EVALUATION OF VEGETATED FILTER STRIP IMPLEMENTATIONS IN DEEP RIVER PORTAGE-BURNS WATERWAY WATERSHED USING SWAT MODEL

by

Linji Wang

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Chandramouli V Chandramouli, Chair

Department of Mechanical and Civil Engineering

Dr. Chien-Chung Chen

Department of Mechanical and Civil Engineering

Dr. Jiliang Li

Department of Mechanical and Civil Engineering

Approved by:

Dr. Zhou Chenn

Head of the Graduate Program

To my parents, who supported me all along.

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ABSTRACT

Author: Wang, Linji. MSE
Institution: Purdue University
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Title: Evaluation of Vegetated Filter Strip Implementations in Deep River Portage-Burns Waterway Watershed Using SWAT Model
Committee Chair: Chandramouli V Chandramouli

In 2011, the Deep River Portage-Burns Waterway Watershed was identified as a priority in the Northwest Indiana watershed management framework by the Northwester Indiana Regional Planning Committee. 319 grant cost-share programs were initiated in effort of maintaining and restoring the health of Deep River Portage-Burns Waterway Watershed. A watershed management plans have been developed for this watershed which proposed the implementation of vegetated filter strips (VFS) as an option. In this thesis work, the effectiveness of VFS as a best management practice (BMP) for the Deep River system was evaluated using a hydrological model scheme.

In this research, a Nonpoint Source Pollution and Erosion Comparison Tool (NSPECT) model and a Soil Water Assessment Tool (SWAT) model were constructed with required watershed characteristic data and climate data. The initial hydrologic and nutrient parameters of the SWAT model were further calibrated using SWAT Calibration and Uncertainty Programs (SWAT_CUP) with historical flow and nutrient data in a two-stage calibration process. The calibrated parameters were validated to accurately simulate the field condition and preserved in SWAT model for effectiveness analysis of BMP implementations.

To evaluate the effectiveness of VFS as a BMP, four different scenarios of VFS implementations along the Turkey Creek was simulated with the calibrated SWAT model. With the implementation of VFS in the tributary subbasin of Turkey Creek, the annual total phosphorus (TP) of the VFS implemented subbasin was reduced by 1.60% to 78.95% and the annual TP of downstream subbasins were reduced by 0.09% to 55.42%. Daily percentage of TP reductions ranged from 0% to 90.3% on the VFS implemented subbasin. Annual TP reductions of the four scenarios ranged from 28.11 kg to 465.01 kg.

1. INTRODUCTION

Human activities and interferences negatively affect the health of the watershed. Nonpoint source pollutants such as nutrients are brought to the water system by human activities in both urban as well as rural watersheds which are dominated by agricultural lands. Non-point source pollutants are introduced to the water body due to the excessive use of fertilizers, herbicides, and insecticides. Watershed health is extremely crucial for the ecosystem. A healthy watershed can provide many ecosystem services to local area that benefit the environment and economy [1].

Contaminated creeks for various water quality constituents were delisted as contaminated creeks by the document 303(d) published by state agencies such as Indiana Department of Environmental Management. In northwest Indiana, many creeks were delisted [2]. Once a watershed is identified as contaminated watershed, sources of contamination should be identified, and best management practices are put in place to improve the water quality.

Thus, best management practices (BMP) are implemented in such area to optimize the nonpoint source pollutant and for keeping the watershed healthy. There are many best management practices available that can improve the water quality of a watershed such as two-stage ditch, parallel terrace, filter strips, etc. These BMPs used in watershed systems are expensive in both construction and maintenance. Understanding the possible improvements and the benefits by these schemes before the implementation will help users substantially.

This thesis work is an effort to examine the Deep River-Portage Burns Waterway Watershed. This watershed is located at the northwest region of Indiana. The watershed primarily consists of urban and agricultural lands from Lake and Porter Counties. Recently, a watershed management plan was drafted [3] and many BMPs were proposed in that document. Quantitative evaluation of proposed BMPs can be extremely beneficial for economic planning.

In this research study, a Soil Water Assessment Tool (SWAT) model was developed and calibrated using historical data. BMP is implemented to the model using suggested values from literatures. The benefits were captured to facilitate the filed users. Another simple model called Nonpoint

Source Pollution and Erosion Comparison Tool (NSPECT) model was also developed and fine-tuned to represent the filed condition. For demonstrative purposes, the usefulness of NSPECT model was also examined in this study.

2. REVIEW OF LITERATURE

To study the potential improvements achieved by the implementation of a BMP in a field condition, simulation models will be very useful. It helps us to understand the water quality status at different locations of the watershed. In this section, essential literature related to watershed rainfall runoff modeling, water quality modeling with best management practices were reviewed.

2.1 Watershed Health

A healthy watershed can benefit the local environment and economy in many ways. Barton et al. indicates the natural benefits such as natural preservation of water, climate stabilization, animal habitat, and recreational befits [4]. Nature also offers essential services such as water filtration, nutrient cycling and nice habitat for all living beings. The value of these services provided by healthy watersheds are often underestimated or ignored when making decisions that could harm watershed health according to the United States Environmental Protection Agency (USEPA) [1]. However, manmade activities which includes altering natural landscaping, agricultural activities, urban developments are essential for comfortable human survival and unavoidable.

2.2 Water Quality Criteria and Nutrients

Different water quality observations were made to assess the physical, chemical, and biological characteristics of water. Water quality criteria standards were established for different uses by USEPA [5] for various water quality constituents such as PH, dissolved solids, nutrients, and trace elements [6]. Among all the criteria, nutrients are closely related to the health of watersheds. It mostly comes from fertilizers applied to the agricultural lands and laws. Excessive nitrogen and phosphorus applications are brought to the creeks as watershed runoff during storm events as nonpoint source pollutants.

As essential nutrients, often nitrogen and phosphorus are instrumental to excessive weed growth and algae growth. Various diseases can occur to human when the concentration is high in drinking water [5].

2.3 BMPs

Artificial substitution is hard to construct and often come with an expensive price although it only replicates a fragment of the services provided by a healthy watershed [1]. It is more practical to implement best management practices to reduce the effect of human activities on the watershed and prevent the watershed health from being harmed [7]. The cost of BMPs are still expensive but rather cheaper than artificial substitutions of ecosystem [1].

Blanco-Canqui et. al. [8] examined the effectiveness of vegetative filter strips in reducing the sediment and nutrient loads. In that study, the grass barrier and vegetative filter strip Effectiveness in reducing the sediment, nitrogen, and phosphorus loss during runoff. Plots with filter strip replications were constructed for the research purpose. Natural rainfall events were simulated, and necessary data were collected in that study. The article concluded that the effectiveness of the filter strip as a BMP increased with the width of the filter strip but effects beyond 4 m were not showing substantial improvements.

The two-stage ditch is another effective BMP which can provide phosphorus and suspended sediment load reduction. Hodaj, et al. [9] studied the two-stage ditch. In that study, a two-stage ditch was constructed at a selected site and a series of monitoring and sampling was conducted at Lafayette, Indiana. They completed a series of monitoring and sampling. This study concluded that the two-stage ditch can reduce the total phosphorus and suspended sediment loads by up to 65% but has a non-significant reduction on nitrate load.

2.4 Modeling

Watershed Models including Soil Water Assessment Tool (SWAT), Nonpoint Source Pollution and Erosion Comparison Tool (NSPECT), Generalized Watershed Loading Function(GWLF), Integrated Catchment Model (INCA), Agricultural Non-Point Source Pollution Model (AGNPS), Hydrological Simulation Program – FORTRAN (HSPF), and Hydrologiska Byråns Vattenbalansavdelning Model (HBV) [10] have been extensively used in the researches of hydrological, environmental, and agricultural studies for numerous tasks. Different types of models utilize different method of spacing, streamflow generation, sediment transport, and nutrient cycling [11]. They are also widely applied in research and studies for establishing scientific measures for management plans of nonpoint source pollution. SWAT is the most commonly used model for such application [10].

SWAT model was developed by Arnold et. al. [12] to assist the assessment of best management, water quality, nonpoint source pollutant in a continuous time simulation manner. It is developed for water quality modeling tasks such as nonpoint source pollutant estimation and evaluation of the effect of land-use changes are completed using watershed models. In addition to the model setup, to successfully model the behavior of a watershed using SWAT, two stage calibration process is required followed by validation using historical data [13].

Niraula et.al [14] developed a SWAT model and a GWLF model for the east-central Alabama watershed to identify the critical source areas of sediment and nonpoint source pollutants for finding the most cost-effective management practices implementation. The research results indicated that the performance of SWAT model was slightly better than the GWLE model in sediment and nutrient simulation and prediction.

Many research studies utilized SWAT model as a tool to evaluate the effectiveness of best management practices of a targeted watershed [15, 16, 17, 18, 19, 20]. Christopher et. al. [21] modeled the nutrient removal of two-stage ditch under a watershed-scale implementation. In that study, empirical data from the monitoring of multiple ditches was used and the relationship for nitrogen and prosperous reduction was found. This relationship was applied to the SWAT model and the simulated result shows the capability of two-stage ditches to improve the water quality.

Gungor et. al [22] conducted a study to quantify the nutrient transport dynamics of a previously ungauged watershed containing a shallow eutrophic lake. A SWAT model was developed and used to establish the baseline nutrient dynamics. Their research suggests to not use dry weather data alone in the model as the model calibrated with dry weather data had limitations on the prediction of wet period.

This literature review indicates the usefulness of using SWAT model and its effectiveness to examine the BMPs. The importance of watershed health and ecosystem can be assessed by modeling the water quality using this user-friendly tool [12, 14, 21]. BMPs can be implemented to a watershed to protect the watershed by reducing the pollution load generated by human activities. Modeling of the BMP implementations and evaluation of the improvements prior to construction can be achieved with SWAT modeling.

3. SYSTEM CONSIDERED

3.1 Deep River-Portage Burns Waterway Watershed

3.1.1 Watershed Inventory

The Deep River-Portage Burns Waterway Watershed (Figure 3.1) is located at the northwest Indiana. The watershed primarily consists of urban and agricultural lands from both Lake and Porter Counties. It has a drainage area of approximately 180 square miles. The outlet of this entire watershed drains to the Lake Michigan on its north side through Burns Ditch.

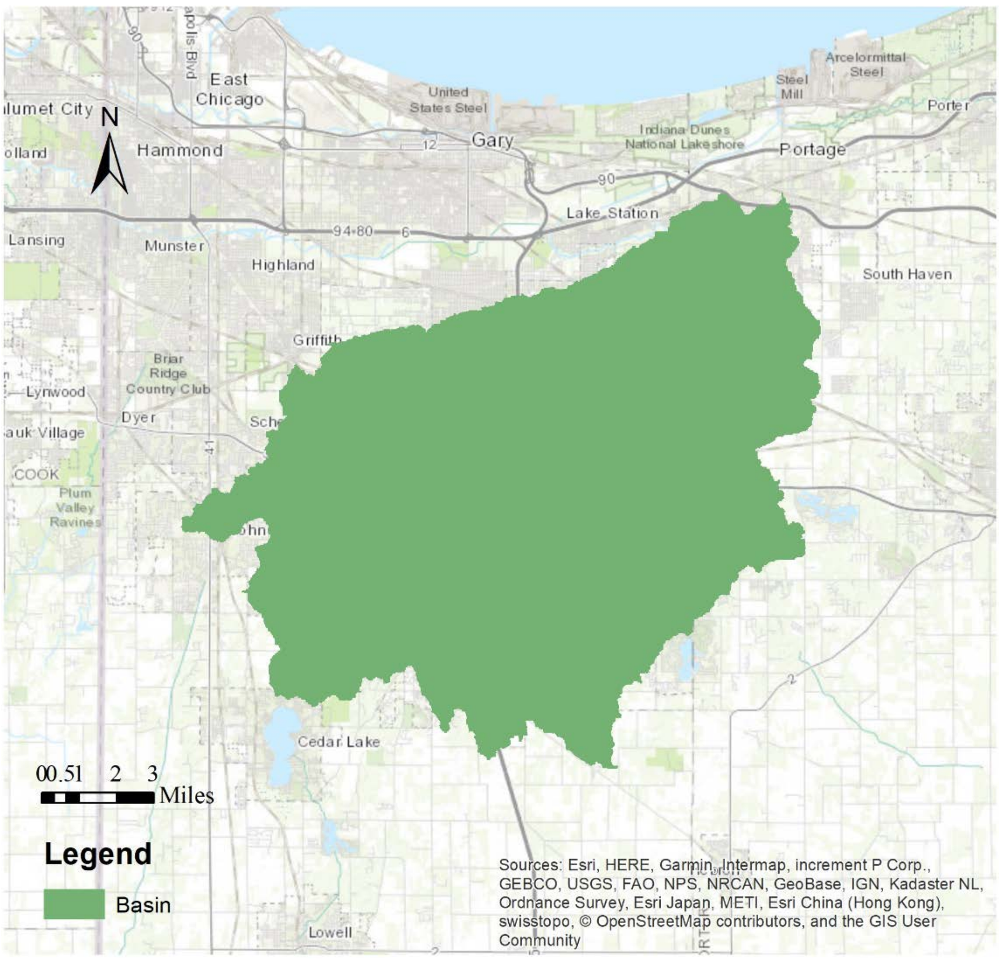


Figure 3.1 Deep River Portage Burns Waterway Watershed Geographical Location

The land use and land cover of the deep river watershed is primarily urban land (37.891%) followed by agricultural land (26.791%). Detailed land use and land cover distribution of this watershed is given in Table 3.1.

Table 3.1 Land Use and Land Cover Type Distributions

Land Use and Land Cover Type	**Area (ha)**	**% Area**
Water	317.50	0.79%
Urban	15229.55	37.89%
Range	4793.45	11.93%
Forest	3662.69	9.11%
Hay	2612.77	6.50%
Agricultural land	10768.4	26.79%
Wetland	2809.02	6.99%

The hydrologic soil group distribution of the watershed is given in Table 3.2 Natural Resources Conservation Service (NRCS) classifies soils in to four categories namely Group A, Group B, Group C and Group D [23]. Group A consists of soils such as sandy loam type of sand or soil with low surface runoff potential and high infiltration. Group B consists of silt loam type of soil that has moderate surface runoff potential and infiltration rate. Group C consists of sandy clay loam type of soil with relatively high surface runoff potential but low infiltration rate. Majority of the Deep River watershed is dominated by Group C soils. Last category Group D has clay type of soil with highest surface runoff potential and very low infiltration.

Table 3.2 Hydrologic Soil Group Distributions

Hydrologic Soil Group	**Area (ha)**	**% Area**
A	3901.16	9.72%
B	6041.58	14.98%
C	29675.40	73.87%
D	575.24	1.43%

Land slope within the watershed falls within the range of 0 to 71.5% [3]. Majority of the land in the watershed has a slope lower than 2%, which can be described as flat or gently rolling plain. More land slope distribution details are given in Table 3.3.

Table 3.3 Land Slope Distributions

Land Slope	**Area (ha)**	**% Area**
< =2%	27324.26	67.98%
>2%	12869.12	32.02%

3.1.2 Current Watershed Planning Efforts

In 2011, the Deep River-Portage Burns Waterway watershed was identified as a priority in the Northwest Indiana Watershed Management Framework by the Northwestern Indiana Regional Planning Committee (NIRPC) [3]. A recent watershed management plan was developed in an effort of maintaining and restoring the health of Deep River-Portage Burns Waterway Watershed with 319 grant cost-share program implementation. Two of the plans were closely related to the research topic of this thesis, which are Total Maximum Daily Load (TMDL) and Indiana Coastal Nonpoint Pollution Control Plan (ICNPC) [24, 25].

Per the requirement of the Clean Water Act, the total maximum daily load of pollutants that allowed to enter a water body while still meeting the water quality standards [2]. The Indiana Department of Environmental Management (IDEM) established a plan of monitoring the daily load for 21 water quality criteria of the deep river watershed with 36 monitoring sites. The plan was executed in year 2013 and collected data was organized for establishing the TMDL.

IDEM established the ICNPC plan in 2005, which evaluated the existing management measures and provided recommended enforcement mechanisms [25]. Vegetated filter strips (VFS) were recommended to be implement on croplands and urban area to filter sediment from soil erosion and sediments bounded nutrients. Based on recommendations of the ICNPC plan, NIRPC proposed the management plan for Turkey Creek sub-watershed, which included VFS as a restoration strategy. VFS are also listed as an option for the urban and agricultural area BMPs in the Deep River-Portage Burn Waterway Watershed Plan 2016 by NIRPC [3].

3.2 Applicable Models

3.2.1 Nonpoint Source Pollution and Erosion Comparison Tool (OpenNSPECT)

OpenNSPECT is an open-source tool for hydrologic model development. This public domain software helps the user to understand the changes in watershed characteristics with the changes in land cover. [26]. This model was developed by Coastal Development Center of National Oceanic and Atmospheric Administration (NOAA). OpenNSPECT is taken into consideration in this study due to its simplicity to use with the different water quality constituents with changing land use pattern and changes in the system with best management practice. OpenNSPECT utilizes spatial watershed characteristic data including elevation, land cover, soil type to estimate the hydrology character and surface flow routing of a watershed. Event based spatial precipitation data is required by OpenNSPECT to estimate flow quantity and nonpoint source pollutant accumulation. It uses SCS curve number method for runoff computation. When one uses this model for a particular watershed, it generates raster files for water quality results and runoff results. However, this model can be used only for preliminary analysis because it is not very suitable and friendly for hydrological calibration like other popular models [27]. OpenNSPECT is an event-based model which simulates the runoff during a storm event.

3.2.2 Soil and Water Assessment Tool (SWAT)

SWAT is a hydrologic modeling tool developed to simulate and predict the impact of management practices on a watershed scale for different water quality criteria and sediment loads [28, 13, 29, 30]. The ArcSWAT ArcGIS extension version of SWAT was considered due to the large amount of available literatures and its compatibility of automatic model calibration with the help of SWAT CUP [31] SWAT requires similar spatial data to OpenNSPECT but it is very popularly used in water quality studies for several advantages [32]. This model requires chronological climate data (precipitation, solar radiation, wind, and relative humidity) for generating a watershed rainfall-runoff model for the considered time step. In this study, daily time steps were used.

3.3 Data Inventory

3.3.1 Watershed Characteristic Data

The 10 m digital elevation model (DEM) of the northwestern region of Indiana was downloaded from USGS National Elevation Dataset (NED) [33]. Using the DEM, in SWAT model, the watershed delineation was done initially, and the flow path and flow accumulations were estimated subsequently. Land cover data layer was obtained from 2006 National Land Cove Database (NLCD) [34]. Soil data was downloaded from NRCS website for Lake and Porter counties [35]. Necessary geoprocessing was done to get the final soil shape file for the required area. Land cover and soil data is required by hydrologic models like OpenNSPECT and SWAT to determine the hydrologic parameters of the considered watershed.

3.3.2 Watershed Climate Data

Daily climate dataset is available to the public from PRISM Climate Group (http://prism.oregonstate.edu/). This rainfall raster data is available for the entire US for a given day. This type of climate data is required by OpenNSPECT because it is an event-based model.
For SWAT model, daily rainfall data were downloaded from National Climatic Data Center, NOAA. This data was used as the primary dataset. There were some missing data points in this raw data file. Another set of weather data from nearby weather station was retrieved as secondary dataset from the same database link. Data from secondary dataset were used to fill the missing data points in primary dataset to formulate a dataset with 100% data coverage from 05/27/2007 to 04/29/2018. Detailed information is given in Table 3.4 and location is indicated in figure 3.2.

Table 3.4 NOAA Rain Gages

Station ID	**Priority**	**Name**	**Latitude (Decimal Degree)**	**Longitude (Decimal Degree)**	**Elevation (m)**	**Data Coverage**
US1INLK0024	Primary	CROWN POINT 2.0 WSW, IN US	41.4089	-87.3899	230.1	95%
US1INLK0026	Secondary	CROWN POINT 1.1 N, IN US	41.4393	-87.3542	217	94%

Figure 3.2 NOAA Rain Gage Locations

Other climate data required by SWAT including temperature, relative humidity, solar radiation, and wind speed was not available from NOAA. Therefore, the Climate Forecast System Reanalysis (CFSR) global weather database created by the National Center for Environmental Prediction (NCEP) was downloaded from https://globalweather.tamu.edu/ for generating necessary climate data in SWAT. The CFSR global weather database has been evaluated and validated to be reliable in streamflow predictions on a watershed modeling application [36, 37].

3.3.3 Hydrologic Data

Historical daily surface water discharge data was downloaded from the United States Geological Survey. Station name and location is shown below in Table 3.5 and Figure 3.3.

Table 3.5 USGS Gage Information

Station ID	**Name**	**Latitude (Decimal Degree)**	**Longitude (Decimal Degree)**	**Data Coverage**
USGS04093000	Deep River at Lake George Outlet at Hobart, IN	41.536111	-87.256944	01/01/2000-02/26/2018

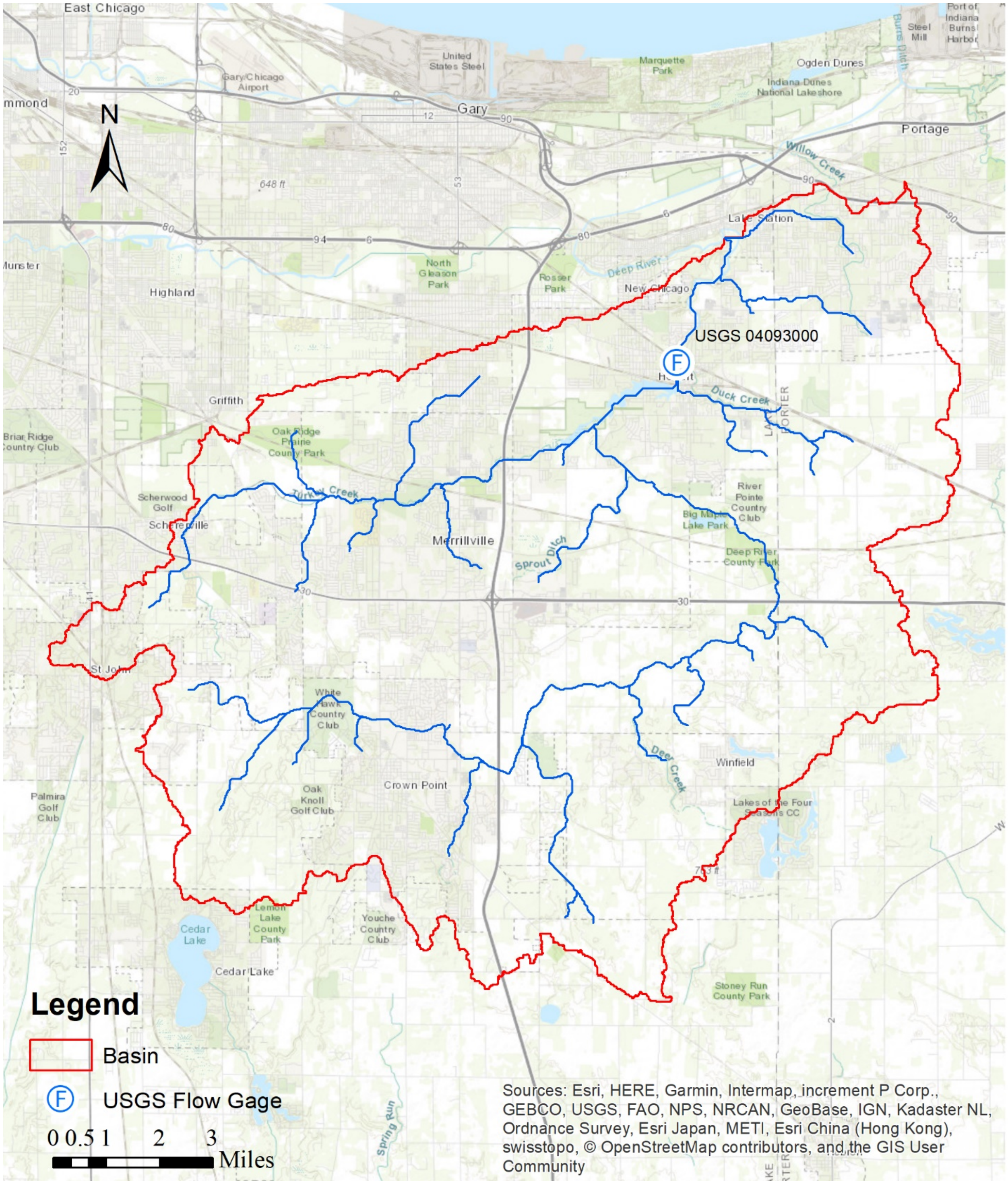


Figure 3.3 USGS Flow Gage Location

Water quality data was available from IDEM. During 2013, IDEM organized data collection for this entire watershed at 36 monitoring stations [24]. 31 of the 36 monitoring stations are within the area of interest. Detailed information of each station is given in table 3.6. Location of each surface water quality station and monitoring site is indicated in Figure 3.4.

Table 3.6 IDEM Surface Water Quality Stations

Site ID	**Latitude (Decimal Degree)**	**Longitude (Decimal Degree)**
3	41.564925	-87.189055
7	41.558829	-87.236351
8	41.535397	-87.256425
9	41.535114	-87.254054
10	41.521586	-87.239837
11	41.516443	-87.210752
12	41.51189	-87.285981
13	41.492959	-87.287620
14	41.476139	-87.220152
15	41.464512	-87.210166
16	41.456330	-87.229307
17	41.449152	-87.247303
18	41.447049	-87.277619
19	41.441925	-87.270185
20	41.423646	-87.296675
21	41.398295	-87.301761
22	41.412818	-87.332920
23	41.435553	-87.354725
24	41.427330	-87.369298
25	41.441741	-87.392582
26	41.434952	-87.403025
27	41.448212	-87.426483
28	41.478671	-87.438275
29	41.498009	-87.427566
30	41.517324	-87.395924
31	41.486074	-87.393392
32	41.498653	-87.364763
33	41.485657	-87.373615
34	41.505881	-87.358707
35	41.485465	-87.340381
36	41.512013	-87.306936

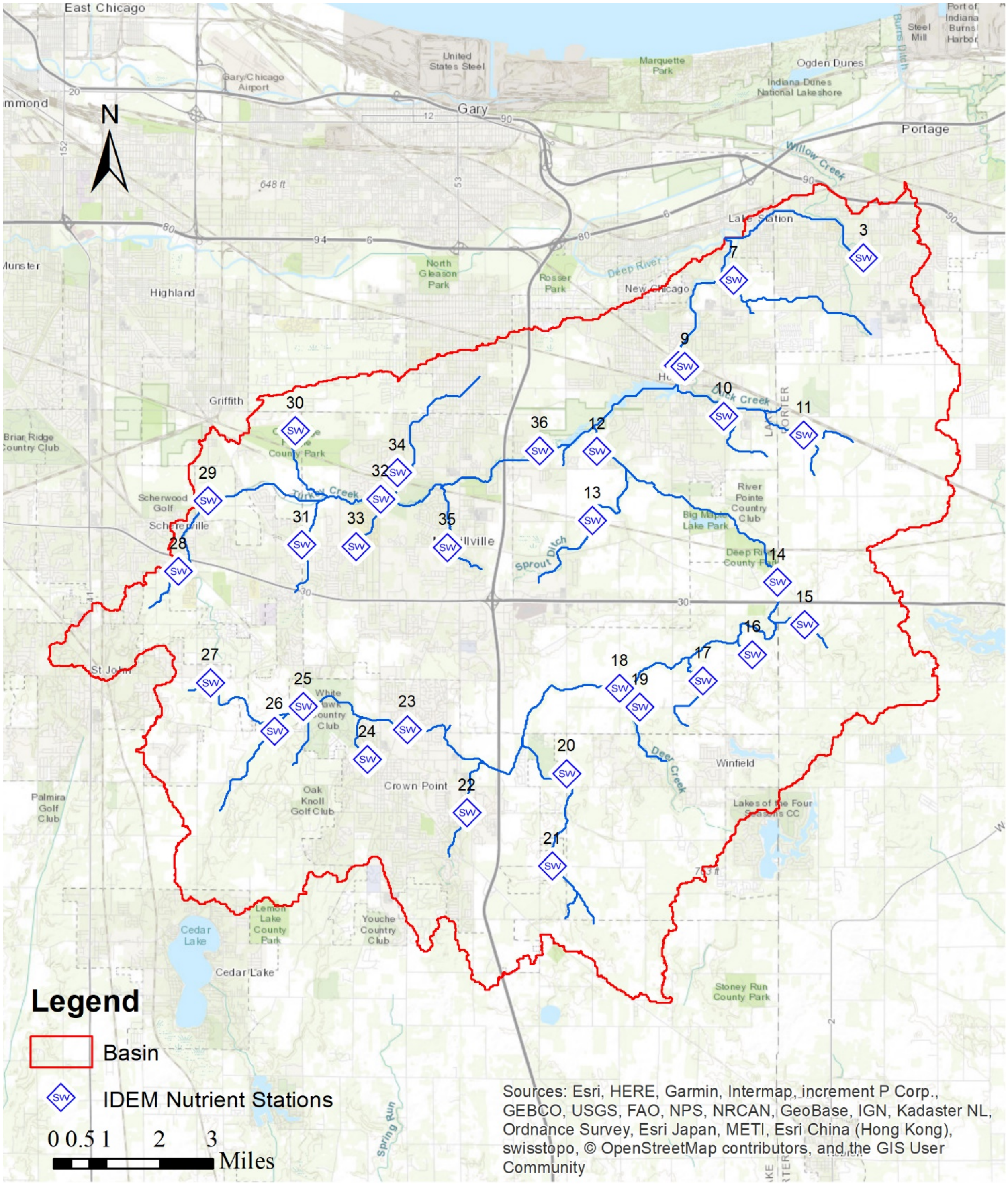


Figure 3.4. IDEM Surface Water Quality Station Locations

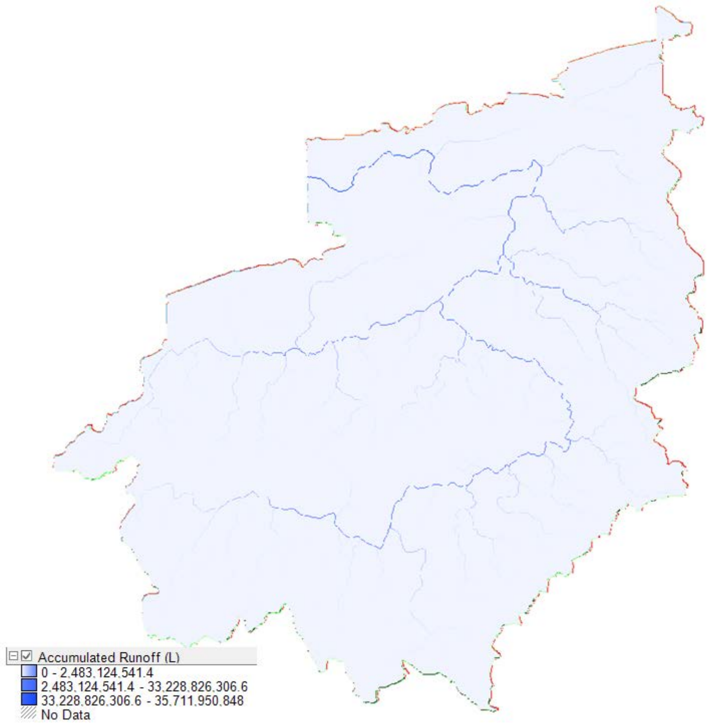
4. METHODOLOGY

4.1 OpenNSPECT Preliminary Modeling

OpenNSPECT is an open-sourced version of NSPECT model. It is an event-based model, hence it is not comparable to SWAT model. Rainfall data in OpenNSPECT was provided as a raster file. During NSPECT model construction process, rainfall raster was overlaid with soil hydrology group raster and land use raster files. For every land use type, and soil group based sub-categories, source tables were created for different water quality parameters. These tables carry the coefficient values for modeling the non-point pollution.

During the modeling process, precipitation scenario can be created for different events. When the model run is completed, the flow raster and water quality raster were created. Since this model uses SCS curve number for runoff calculation, overland flow is estimated as volume with unit of liters instead of discharge. In this work, an NSPECT model was developed for the DR system, and an event-based simulation was done for 2013/04/08. Simulated overland flow and phosphorus accumulation result is given in figure 4.1 A and B.

A)



B)

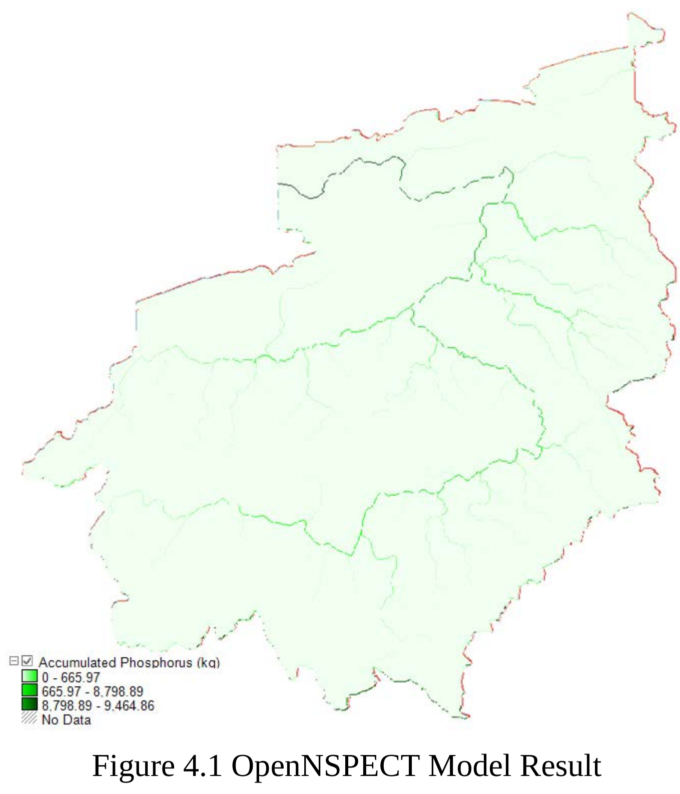


Figure 4.1 OpenNSPECT Model Result

The main issue with NSPECT model is the difficulty with hydrology calibration. This model does not facilitate in providing any initial conditions. The event-based simulation is done without any prior knowledge of the system before the event such as wet or dry conditions. This limitation limits the use of NSPECT as an evaluation/exploratory tool. Thus, further analysis was not made with the NSPECT model result.

4.2 SWAT Modeling

Hydrological models are very useful when analyzing the benefits of water quality and water resources best management policies and practices [38, 39]. SWAT (Soil Water Assessment Tool) is popularly used for watershed rainfall runoff process development and showed its versatility for such works in many studies [12]. Several successful applications of SWAT model were discussed in the Literature Review section.

The land phase of the hydrologic cycle in SWAT model is simulated based on the following water balance equation:

$$SWF = SWI + \sum_{i=1}^{t} (PCP_i - Q_{sr} - E_i - I_i - Q_{return})$$

Where:

SWF = Final soil water content (mm)

SWI = Initial soil water content on day i (mm)

PCP_i = Precipitation on day i (mm)

Q_{sr} = Surface runoff on day i (mm)

E_i = Evapotranspiration on day i (mm)

I_i = Amount of water entering the vadose zone from the soil profile on day i (mm)

Q_{return} = Return flow on day i (mm)

In SWAT, entire watershed is divided into sub-watersheds and the sub-watersheds were further subdivided into Hydrologic Response Units (HRUs). Each HRU has a unique soil type and land use type grouping.

After documenting the dataset required for the SWAT model development for Deep River-Portage Burns Waterway watershed, year 2013 was considered as the pivotal year for the work because of the availability of water quality data observations. Details of watershed model development using SWAT were presented in Figure 4.2. ArcSWAT model was used in ARCGIS version 10.3 for this work. Watershed data such as DEM, land cover etc., and climate data were used in the model building process. After initial model development, historical streamflow data and nutrient data were used in SWAT_CUP [31] model subsequently for a two-stage calibration of hydrological and nutrient parameters.

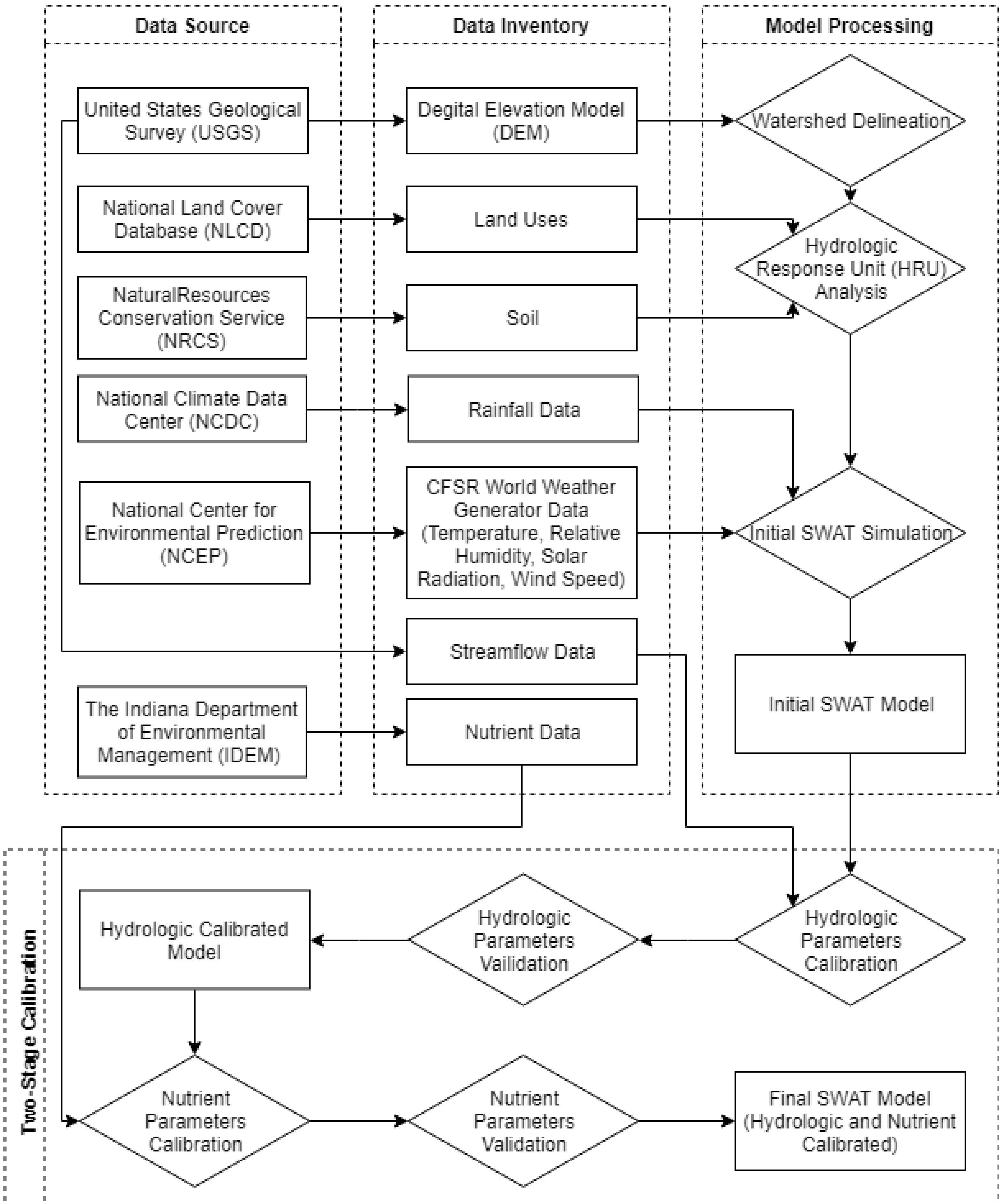


Figure 4.2 SWAT Model Development Process Diagram

4.2.1 Watershed Delineation

Watershed delineation refer to the process in which the boundaries, flow direction, flow accumulation, subbasin boundaries and outlets were determined based on elevation data. This process is the first step in the model development process. DEM based watershed delineation was done through SWAT automated watershed delineation function. Basic parameters used in the automated delineation process were decided based on the number of subbasins needed for the work. Number of subbasins needed were decided based on the USGS flow observation station and IDEM water quality observation stations. The entire watershed was delineated into 52 subbasins with drainage network including reaches and flow paths. The delineated flow path and subbasins are given in Figure 4.3.

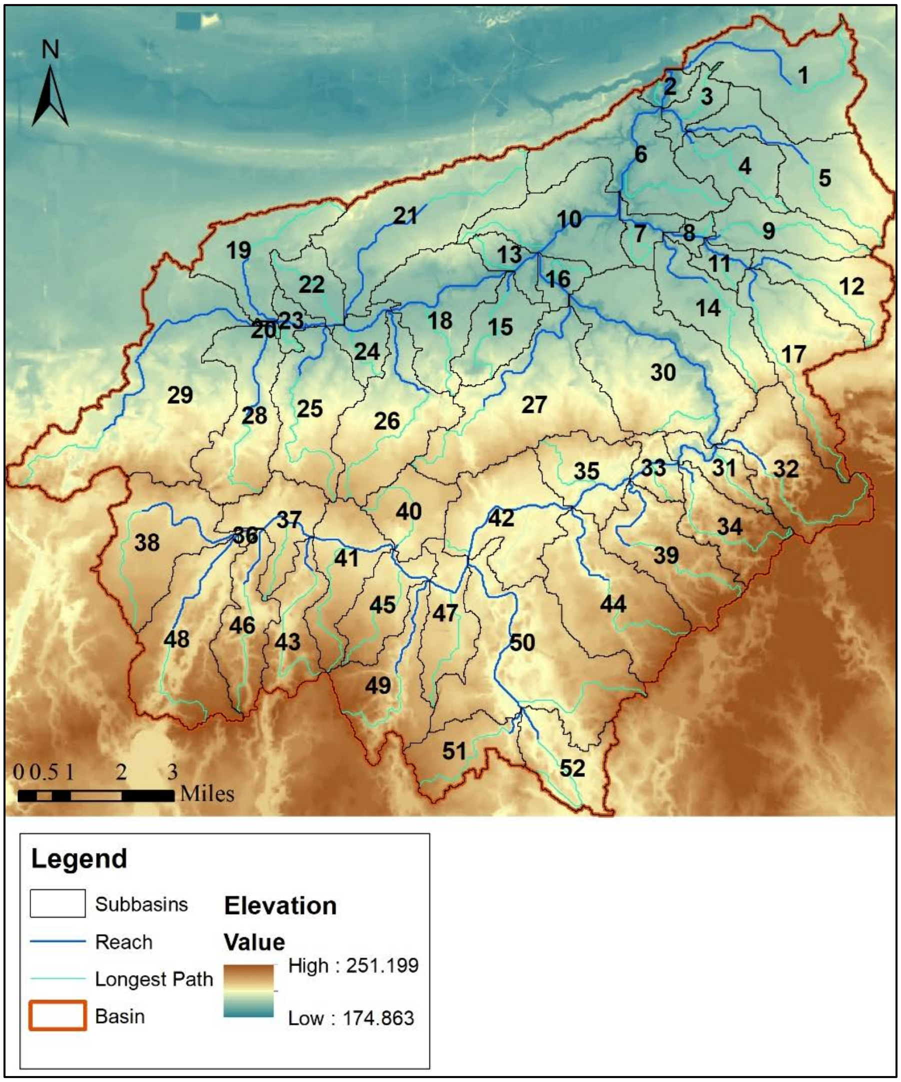


Figure 4.3 Watershed Delineation

4.2.2 HRU Analysis

Initially the land cover, soil and slope data were used in sequence to define HRUs. SWAT provides a built-in algorithm which automatically creates the HRU by properly grouping them to different combinations recommended by the users. In this study, recommended values for HRU thresholds from SWAT manual was used [40]. For example, subbasin number 1 has two HRUs based on different combinations (HRU 1 – Residential Medium Density with soil 160695 and slope 0 to 2% and HRU 2 - Residential Medium Density with soil 160704 and slope 0 to 2%).

The 2011 National Land Cover Database (NLCD) used for this analysis is a raster dataset in which more than 10 categories were presented. This data was reclassified, and a revised land cover data was prepared for the SWAT model. Figure 4.4 is the final overlaid land cover raster file. Code references and area distributions of each type of land use is presented in in Table 4.1.

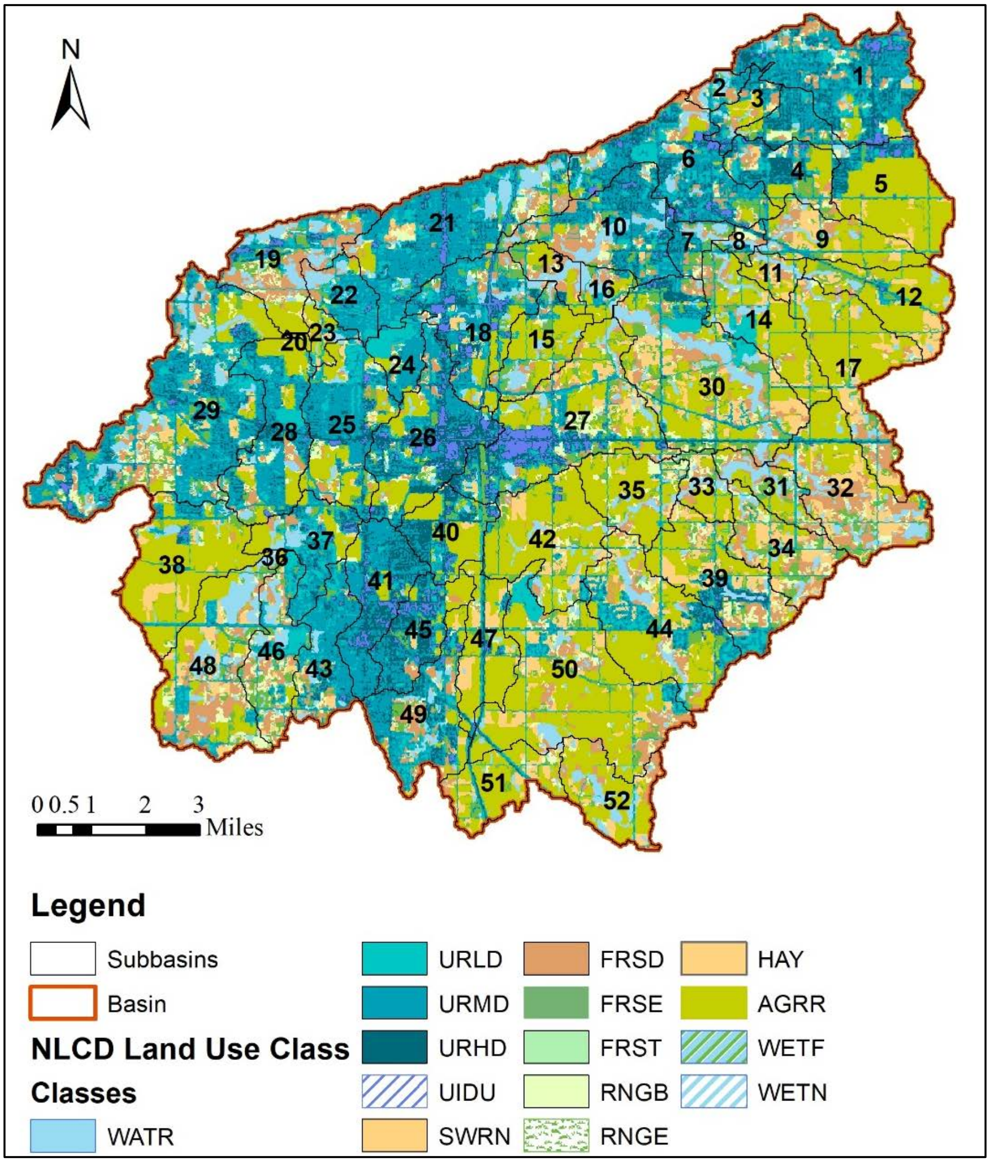


Figure 4.4 Land Use and Land Cover Raster Overlay

Table 4.1 Land Use and Land Cover Code Reference and Area Distribution

NLCD Land Use Code	**NLCD Land Uses**	**Area (ha)**	**% Area**
WATR	Water	317.50	0.790
URLD	Residential-Low Density	3292.25	8.191
URMD	Residential-Medium Density	7856.17	19.546
URHD	Residential-High Density	3273.95	8.146
UIDU	Industrial	807.18	2.008
SWRN	Southwestern US (Arid) Range	227.37	0.566
FRSD	Forest-Deciduous	3584.86	8.919
FRSE	Forest-Evergreen	35.02	0.087
FRST	Forest-Mixed	42.82	0.107
RNGB	Range-Brush	1857.03	4.620
RNGE	Range-Grasses	2709.06	6.740
HAY	Hay	2612.77	6.501
AGRR	Agricultural Land-Row Crops	10768.40	26.791
WETF	Wetlands-Forested	2441.05	6.073
WETN	Wetlands-Non-Forested	367.97	0.916

Downloaded soil data comes with GIS shape file as well as a database file. Using soil data option in the HRU Analysis section, the database file was connected to GIS file and the data were extracted for SWAT model from the database. Soil Survey Geographic Database (SSURGO) option was used to reclassify the soil type for the entire watershed. The SSURGO contains soil properties and interpretation details accompanying the soil type data layer [35]. Incorporating the SSURGO as a lookup table, all necessary soil parameters were assigned accordingly. The soil data overlay is shown in Figure 4.5. Code references, area distributions and soil hydrologic groups are provided in Appendix A.

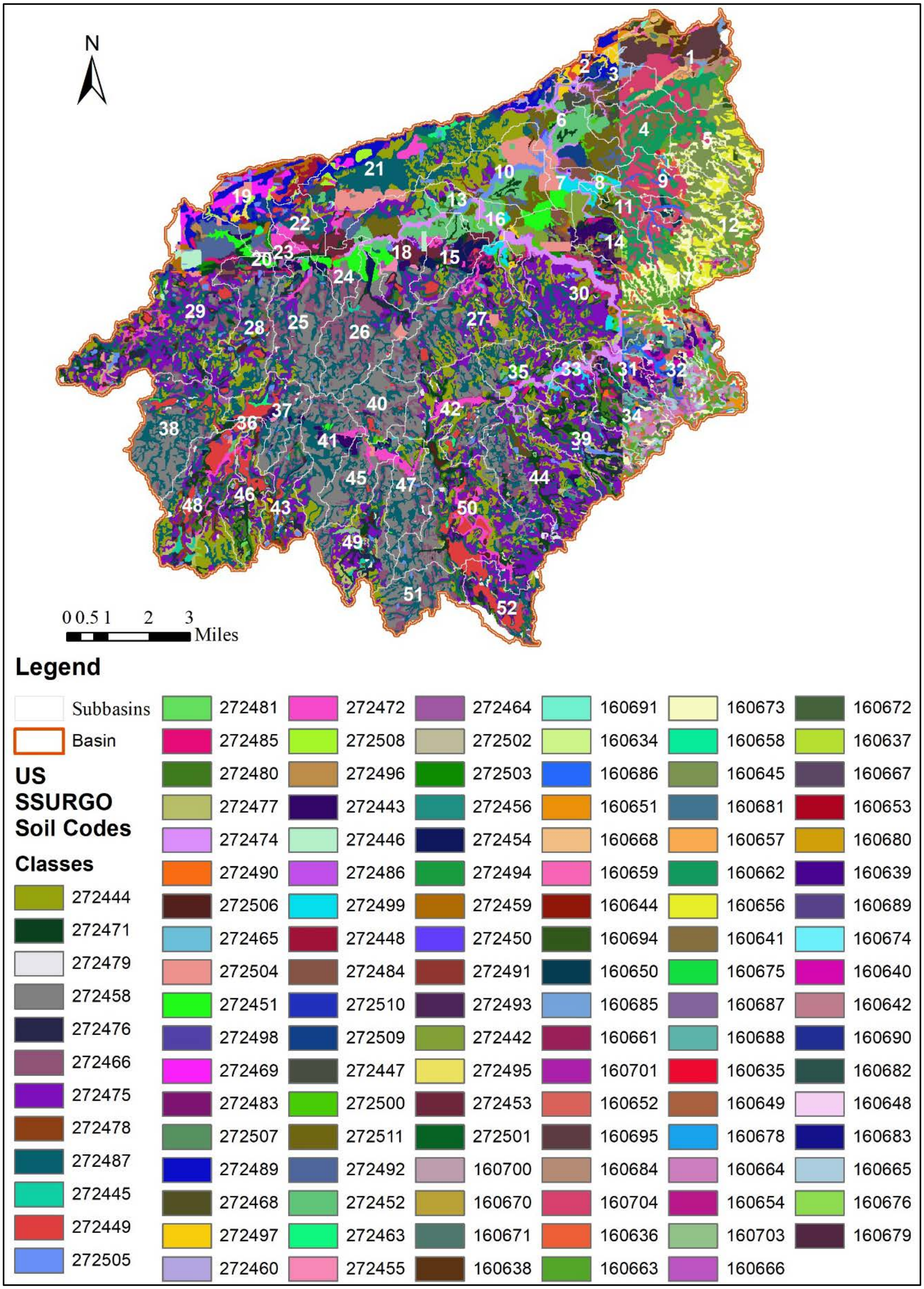


Figure 4.5 US SSURGO Soil Code Overlay

Two land slope classes were defined according to the slop characteristic of the watershed. This watershed is predominantly flat or gently rolling. The slope distribution is given in Figure 4.6. Upper limit, lower limit, and coverage information of each slope class are in Table 4.2.

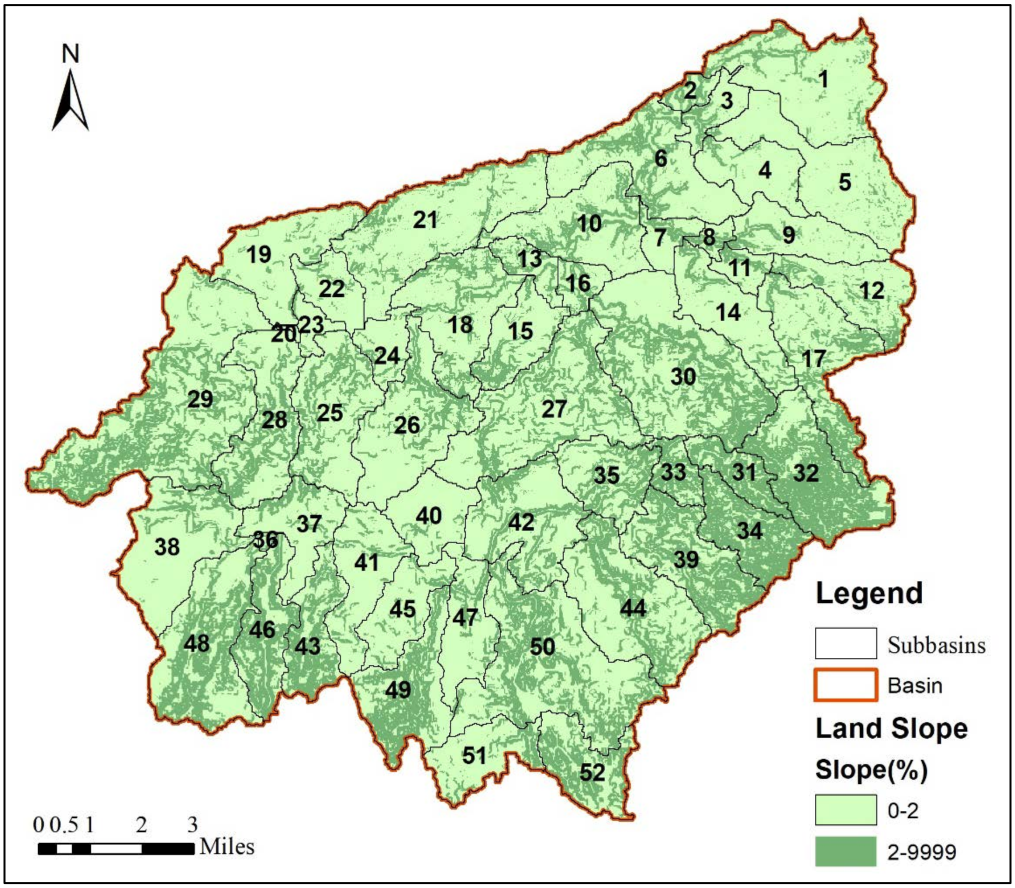


Figure 4.6 Land Slope Overlay

Table 4.2 Land Slope Area Distribution

Slope Class	Lower Limit (%)	Upper Limit (%)	Area (ha)	% Area
1	0	2	27324.26	67.98
2	2	9999*	12869.12	32.02

* Note: Upper limit of slope class 2 is 9999%, which indicates no upper limit for class 2.

Multiple HRUs were created after the compilation of soil, land uses, and slope definition for each subbasin. The watershed was subdivided into areas having unique land use, soil type, and slope combinations, which enables the model to differentiate the runoff, evapotranspiration, routing and other hydrologic conditions. Recommended HRU definition settings with 20% land use threshold, 10% soil threshold, and 20% slope threshold were adopted for HRU separation [40].

After HRU creations, necessary tables needed to run the model were provided in the next step. Weather data were provided to the model initially. NCDC rainfall data were converted to mm and formatted for SWAT model requirement. This data was used as the primary input. As indicated in chapter 3, apart from rainfall data, other required climate data such as temperature, relative humidity, solar radiation, and winds peed were downloaded using a built in SWAT model weather generator routine which takes the climate data from SFSR global weather database. Even though CFSR provides rainfall data, observed rainfall data were used in the model. SWAT provides options to select Skewed Normal or Mixed Exponential distributions for rainfall distribution. This option is usually needed when one needs disaggregation of rainfall data [41]. In our study, this step is not essential. Appropriate printout settings were chosen to run the SWAT model.

4.2.3 Initial SWAT Simulation

While using SWAT model, conventionally a year or two were used as warm up period. In this research, a two years warm-up period (2011 to 2012) was considered to provide a steady state data for the starting time step. Simulation results from warmup period was ignored as the data in warmup period yield may be affected by unsteadiness [42]. Multiple simulation runs were executed to test the model stability. Identical results were produced, which indicate that the initial SWAT model is ready for calibration.

After building the SWAT model, the model run was completed, and the results were printed on a daily basis for different reaches and HRUs. After the results were printed, SWAT CUP [31] was initiated with initial default SWAT parameters used in the model building process.

4.3 Two-Stage Calibration Using SWAT_CUP

SWAT model parameters and optimal values were already well documented in SWAT input and output manual [43]. For calibrating SWAT Model, The Sequential Uncertainty Fitting version 2 (SUFI-2) calibration procedures in SWAT_CUP was used [44]. In SWAT_CUP, random parameter values are generated from user-defined parameter list and interval. Simulations are completed for each set of random parameter values and desired output are compared with historical data. Statistical indices such as Nash-Sutcliffe Coefficient (NS), Coefficient of Determination (R^2), and the Mean Square Error (MSE) are automatically calculated by SWAT_CUP for each individual simulation and used for model performance evaluation. Additionally, SWAT_CUP generates new recommended intervals for all desired parameters after each iteration. These values were used as new inputs in further iterations.

NS and R^2 were used for evaluation calibration performance in this SWAT_CUP calibration. Higher value of NS and R^2 close to 1 indicates excellent fit [45, 46]. The initial SWAT model developed for the Deep River system was imported into SWAT_CUP for the first-stage flow calibration and the second-stage nutrient calibration.

4.3.1 First-Stage Flow Calibration

Observed flow values from USGS station for 2013 were included in recommended SWAT-CUP format for calibration. Extensive details of this preparatory works are presented in Appendix B. The first stage calibration process is demonstrated in Figure 4.7.

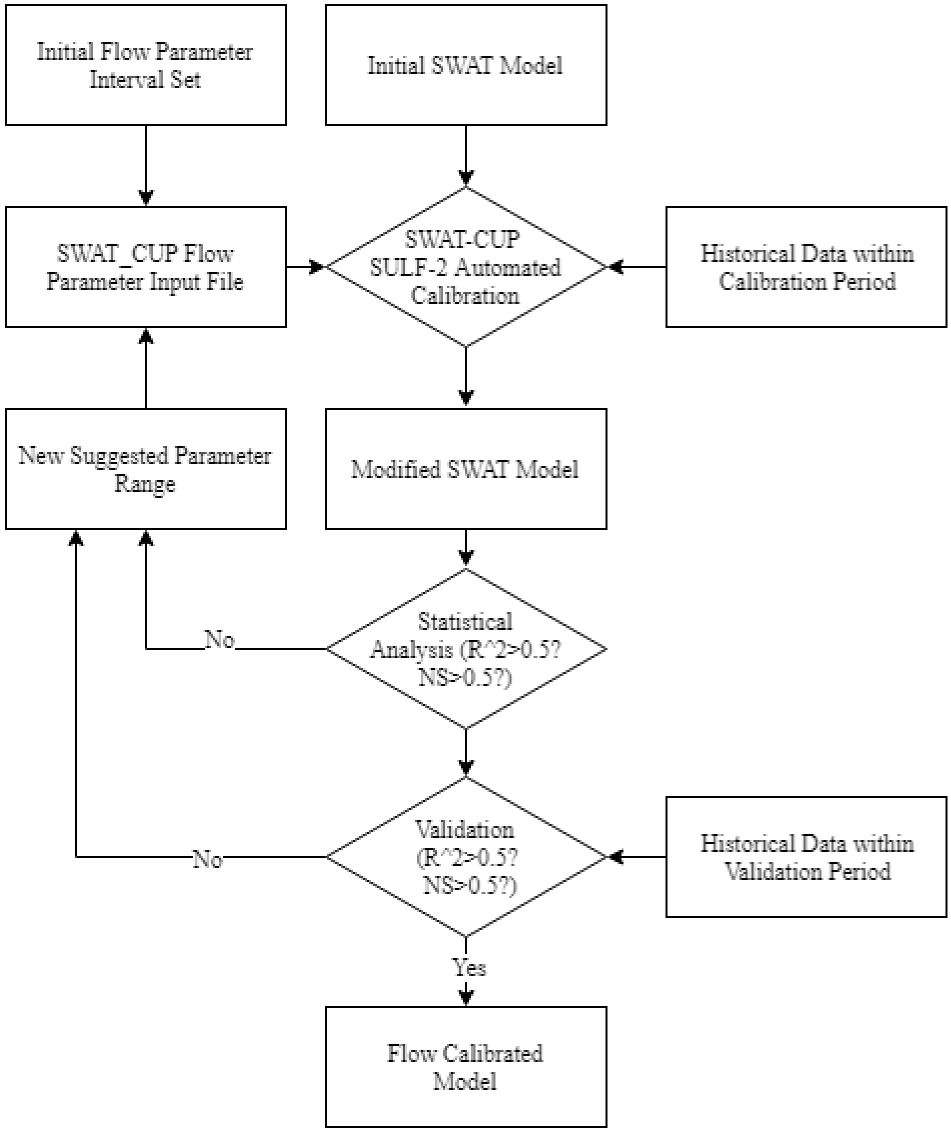


Figure 4.7 First-Stage Flow Calibration Process Diagram

Malago et, al made an analysis of a similar watershed in lake Yenicaga Golu area in Turkey recommended 18 hydrological parameters for improving the calibration [47]. Details about these parameters and calibrated values are given in Table 4.3.

Table 4.3 First-Stage Flow Calibration Parameters

Parameter	**Min**	**Max**	**Calibrated**	**Description**
CN2	35	98	N/A* (0.8193)	SCS runoff curve number f.
SOL_AWC	0	1	N/A* (1.1893)	Available water capacity of the soil layer.
SOL_K	0	2000	N/A* (1.0508)	Saturated hydraulic conductivity.
ALPHA_BF	0	1	0.3786	Baseflow alpha factor (days).
GW_DELAY	0	500	2.6172	Groundwater delay (days).
GWQMN	0	5000	334.8473	Threshold depth of water in the shallow aquifer required for return flow to occur (mm).
EPCO	0	1	0.7665	Plant uptake compensation factor.
GW_REVAP	0.02	0.2	0.2249	Groundwater revamp coefficient.
ESCO	0	1	0.6497	Soil evaporation compensation factor.
PLAPS	-1000	1000	111.3822	Precipitation lapse rate.
RCHRG_DP	0	1	0.1687	Deep aquifer percolation fraction.
REVAPMN	0	500	601.3608	Threshold depth of water in the shallow aquifer for revamp to occur (mm).
SFTMP	-20	20	-4.7267	Snowfall temperature.
SMFMN	0	20	6.1098	Minimum melt rate for snow during the year (occurs on winter solstice).
SMFMX	0	20	0.1005	Maximum melt rate for snow during year (occurs on summer solstice).
SMTMP	-20	20	-4.699	Snow melt base temperature.
TIMP	0	1	0.0662	Snow pack temperature lag factor.
TLAPS	-10	10	-10.000	Temperature lapse rate.

*Note: CN2, SOL_AWC, and SOL_K was calibrated with relative approach to maintain special variability in which initial modeled values were modified by multiplying the coefficient given in the table.

Initially, with default parameter values of SWAT model, the R^2 and NS was 0.18 and -0.67 respectively. The SWAT CUP was running for 5 iterations with 20 simulations in each to improve R^2 to 0.59 and NS to 0.54. Two extended iterations were made but no further improvement on calibration was observed. The flow data from last 3 month of 2013 was used for validation. The calibration and validation performance are presented in Table 4.4.

Table 4.4 First-Stage Flow Calibration and Validation Performance

Action	Time		R^2	NS
	From	To		
Initial	1/1/2013	9/30/2013	0.18	-0.67
Calibration	1/1/2013	9/30/2013	0.59	0.54
Validation	10/1/2013	12/31/2013	0.66	0.56

The observed and simulated flow hydrographs are presented in Figure 4.8.

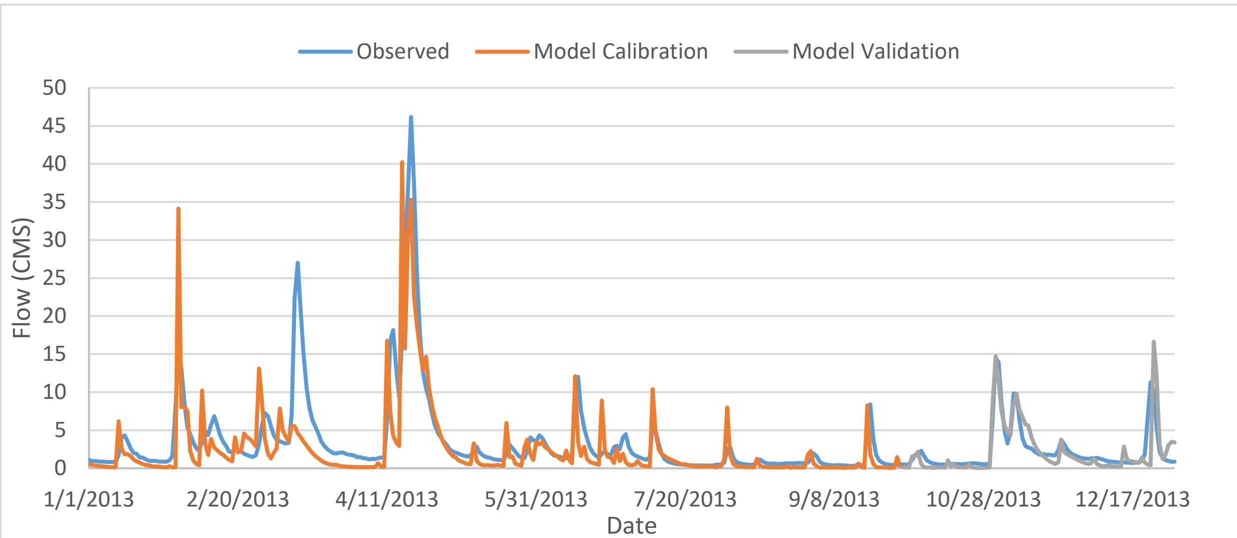


Figure 4.8 First-Stage Flow Calibration and Validation Hydrograph

After satisfactory hydrology calibration, the calibrated flow parameters were preserved for the second-stage calibration.

4.3.2 Second-Stage Nutrient Calibration

The SWAT_CUP was prepared again with emphasize on selected parameters for water quality in the second-stage nutrient calibration. This second-stage calibration process is presented in Figure 4.9.

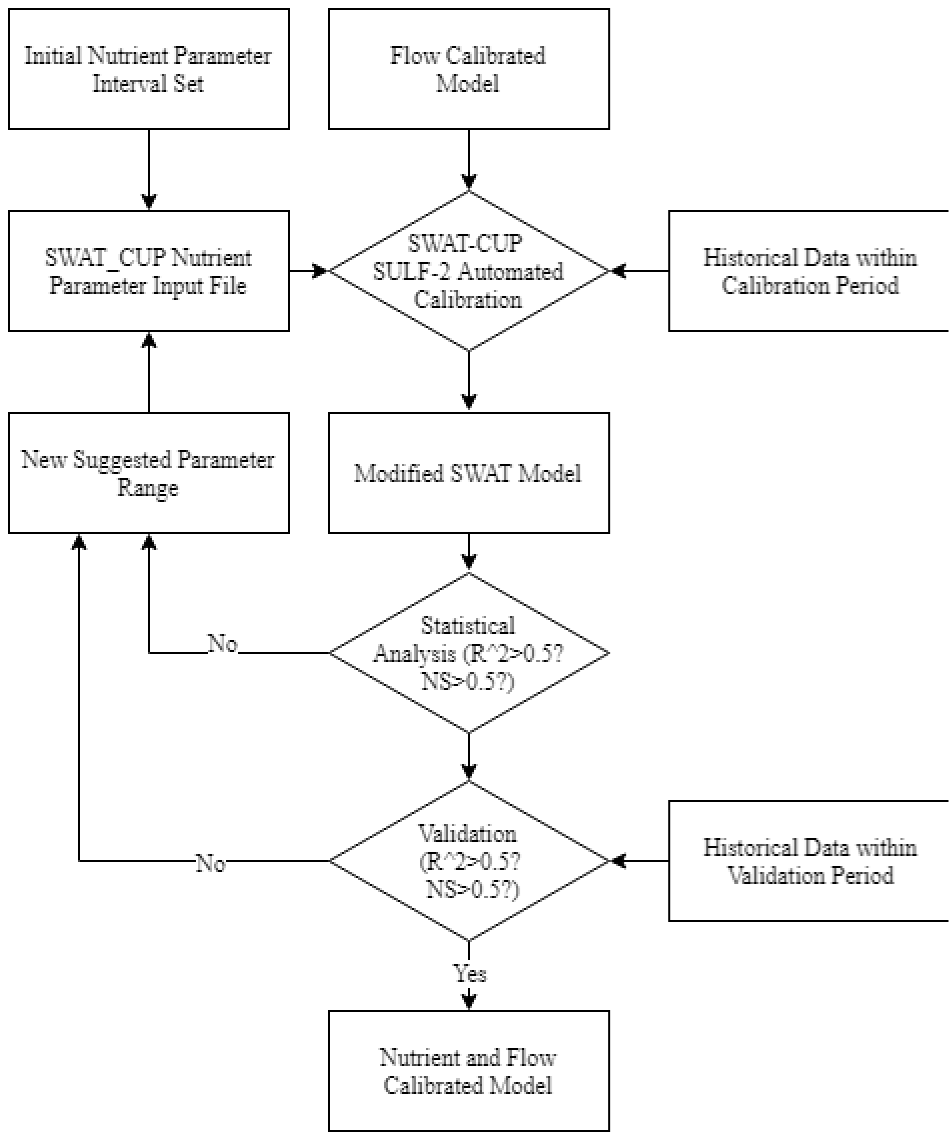


Figure 4.9 Second-Stage Nutrient Calibration Process Diagram

During 2013, the water sample collection and analysis was done in 30 stations. In total, 182 data points were included in the calibration and validation process. The special distribution of these stations is given in Figure 4.10. All available data points were prepared according to the requirements in SWAT_CUP. Details of this preparation is given in Appendix C.

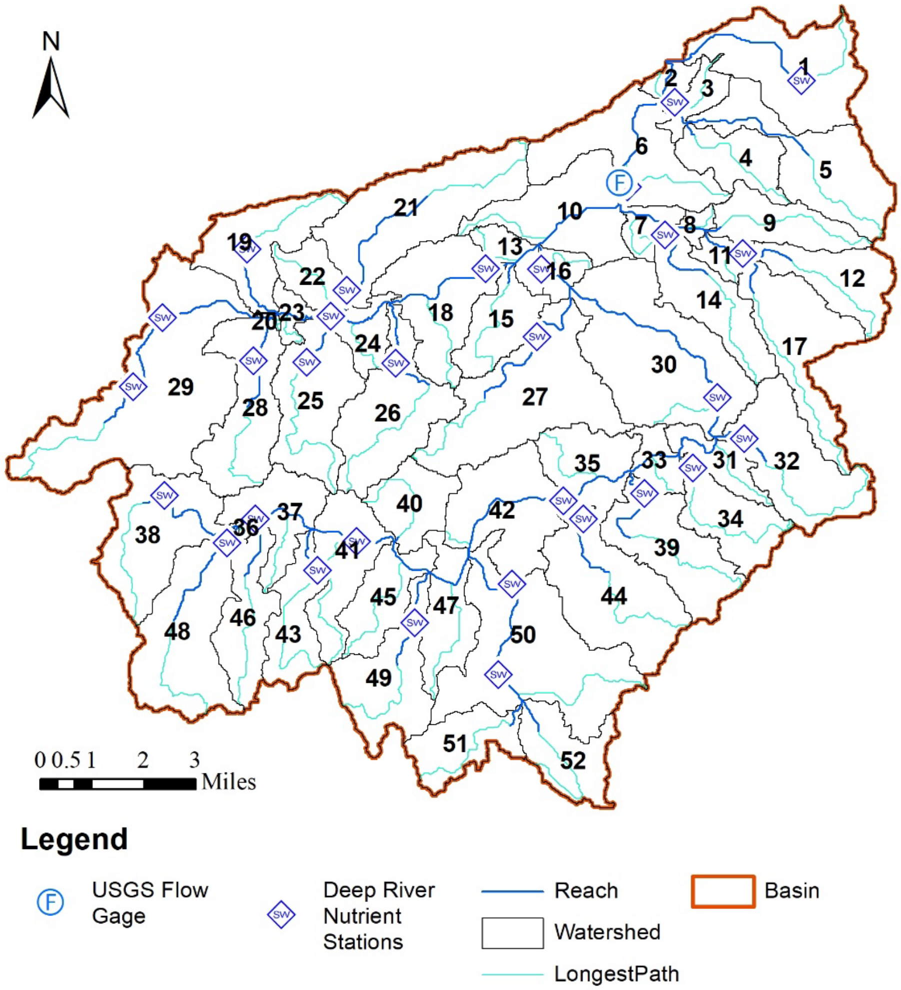


Figure 4.10 Spatial Distribution of Stations

In the Deep River system, VFS implementations along the Turkey Creek was planned. To study the benefit of VFS in controlling phosphorus, phosphorus was taken as the primary objective of this analysis. Malago et, al. implemented VFS in Danube River Basin watershed, and optimized the width of the filter strip [48]. In their work, 13 nutrient parameters where used as the primary variables to improve the calibration. Parameters that are sensitive to phosphorus were taken from their study for the second stage calibration. Additional parameters were also included in the calibration based on their sensitivity during preliminary runs. Involved nutrient parameters and calibrated values are presented in Table 4.5.

Table 4.5 Second-Stage Nutrient Calibration Parameters

Parameter	**Min**	**Max**	**Calibrated**	**Description**
GWSOLP	0	1000	0.9390	Concentration of soluble phosphorus in groundwater contribution to streamflow from subbasin (mg P/l).
ORGP_CON	0	50	4.0358	Organic phosphorus concentration in runoff, after urban BMP is applied
SOLP_CON	0	3	0.0001	Soluble phosphorus concentration un runoff, after urban BMP is applied
PPERCO	10	17.5	11.1678	Phosphorus percolation coefficient.
PHOSKD	100	200	102.3184	Phosphorus soil partitioning coefficient.
PSP	0.01	0.7	0.6540	Phosphorus sorption coefficient.
P_UPDIS	0	100	19.6907	Phosphorus uptake distribution parameter.
CH_OPCO_BSN	0	100	16.8657	Channel organic phosphorus concentration in basin (ppm).
BC4_BSN	0.01	0.7	0.6559	Rate constant for decay of organic phosphorus to dissolved phosphorus (1/day).
PPERCO_SUB	10	17.5	16.2345	Phosphorus percolation coefficient.
RS2	0.001	0.1	0.08300	Benthic (sediment) source rate for dissolved phosphorus in the reach at 20 ^{o}C [mg/(m^2.day)].
RS5	0.001	0.1	0.0297	Organic phosphorus settling rate in the reach at 20 ^{o}C [1/day].
PSETLP1	0	20	17.6892	Phosphorus settling rate in pond for months IPND1 through IPND2.
PSETLP2	0	20	14.1088	Phosphorus settling rate in pond for months other than IPND1-IPND2.
PSETLW1	0	20	10.3933	Phosphorus settling rate in wetland for months IPND1 through IPND2.
PSETLW2	0	20	5.0233	Phosphorus settling rate in wetlands for months other than IPND1-IPND2.
AI2	0.01	0.02	0.0106	Fraction of algal biomass that is phosphorus.
K_P	0.001	0.05	0.0010	Michaelis-Menton half-saturation constant for phosphorus.
IPND1	0	12	7.8546	Beginning month of mid-year nutrient settling season.
IPND2	0	12	6.1939	Ending month of mid-year nutrient settling season.
LAT_ORGP	0	200	0.0009	Organic P in baseflow (mg/l).
ERORGP	0	5	3.36384	Organic P enrichment ratio.

Table 4.5 continued

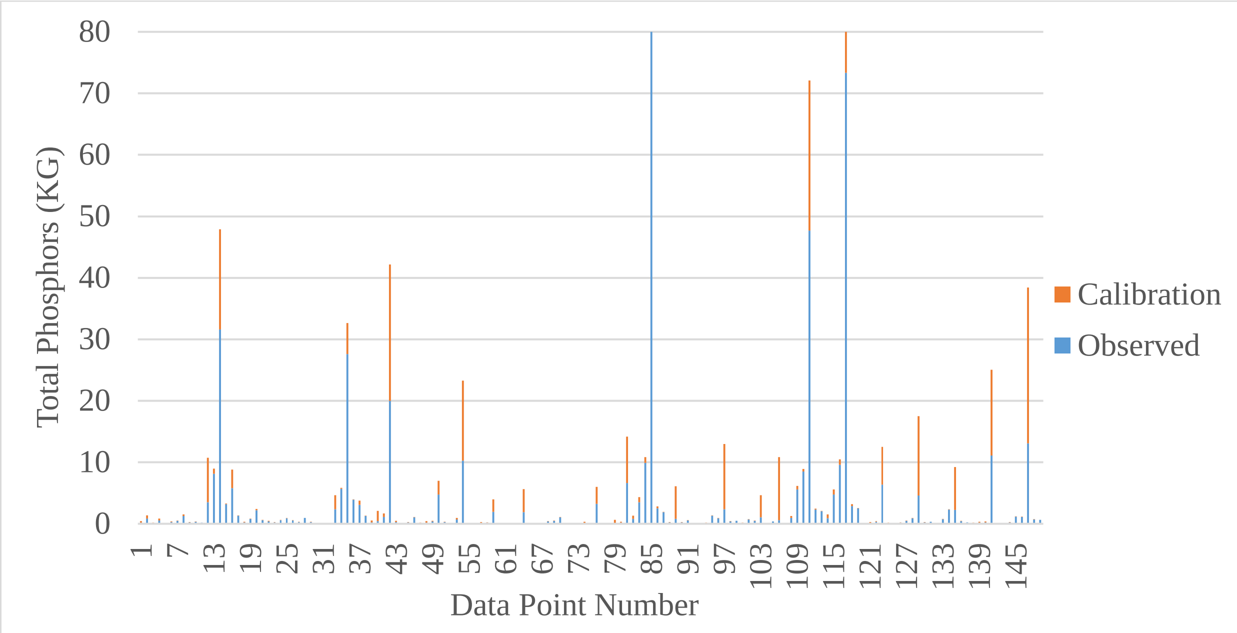
SOL_ORGP	0	100	0.014593	[mg/kg] Initial organic P concentration in surface soil layer.
BC4	0.01	0.7	0.029381	Rate constant for mineralization of organic P to dissolved P in the reach at 20 ºC [1/day].
PND_SOLP	0	50	31.178606	Initial concentration of soluble P in pond.
PND_ORGP	0	50	43.954762	Initial concentration of organic P in pond.
WET_SOLP	0	50	38.355225	Initial concentration of soluble P in wetland.
WET_ORGP	0	50	37.372627	Initial concentration of organic P in wetland.
COEFF_PSORPMAX	0	17600	6158.381348	Maximum P sorption capacity (mg P/kg Soil).
COEFF_SOLPSLP	0	0.3	0.270131	Slope of the linear effluent soluble P equation.
COEFF_SOLPINTC	0	10	0.06431	Intercept of the linear effluent soluble P equation.

12 iterations of 500 simulations were completed with NS=0.84. Four additional iterations were performed but no further improvement was achieved. R^2 was not taken into consideration because observed data was not in a continuous chronological sequence. The calibration and validation performances are given in Table 4.6. Detailed data comparison is given in Table 4.6 and Figure 4.11.

Table 4.6 Second-Stage Nutrient Calibration and Validation Performance

Action	**Time**		**NS**
	From	**To**	
Calibration	1/1/2013	9/30/2013	0.85
Validation	10/1/2013	12/31/2013	0.74

A)



B)

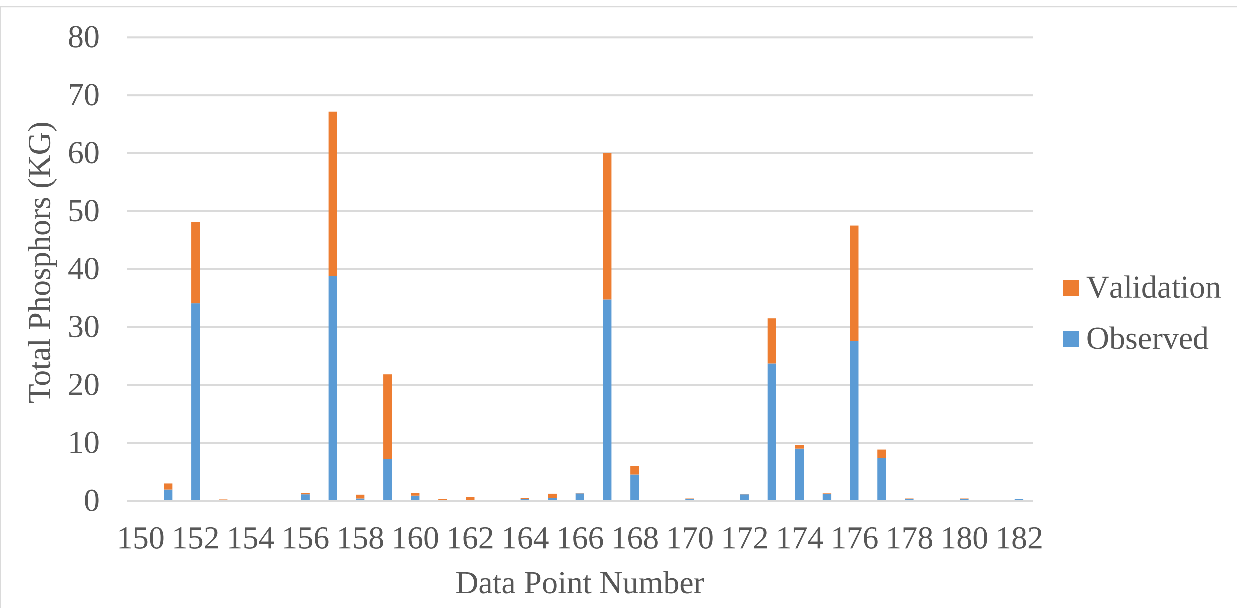


Figure 4.11 Second Stage Nutrient Calibration Stacked Column Chart

The calibrated parameter set showed satisfactory model performances in both calibration and validation period with acceptable NS. These parameters were preserved in SWAT model for the analysis of VFS implementations.

4.4 Vegetated Filter Strip Implementation in SWAT

Vegetated filter strip is usually developed near the banks of the stream on both sides or on one side. A fully developed VFS will be a dense vegetation, mostly local vegetation. VFS will run parallel along the stream. They slow down the flow and deposit the sediments and nutrients in the strip area before the water reaches the stream as overland flow. Detailed explanation of VFS is given in section 33.2.4 (page 491) of SWAT Model I/O Manual as well as in section 6 of Chapter 5 [49, 43]. SWAT uses an algorithm developed by White and Arnold [50]. Several variables control the simulation of filter strip in SWAT model [51]. Muñoz-Carpenaa et al. presented the trapping efficiency details [52].

SWAT manual indicated that for modeling VFS, few results from earlier developed Vegetative Filter Strip Model (VFSMOD) simulations were used. To find the runoff reductions due to VFS, empirical models were developed using VFSMOD simulations. More details of this model are available in SWAT Manual page 411-412 [40]. Nutrient reduction is estimated using a three-stage calculation with three different empirical models.

Initially, the runoff reduction (%) was estimated by SWAT using an empirical relation shown below:

$$R_R = 75.8 - \ln(R_L) + 25.9\ln(K_{SAT})$$

Where:

R_R = Runoff reduction due to VFS (%)

R_L = Runoff Loading in depth unit (mm)

K_{SAT} = Saturated hydraulic conductivity in mm/hr.

Using the runoff reduction, sediment reduction was estimated in SWAT subsequently with another empirical relationship developed by Dosskey et al. [53].

$$S_R(\%) = 79.0 - 1.04S_L + 0.213R_R$$

Where:

S_R = Sediment reduction expected (%)

S_L = Sediment Load (Kg/m^2)

In the third stage, another empirical relationship based on SR was used in SWAT to find the total phosphorus reduction

$$TP_R = 0.90S_R$$

Where:

TP_R = Total Phosphorus Reduction (%)

In order to facilitate the simulation of VFS, SWAT model requires the following parameters shows in Table 4.7 to be specified by users.

Table 4.7 SWAT Model VFS Parameters

Parameters	**Description**	**Min**	**Max**
VFSRATIO	Ratio of field area to filter strip area (dimensionless)	0	300
VFSCON	Fraction of the HRU which drains to the most concentrated ten percent of the filter strip area (dimensionless)	0.25	0.75
VFSCH	Fraction of the flow within the most concentrated ten percent of the filter strip which is fully channelized (dimensionless)	0	100

Suggested VFSCON and VFSCH value in the SWAT user's manual were adopted, which were 0.5 and 0 respectively. The value of VFSRATIO can be calculated using the following equation:

$$VFSRATIO = \frac{Field\ Area\ (km^2)}{Filter\ Strip\ Area\ (km^2)}$$

Where field area is the area of the selected subbasin, and the filter strip area can be derived by multiplying the filter strip width and the hydrologic flow path length of the subbasin.

In the calibrated model, four different VFS implementation scenarios in the Turkey Creek tributaries where multiple BMPs including VFS were propose, were simulated [3]. In each scenario, VFS was implemented in one selected tributary subbasin of the Turkey Creek. 5-meter width on both sides of the Turkey Creek stream were considered as the VFS implementation area in all scenarios according to the suggested VFS width in SWAT [54]. Then, VFS area and VFSRATIO value for each subbasin were calculated based on different hydrologic flow path length and subbasin area. Calculated VFSRATIO value for each scenario was applied to the SWAT model by editing the operation file of selected subbasin. Simulations were completed for all scenarios and the result was recorded for analysis. Details of each scenario are given in Table 4.8 and Figure 4.12.

Table 4.8 VFSRATIO Values of VFS Implementation Scenarios

Scenario	Selected Subbasin	Subbasin Area (km^2)	Hydrologic Flow Path Length (km)	VFS Area (km^2)	Calculated VFSRATIO Value
1	29	25.20	8.51	0.0851	80
2	23	1.55	1.95	0.0195	297
3	24	2.93	1.96	0.0196	150
4	18	10.08	4.69	0.0469	215

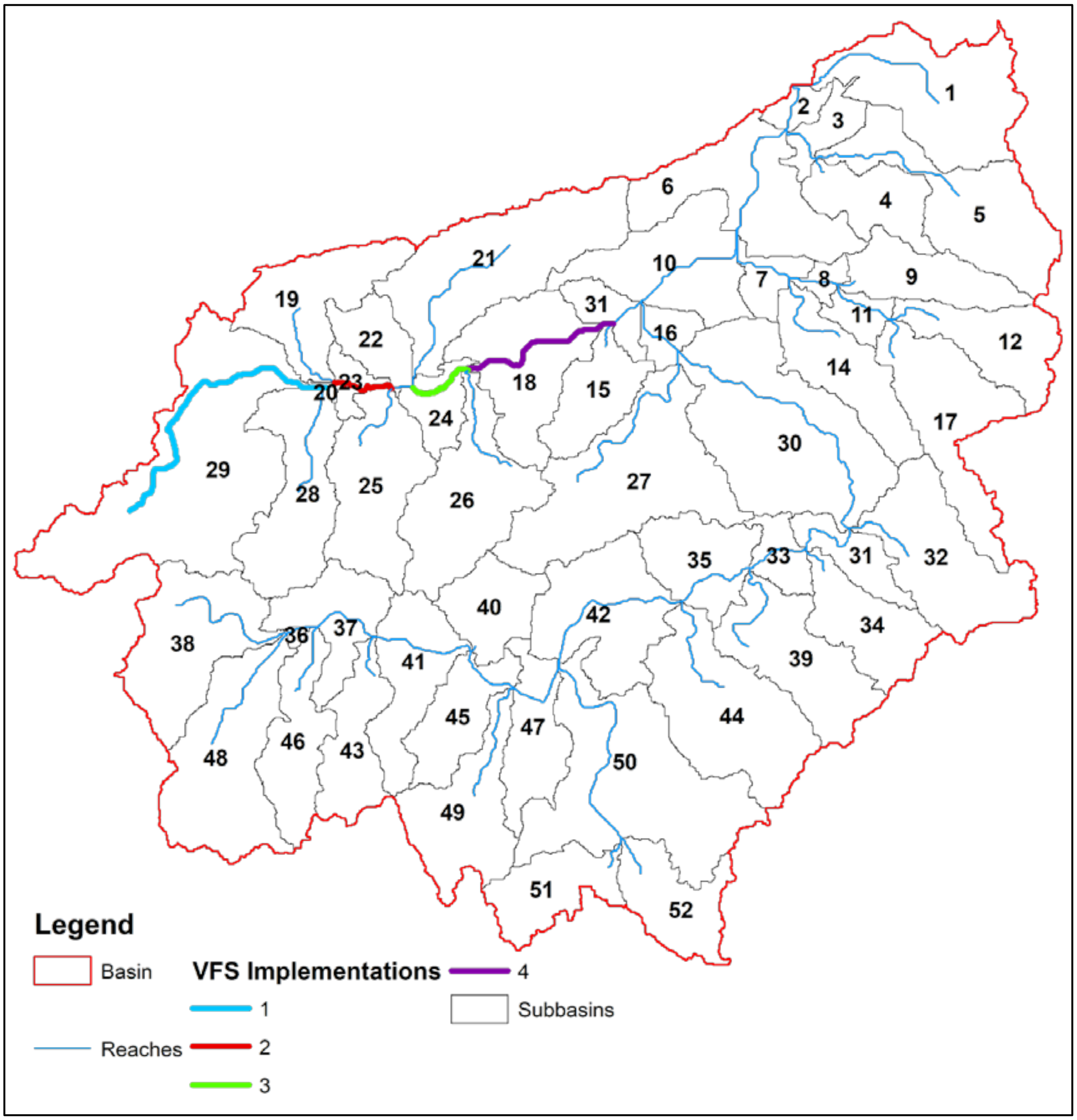


Figure 4.12 VFS Locations of VFS Implementation Scenarios

4.5 Result

Collected data from all VFS simulations was summarized and evaluated based on daily maximum, daily average, and annual total percentage TP reduction. Tabular and visualized performances of all scenario are given in Figure 4.12, 4.13, 4.14, 4.15 and Table 4.9, 4.10, 4.11, 4.12.

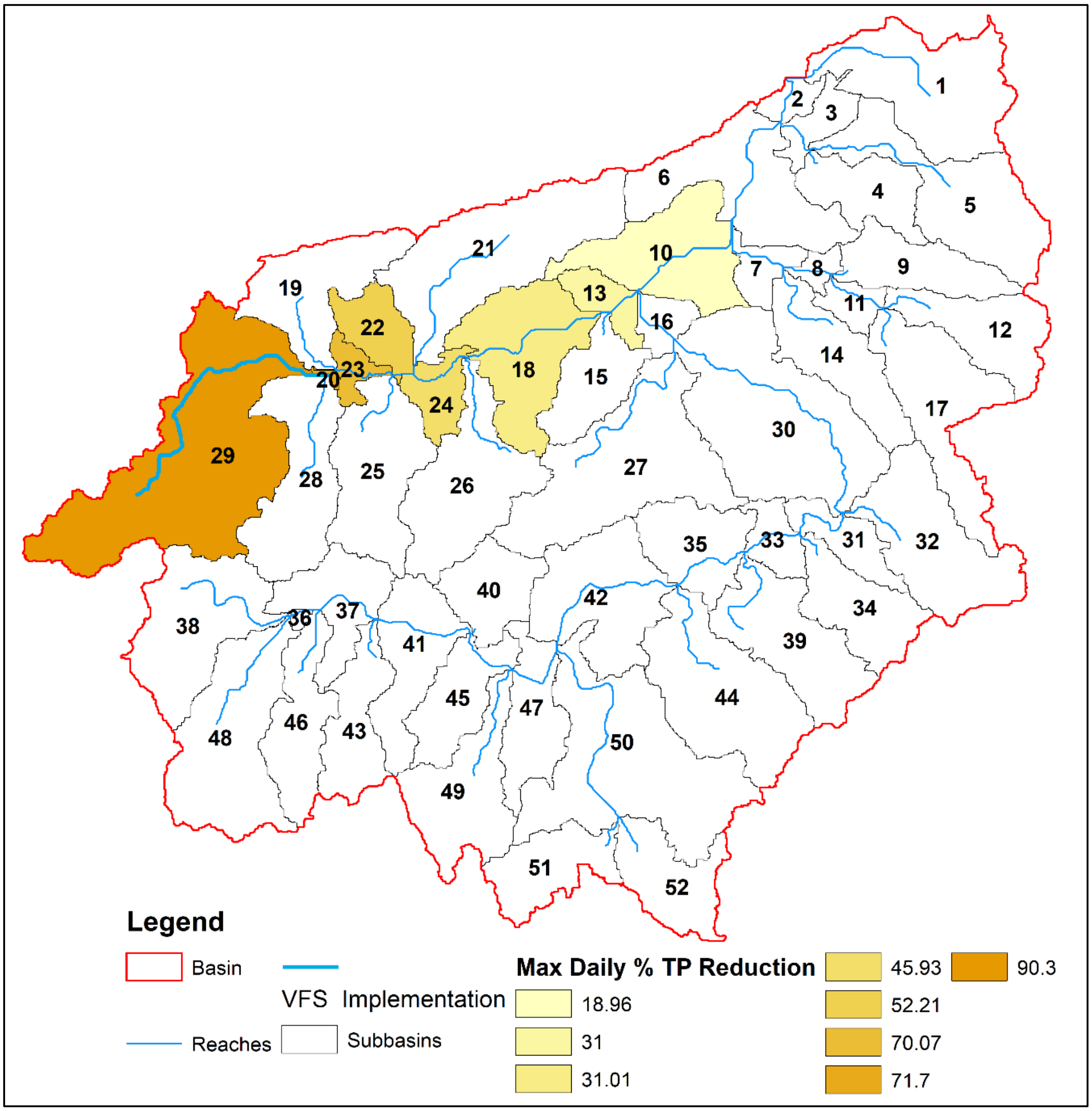


Figure 4.13 VFS Implementation Scenario 1 Maximum Daily TP Percentage Reduction

Table 4.9 VFS Implementation Scenario 1 Performance

	% TP Reduction		
Subbasin	**Daily Max**	**Daily Ave**	**Annual Total**
29	90.30%	23.79%	78.59%
20	71.70%	16.74%	55.42%
23	70.07%	15.18%	51.46%
22	52.21%	10.99%	29.90%
24	45.93%	8.76%	26.34%
18	31.01%	6.02%	20.11%
13	31.00%	5.65%	16.26%
10	18.96%	2.56%	1.46%
Total	-	-	465.01 kg

The first VFS implementation scenario performed well with a 465.01 kg annual TP reduction as shown in Table 4.9 Daily maximum TP reduction was as high as 90.3% in the VFS implemented subbasin 29 and 19% in the downstream subbasin 10 as shown in Figure 4.12. Annual TP reduction performance was still significant in downstream subbasins. Poor performance observed in subbasin 10 because another major tributary enters the Turkey Creek in the subbasin 10 together.

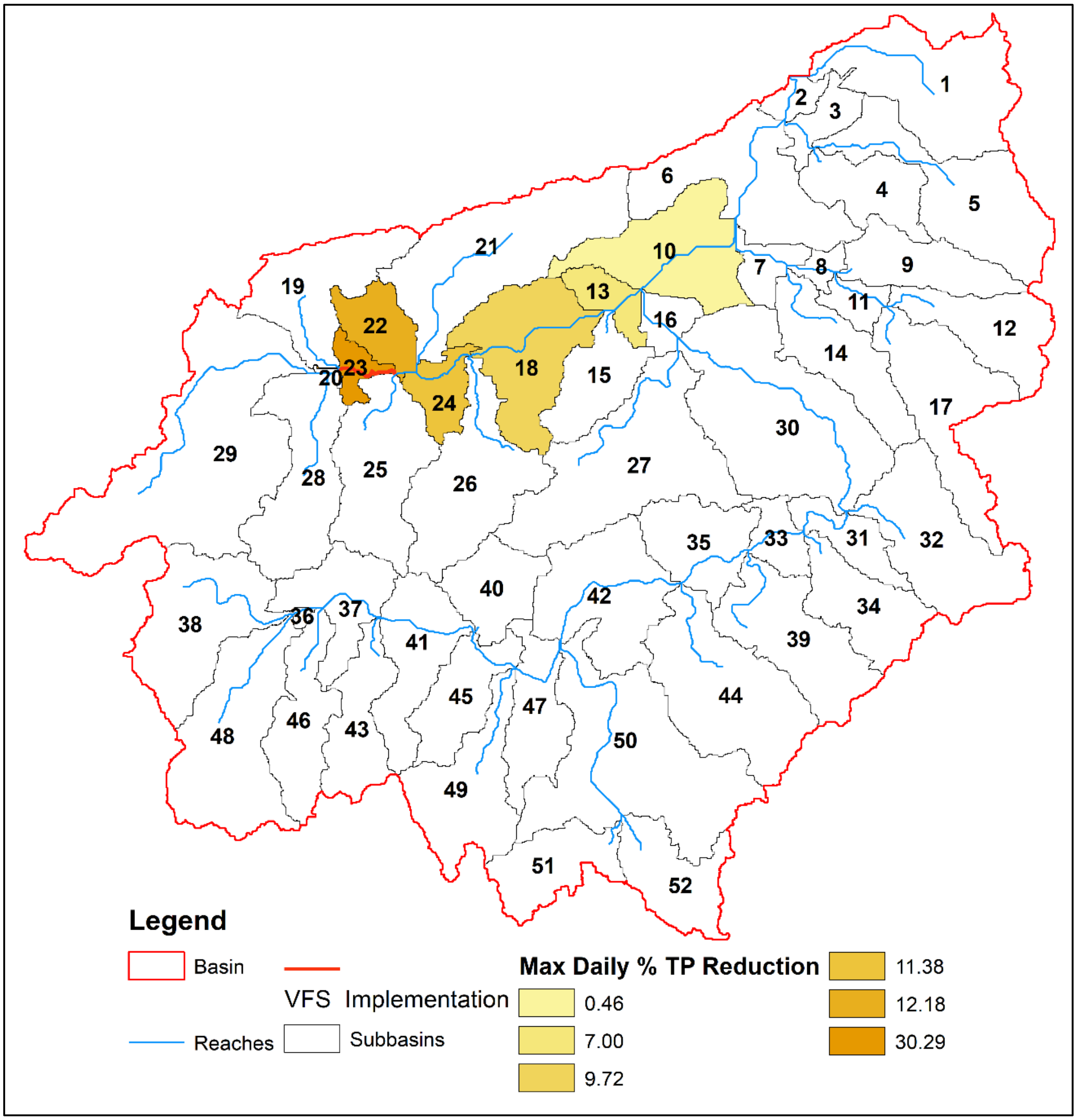


Figure 4.14 VFS Implementation Scenario 2 Maximum Daily TP Percentage Reduction

Table 4.10 VFS Implementation Scenario 2 Performance

Subbasin	**% TP Reduction**		
	Daily Max	**Daily Average**	**Annual Total**
23	30.29%	0.65%	4.28%
22	12.18%	0.25%	2.49%
24	11.38%	0.23%	2.19%
18	9.72%	0.19%	1.67%
13	7.00%	0.13%	1.35%
10	0.46%	0.01%	0.12%
Total	-	-	38.59 kg

The scenario 2 implementation of VFS along the Turkey Creek in subbasin 23 yielded a relatively inferior performance on TP reduction within subbasin 23 as well as in other downstream subbasins as shown in Table 4.10 and Figure 4.13. It is because the subbasin 23 was a relatively small tributary area of the Turkey Creek when compared with subbasin 29. Large portion of TP in subbasin 23 was generated by subbasin 29 and carried to subbasin 23 by channel flow.

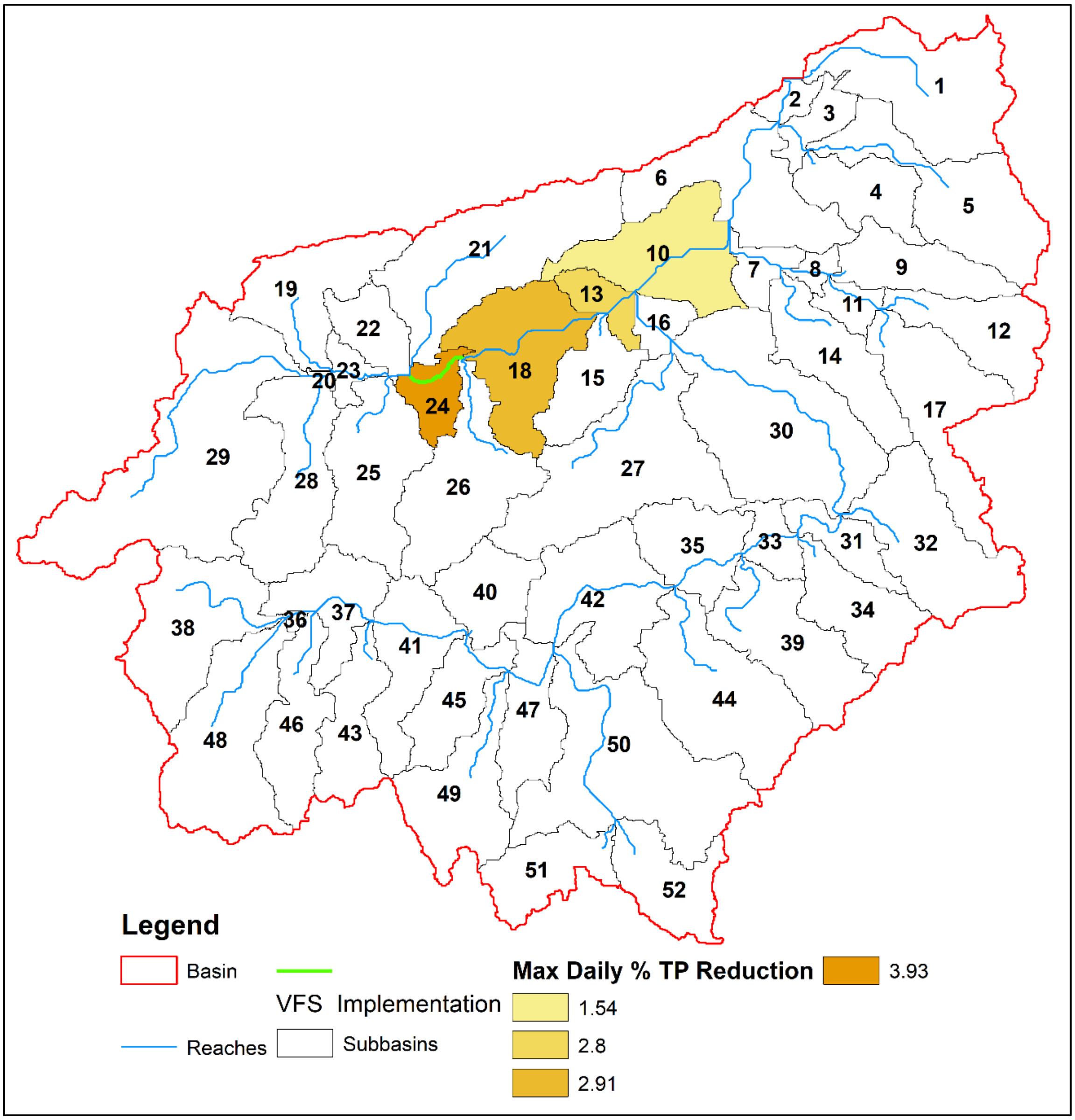


Figure 4.15 VFS Implementation Scenario 3 Maximum Daily TP Percentage Reduction

Table 4.11 VFS Implementation Scenario 3 Performance

Subbasin	**% TP Reduction**		
	Daily Max	**Daily Average**	**Annual Total**
24	3.93%	0.61%	1.60%
18	2.91%	0.42%	1.22%
13	2.80%	0.40%	0.99%
10	1.54%	0.19%	0.09%
Total	-	-	28.11 kg

The VFS implementation of scenario 3 in subbasin 24 showed inferior performance as shown in Table 4.11 and Figure 4.14. It also results in less than 4% reduction in daily maximum and 2% reduction in annual total load in subbasin 24. Similar to scenario 2, subbasin 24 is a small subbasin and majority of the nutrient load was from upstream subbasins.

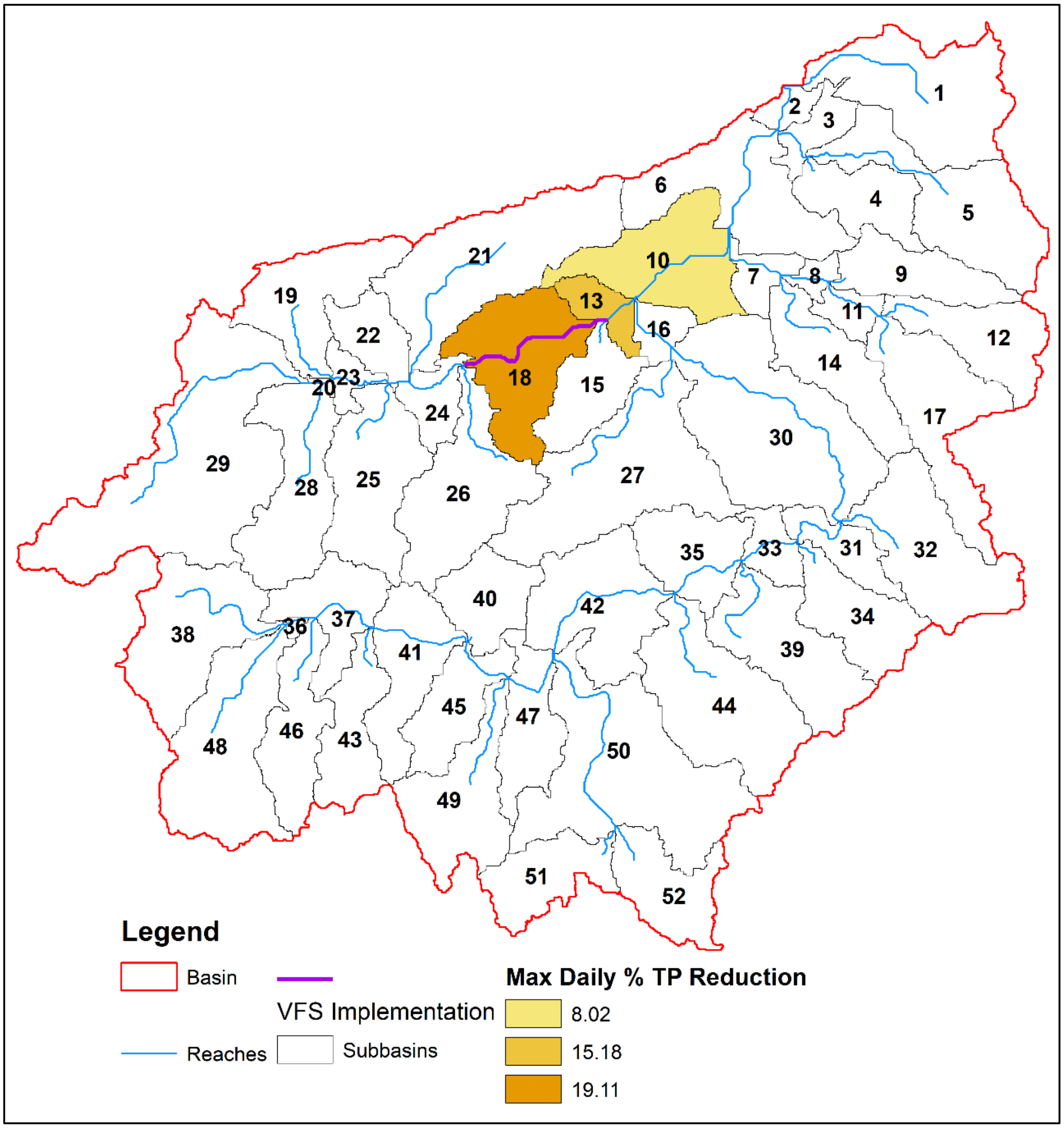


Figure 4.16 VFS Implementation Scenario 4 Maximum Daily TP Percentage Reduction

Table 4.12 VFS Implementation Scenario 4 Performance

Subbasin	**% TP Reduction**		
	Daily Max	**Daily Average**	**Annual Total**
18	19.11%	2.51%	8.29%
13	15.18%	2.37%	6.70%
10	8.02%	1.10%	0.61%
Total	-	-	190.11 kg

The VFS implementation scenario 4 yield a slightly better performance than scenario 3 and 2 with a considerable annual TP reduction of 190.11 kg. Maximum daily load of 19.11% was observed as shown in Table 4.12 and Figure 4.15. This better performance was due to relatively larger subbasin area of subbasin 18 comparing to subbasin 23 and 24. However, the annual total reduction was still insignificant (less than 10%). This indicates that significant amount of nutrient load was generated in upstream subbasins.

The overall result of all for VFS implementation indicated that scenario 4 had the best performance as subbasin 29 was the most critical source of phosphorus load. Implementation of VFS in subbasin 29 was crucial for reducing the phosphorus load in the Turkey Creek. Since the length of implemented VFS in each scenario was not the same, another calculation was done and presented in table 4.13 for capturing the cost efficiency.

Table 4.13 Annual TP Reduction to VFS Area Ratio

Scenario	**Selected Subbasin**	**Annual TP Reduction (kg)**	**VFS Area (km^2)**	**Annual TP Reduction to VFS Area Ratio (kg/km^2)**
1	29	465.01	0.0851	5464.28
2	23	38.59	0.0195	1978.97
3	24	28.11	0.0196	1434.18
4	18	190.11	0.0469	4053.52

This ratio represents the amount of potential annual TP reduction per unit area (km^2). Higher ratio represents higher cost efficiency. Both scenario 1 and 4 has a high cost efficiency so implementation of VFS in subbasin 29 and 18 are highly recommended. Implementation of VFS in subbasin 29 is very beneficial.

5. CONCLUSION

The objective of this thesis work was to construct a watershed model for the Deep River Portage-Burns Waterway Watershed system for the proposed BMP evaluation. This study captured the potential benefit of VFS implementations along the Turkey Creek in the Deep River system.

A preliminary NSPECT model was developed but later abandoned due to its difficulty in hydrologic calibration. ArcSWAT 2012 was then used as modeling tool.

An initial daily-based continuous hydrologic model for year 2013 was developed for the Deep River Portage-Burns Waterway Watershed system using SWAT.

The initial model was then calibrated with a two-stage calibration and validation process using SWAT_CUP. Historical flow data from a USGS gaging station for year 2013 was used in the first-stage flow calibration and validation of hydrological parameters. Calibrated hydrological parameters were preserved and taken into the second-stage nutrient calibration. Historical nutrient data from IDEM nutrient stations for year 2013 were used in this process. Calibrated flow and nutrient parameters were preserved in SWAT model for BMP analysis.

SWAT utilizes a simple VFS model to predict the effects of VFS as a BMP. It uses runoff reduction empirical equation to predict the sediment reduction for the estimation of nutrient reduction. By changing the input parameter value, VFSs were implemented to the calibrated SWAT model in four different scenarios. Two of the four scenarios yielded significant TP reduction ruing simulation. The implementation of 5-meter width VFS on both side of the Turkey Creek in the most upstream reach could potentially provide up to 90.3% daily TP reduction and 78.59% annual TP reduction in the implemented subbasin. Downstream subbasins would be benefited by this implementation with 55.42% annual TP reduction. The reduction decreases in further downstream subbasins.

APPENDIX A. SOIL DATA RASTER DETAILS

Table A.1 US SSURGO Soil Codes References

US SSURGO Soil Codes	US SSURGO Soil Types	Hydrologic Group	Area (ha)	% Area
160634	Adrian	A	12.4482	0.03
160635	Alida	B	12.2982	0.03
160636	Blount	C	264.7118	0.66
160637	Bourbon	A	15.1478	0.04
160638	Brems	A	119.8327	0.30
160639	Chelsea	A	126.5817	0.31
160640	Chelsea	A	60.4413	0.15
160641	Del Rey	C	127.0317	0.32
160642	Door	B	17.6225	0.04
160644	Edwards	C	2.6996	0.01
160645	Elliott	C	1009.6540	2.51
160648	Gilford	A	21.2219	0.05
160649	Hanna	C	14.5479	0.04
160650	Haskins	B	39.5943	0.10
160651	Houghton	A	42.9688	0.11
160652	Houghton	A	68.0152	0.17
160653	Lydick	B	9.1487	0.02
160654	Lydick	B	5.3992	0.01
160656	Markham	C	392.6434	0.98
160657	Martinsville	B	24.4465	0.06
160658	Martinsville	B	4.9493	0.01
160659	Maumee	A	28.0460	0.07
160661	Metea	B	9.2237	0.02
160662	Milford	C	767.1394	1.91
160663	Morley	C	758.1407	1.89
160664	Morley	C	296.1323	0.74
160665	Morley	C	108.5843	0.27
160666	Morley	C	47.6931	0.12
160667	Morley	C	18.2224	0.05
160668	Morocco	A	74.6892	0.19
160670	Oakville	A	97.4859	0.24
160671	Oakville	A	11.3984	0.03
160672	Palms	B	11.6983	0.03
160673	Pewamo	C	702.5737	1.75

Table A. 1 continued

160674	Pinhook	A	1.6498	0.00
160675	Pits	B	6.4491	0.02
160676	Plainfield	A	0.4499	0.00
160678	Rawson	C	27.1461	0.07
160679	Rawson	C	3.5245	0.01
160680	Riddles	B	9.8236	0.02
160681	Riddles	B	89.9120	0.22
160682	Riddles	B	29.9957	0.07
160683	Riddles	B	16.1977	0.04
160684	Sebewa	B	131.606	0.33
160685	Selfridge	A	72.3646	0.18
160686	Suman	C	132.5059	0.33
160687	Tracy	B	17.6225	0.04
160688	Tracy	B	125.007	0.31
160689	Tracy	B	57.2168	0.14
160690	Tracy	B	13.4231	0.03
160691	Tyner	A	8.3988	0.02
160694	Udorthents, loamy, 3 to 30 percent slopes	B	25.2714	0.06
160695	Urban land-Brems complex	B	309.2554	0.77
160700	Water	D	57.7417	0.14
160701	Wallkill	B	46.1184	0.11
160703	Washtenaw	B	62.6160	0.16
160704	Whitaker	B	834.7047	2.08
272442	Alida	B	214.0941	0.53
272443	Alida	B	334.3768	0.83
272444	Blount	C	3073.7320	7.65
272445	Bono	C	72.5145	0.18
272446	Borrow pits	B	85.1877	0.21
272447	Brady	A	171.5003	0.43
272448	Brems	A	121.7824	0.30
272449	Houghton	A	1004.8550	2.50
272450	Clay pits	B	5.5492	0.01
272451	Darroch	B	390.6937	0.97
272452	Del Rey	C	744.9426	1.85
272453	Del Rey	C	298.9819	0.74
272454	Door	B	194.0720	0.48
272455	Door	B	37.7196	0.09

Table A.1 continued

272456	Door	B	21.4469	0.05
272458	Elliott	C	4128.9050	10.27
272459	Gilford	A	135.9554	0.34
272460	Gilford	A	10.4985	0.03
272463	Palms	B	56.2419	0.14
272464	Lydick	B	89.3121	0.22
272465	Lydick	B	9.3736	0.02
272466	Markham	C	1597.9450	3.98
272468	Marsh	B	59.4664	0.15
272469	Maumee	A	203.2957	0.51
272471	Milford	C	1020.3780	2.54
272472	Milford	C	656.2304	1.63
272474	Milford	C	663.5793	1.65
272475	Morley	C	4494.4770	11.18
272476	Morley	C	657.2802	1.64
272477	Morley	C	301.5315	0.75
272478	Morley	C	191.9723	0.48
272479	Morley	C	168.1258	0.42
272480	Morley	C	981.1585	2.44
272481	Morley	C	55.4920	0.14
272483	Oakville	A	15.5978	0.04
272484	Oshtemo	A	260.0625	0.65
272485	Oshtemo	A	138.1301	0.34
272486	Oshtemo	A	63.1409	0.16
272487	Pewamo	C	5591.8690	13.91
272489	Plainfield	A	629.9092	1.57
272490	Plainfield	A	37.5696	0.09
272491	Gravel pits and sand pits	B	22.1218	0.06
272492	Rensselaer	B	365.4973	0.91
272493	Rensselaer	B	290.3581	0.72
272494	Rensselaer	B	31.6454	0.08
272495	Rensselaer	C	15.1478	0.04
272496	Sparta	A	30.8955	0.08
272497	Sparta	A	125.6069	0.31
272498	Adrian	A	34.2701	0.09
272499	Tracy	B	232.2415	0.58
272500	Tracy	B	214.0941	0.53
272501	Tracy	B	10.4235	0.03
272502	Tracy	B	34.0451	0.08

Table A.1 continued

272503	Tyner	A	65.4656	0.16
272504	Urban land	B	587.6903	1.46
272505	Water	D	517.5004	1.29
272506	Wallkill	B	192.8722	0.48
272507	Warners	C	1.3498	0.00
272508	Watseka	A	91.4868	0.23
272509	Watseka	C	200.2961	0.50
272510	Wauseon	C	86.5375	0.22
272511	Whitaker	B	653.4558	1.63

APPENDIX B. 2013 USGS FLOW DATA FORMAT PREPARATION

Preparation work was done in Microsoft Office 2016 Excel. The flow data obtained from USGS was in cubic feet per second (cfs) unit. A unit conversion was done as SWAT_CUP requires cubic meter per second (cfs) as the flow unit. Details are given in Table B.1.

Table B.1 Conversion of Flow from cfs to cms

Time	**Flow (cfs)**	**Flow (cms)**
01/01/2013	39.0	1.104357
01/02/2013	33.6	0.951446
01/03/2013	33.7	0.954278
01/04/2013	32.0	0.906139
01/05/2013	30.2	0.855169
01/06/2013	30.2	0.855169
01/07/2013	29.3	0.829684
01/08/2013	29.3	0.829684
01/09/2013	29.4	0.832515
01/10/2013	29.2	0.826852

SWAT_CUP requires a special format for historical data inputs. The function used for this formatting is:

$$= Sequence\ Number"\ FLOW\_OUT\_"\&DAY\ of\ the\ Year\&"\_"\&Year\&"\ "\&Flow\ (cms)$$

Detail about this format change is given in Table B. 2.

Table B.2 USGS Flow in SWAT_CUP Format

Sequence	**Day**	**Year**	**Flow (cms)**	**SWAT_CUP Format**
1	1	2013	1.104357	1 FLOW_OUT_1_2013 1.104357033
2	2	2013	0.951446	2 FLOW_OUT_2_2013 0.9514460592
3	3	2013	0.954278	3 FLOW_OUT_3_2013 0.9542777439
4	4	2013	0.906139	4 FLOW_OUT_4_2013 0.906139104
5	5	2013	0.855169	5 FLOW_OUT_5_2013 0.8551687794
6	6	2013	0.855169	6 FLOW_OUT_6_2013 0.8551687794
7	7	2013	0.829684	7 FLOW_OUT_7_2013 0.8296836171
8	8	2013	0.829684	8 FLOW_OUT_8_2013 0.8296836171
9	9	2013	0.832515	9 FLOW_OUT_9_2013 0.8325153018
10	10	2013	0.826852	10 FLOW_OUT_10_2013 0.8268519324

Note: the numbers in the “Day” column refers to the number of days from start of the year.

APPENDIX C. NUTRIENT DATA PREPARATION

Majority part of this preparation work was done in Microsoft Office Excel. Observed nutrient data sample from TMDL report is given in table C.1.

Table C.1 TMDL Original Nutrient Data

Site ID	Reach	Date	Phosphorus (mg/L)
3	1	04/08/2013	0.060
3	1	06/10/2013	0.084
3	1	07/08/2013	0.200
3	1	08/05/2013	0.053
3	1	09/09/2013	0.084

SWAT requires the total phosphorus in weight unit kg instead of daily average concentration. Simulated flow data from flow hydrologic calibrated SWAT model was used for estimating the daily total phosphorus in kg. Examples of TP data in SWAT_CUP required format is given in Table C.2.

Table C.2 TMDL Nutrient Data in SWAT_CUP Format

Reach	Date	Day	Flow (cms)	TP (kg)	SWAT_CUP Format
1	4/8/2013	98	0.02267	0.25462944	98 TOT-P_98_2013 0.25462944
1	5/6/2013	126	0.06907	0.465476544	126 TOT-P_126_2013 0.465476544
1	6/10/2013	161	0.13140	1.2488256	161 TOT-P_161_2013 1.2488256
1	7/8/2013	189	0.02413	0.22933152	189 TOT-P_189_2013 0.22933152
1	8/5/2013	217	0.02608	0.31546368	217 TOT-P_217_2013 0.31546368
1	9/9/2013	252	0.01207	0.1564272	252 TOT-P_252_2013 0.1564272
1	10/8/2013	281	0.01179	0.1018656	281 TOT-P_281_2013 0.1018656

Note: the numbers in the “Day” column also refers to the number of days from the start of the year.

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