1.41
Farmstead, Small	1.04
Residential	0.95
Commercial/Industrial	0.89
Road, Paved	1.00
Road, Unpaved	1.00
Forest	0.21
Grass/Shrub	0.35
Wetland	0.43

The organic phosphorus in the channel (CH_OPCO) was also varied during the calibration process. Table 28 shows the calibrated value of CH_OPCO by each HUC8 watershed. The value for this parameter was guided by studies completed in the Lake Champlain basin on the concentration of phosphorus in sediment in stream channels. These studies have reported highly variable concentrations of total phosphorus in channel sediment ranging from approximately 500 mg/kg to as high as 3,500 mg/kg (Ross et al. 2011, USGS 1998).

Table 28. Average value of CH_OPCO by each watershed

Watershed	CH_OPCO
Mettawee/Poultney	1014
Otter	950
Lamoille	775
Winooski	740
Missisquoi	479
Ausable	404
Saranac	157
Lake Champlain	546

The water quality calibration results in Appendices C–K provide the mean, minimum, maximum and interquartile annual phosphorus export rates by land use category in each HUC8 watershed. The relative contribution of each land use to the total upland load by HUC8 watershed is also provided, as well as the proportion of upland-erosion-based to stream-channel-erosion-based loads. For each HUC8 watershed, scatter plots of HUC12 loads versus their respective channel erosion susceptibility rating are also provided.

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