Article

SWAT modeling of fecal indicator bacteria fate and transport in a suburban watershed with mixed land uses

Zeyuan Qiu[1], **Subhasis Giri**[2], **Lizhong Wang**[3], **Biliang Luo**[4]
[1]Department of Chemistry and Environmental Science, New Jersey Institute of Technology, University Heights, Newark, New Jersey 07102, USA
[2]Department of Ecology and Evolution, Rutgers, the State University of New Jersey, New Brunswick, New Jersey 08901, USA
[3]Environmental Monitoring and Science Division, Alberta Environment and Parks, Deerfoot Square, 2938-11th Street NE, Calgary, AlbertaT2E 7L7, Canada
[4]National School of Agricultural Institution and Development, South China Agricultural University, Guangzhou, Guangdong 510640, P.R. China
E-mail: zeyuan.qiu@njit.edu

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Abstract

This paper presents a case study of modeling the fate and transport of fecal indicator bacteria (*FIB*) in Neshanic River Watershed, a suburban watershed with mixed land uses in central New Jersey using the Soil and Water Assessment Tool (SWAT). *FIB* loadings from livestock grazing, manure application, and wildlife were modeled as nonpoint sources while *FIB* loadings from direct deposit of livestock manure to streams during grazing period and failing septic systems were modeled as point sources. The simulated *FIB* concentrations were compared to the observed concentrations at seven monitoring stations in the watershed. The model was calibrated from 1997 to 2002 and then validated from 2003 to 2008. The percent bias (PBIAS) value for simulating fecal coliform was 13.81 during calibration, and 24.11 during validation at a long-term monitoring station in the watershed, which was satisfactory. The range of the simulated *FIB* concentrations was comparable to the observed concentrations at all monitoring stations. Failing septic systems, manure application and livestock access to streams contributed 46, 31 and 19 percent, respectively, of the *FIB* concentration in streams at the watershed outlet. Seasonal pattern of the simulated *FIB* loadings at the watershed outlet revealed the highest *FIB* loadings occurred in April when manure was applied in agricultural lands compounded by spring storms. There were also elevated *FIB* loadings in October due to the wash-off effect of the accumulative *FIB* from livestock grazing during the grazing season. These results suggest that the SWAT model is capable of simulating *FIB* fate and transport in suburban watersheds despite the difficulties of representing the spatial and temporal distributions of *FIB* sources.

Keywords bacteria fate and transport; SWAT; fecal coliform; *Escherichia coli* (*E. coli*); Neshanic River Watershed; mixed land uses.

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1 Introduction

Fecal indicator bacteria (*FIB*) is one of the leading pollutants that degrade water quality in the U.S. (USEPA, 2016) as well as the world. *FIB*-impaired water quality is attributed to several major water-borne diseases and increased health risk worldwide especially in developing countries (WHO, 2015). Fecal coliform and *Escherichia coli* (*E. coli*) are two commonly used indicator bacteria among *FIB* (McMurry et al., 1998; Rochelle-Newall et al., 2015). *FIB* primarily lives in the lower intestine of all warm-blooded animals including human and depicts the presence of fecal contamination (Francy et al., 1993; Paul, 2003). While fecal coliform may contain bacteria species that are not necessarily fecal in origin, *E. coli* is a species of fecal coliform bacteria that is more specific to fecal materials from humans and other warm-blooded animals, and its presence indicates potential for pathogen contamination (Odonkor and Ampofo, 2013; Beutel and Larson, 2015).

Different watershed models, such as the Hydrologic Simulation Program FORTRAN (HSPF), the Soil and Water Assessment Tool (SWAT), and the Loading Simulation Program in C++ (LSPC), have been expanded to simulate the fate and transport of *FIB* in watersheds (Cho et al., 2016b). The SWAT model has been more widely used than other models to evaluate *FIB* fate and transport because it is user-friendly and has greater flexibility to simulate pollution from both non-point and point sources, especially in agricultural watersheds (Coffey et al., 2007; Chin et al., 2009; Baffaut and Sadeghi, 2010). The examples of applying the SWAT model to simulate *FIB* fate and transport in watersheds are Parajuli et al. (2009) in Upper Wakarusa Watershed in Kansas; Coffey et al. (2010) in an Irish watershed; Cho et al. (2012) in Wachusett Reservoir Watershed in Massachusetts; Frey et al. (2013) in Payne River Watershed in Ontario, Canada; Jaykody et al. (2014) in Pelahatchie Watershed in Mississippi; and Niazi et al. (2015) in Upper Salem River Watershed in New Jersey.

Despite prolific SWAT applications in modeling *FIB* fate and transport in watersheds, most of these applications were performed in agricultural or forest watersheds with focus on limited *FIB* sources. Suburban watersheds with mixed land uses have diverse land uses and present a challenge to model *FIB* fate and transport as land use clearly plays a role in *FIB* occurrence (Bradshaw et al., 2016). Such modeling would have to consider *FIB* sources from urban lands in addition to agriculture and forest and represent those *FIB* sources through both non-point and point source loadings from urbanization-related livestock, wildlife, and failing on-site wastewater treatment system such as septic. There are inherent uncertainties in characterizing the essential parameter inputs for *FIB* models (Niazi et al., 2015). Furthermore, suburban watersheds generally tend to experience more severe water quality problems related to *FIB* contamination because of presence of on-site wastewater treatment systems and limited spaces for proper animal manure disposal (NJDEP, 2012).Whelan et al. (2018) is the only study that clearly addresses the challenges of modeling *FIB* fate and transport in such watersheds with mixed land uses, details modeling processes related to multiple *FIB* sources, and presents an integrated framework for real world applications. The integrated framework is based on HSPF; and there is no application of SWAT in simulating *FIB* fate and transport in suburban watersheds with mixed land uses.

The objective of this study is to complement the existing SWAT applications by presenting a comprehensive case study of using SWAT to model *FIB* fate and transport in a suburban watershed with mixed land uses that include urban, agriculture and forest. More specifically, this study will apply the SWAT model to simulate the source loadings, the fate and transport of fecal coliform and *E. coli* in Neshanic River Watershed in central New Jersey that has concern of *FIB* contamination (NJDEP, 2012) and to evaluate the capability of the SWAT model in predicting *FIB* loadings and transport in streams. The improved understanding of the modeling capacity helps develop and implement mitigation strategies to reduce *FIB* concentration in the impaired streams.

2 Materials and Methods

2.1 Study area

Neshanic River Watershed is located in Hunterdon County in central New Jersey (Fig. 1). The watershed consists of five hydrological unit code (HUC) 14 sub-watersheds. Neshanic River flows toward east to the south branch of Raritan River that eventually drains into Atlantic Ocean. The total watershed area is 7,896 ha, out of which 40 percent is agricultural land, 33 percent urban area, 21 percent forest, six percent wetlands, and remaining is water according to the 2002 land use/cover data maintained by New Jersey Department of Environmental Protection (NJDEP). Agricultural land primarily comprises of corn, soybean, and limited rye along with hay and pasture. Urban areas consist of low density-residential, medium density-residential, high density-residential, commercial and industrial lands, and lands for transportation and institutions. Forest is dominated by deciduous vegetation followed by mixed and evergreen types of vegetation. Neshanic River Watershed has relatively uniform soils of the Brunswick formation developed from Triassic red shale. In non-wetland areas, the soils are characteristically shallow, well-drained and loamy. Texturally, all soils in the watershed are silt-loams (USDA, 1974). The elevation in the watershed ranges from 31 m to 210 m above the mean sea level. Higher elevation is observed at the north-western edge of the watershed whereas lower elevation is found in the center and eastside of the watershed. The maximum temperature during summer is in the range of 27 to 30 °C while the minimum temperature during the winter ranges from -12 to -7 °C. The mean annual precipitation in the watershed is 1,218 mm. Water quality concerns include low dissolved oxygen and excessive total phosphorus, total suspended solids, and *FIB* in the river (NJDEP, 2012).

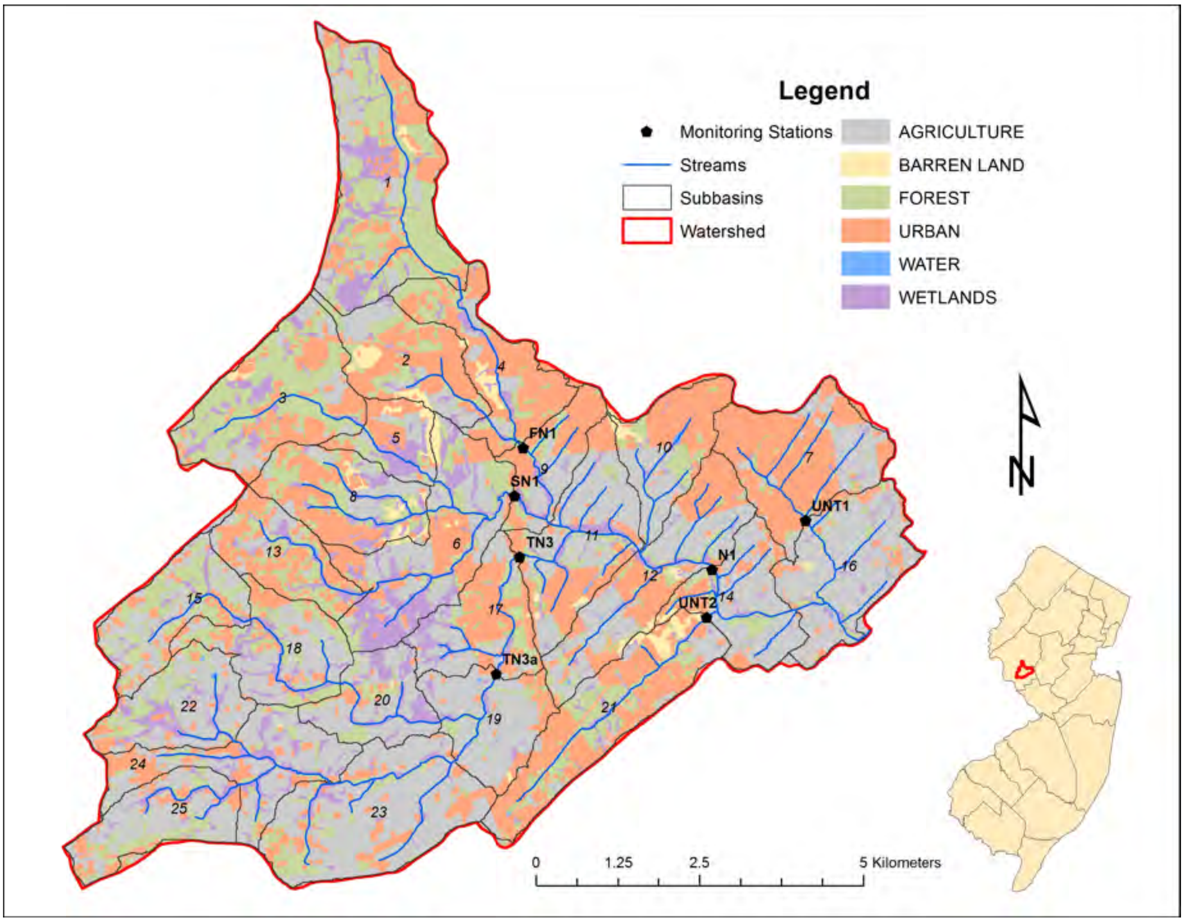


Fig. 1 Land uses, location, and water quality monitoring station in Neshanic River Watershed.

2.2 *FIB* modeling in SWAT

SWAT2005 was used to assess *FIB* fate and transport in the watershed in this study. SWAT is a physically based, spatially distributed model developed by the U.S. Department of Agriculture Agricultural Research Service (Arnold et al., 1998; Neitsch et al., 2005; Gassman et al., 2008). SWAT divides a watershed into smaller units called subbasins and each subbasin is further partitioned into hydrologic response units (HRUs) based on unique combination of soil, slope and land use to represent the differences in evapotranspiration and other hydrologic conditions across a watershed.

Sadeghi and Arnold (2002) developed the microbial sub-model in SWAT simulating *FIB* fate and transport in watersheds. The modeling capacity of *FIB* fate and transport was significantly improved in SWAT2005. SWAT considers two types of *FIB*: persistent and less persistent *FIB* (Coffey et al., 2010). The primary sources of *FIB* considered in SWAT include livestock manure application, manure deposition from grazing animals, wildlife, urban runoff, and failing septic systems (Neitsch et al., 2005). The model calculated *FIB* fate and transport going through different processes such as wash-off, die-off, and leaching using different governing equation described by Neitsch et al. (2005). Because of the slower die-off rate of persistent *FIB* during transport process, much smaller amount of persistent *FIB* is assumed at the initial stage of SWAT simulation (Coffey et al., 2007).

SWAT uses a mass balance equation to simulate the transport of *FIB* in two subsystems: 10-mm topsoil layer and streams (Baffaut and Sadeghi, 2010). *FIB* in the 10-mm topsoil layer undergoes adsorption and decay processes to be integrated into soil and extracted by runoff while *FIB* in streams undergoes only decay process (Baffaut and Sadeghi, 2010). The bacterial partition coefficient is used in SWAT to account for the amount of *FIB* adsorbed by soil particle (Coffey et al., 2010). Chick's law of first order decay equation is used to calculate the amount of *FIB* die off and regrowth in the system (Sadeghi and Arnold 2002). The fertilizer database in SWAT contains different types of manure and their associated *FIB* counts, which are expressed in colonies forming units (cfu) per gram of manure and derived from various published literature and other authentic data sources as described in details in Section 2.4. However, one issue with SWAT2005 was that the model generated inaccurate summary outputs for monthly and annual loadings or concentrations from HRUs, subbasins, and reaches although the daily *FIB* loadings from reaches were exported accurately (personnel communications with model developers). In this study, the daily *FIB* loadings from reaches were used to calculate the monthly and annual *FIB* loadings and concentrations at the subbasin and watershed scales.

2.3 Input data for SWAT modeling and calibration

A 10-m digital elevation model obtained from NJDEP was used to represent the topography of the watershed. The soil texture and physiochemical properties of 52 different soils in the watershed were derived from the Soil Survey Geographic (SSURGO) database obtained from the U.S. Department of Agriculture Natural Resources Conservation Service. The land use conditions in the watershed were derived from the 2002 land use/cover data developed and maintained by NJDEP based on a modified Anderson Land Classification system consisting of six broad land use categories including agriculture, barren land, forest, urban, water, and wetlands and many sub categories under each. However, the NJDEP land use/cover data did not have more desired sub categories under agricultural lands for the modeling purpose. Two rounds of agricultural land use inventory were conducted in 2007-2008 by a research team to further identify the spatial patterns of agricultural lands in the watershed including spatial distribution of specific crops, pasture, hay and animals such as horses, cows and sheep. The precipitation, temperature, solar radiation, and relative humidity data collected at the Flemington Weather Station located just outside the watershed was used to generate weather input files for the SWAT model. The weather data at the Flemington Weather Station was downloaded from the National Climatic Data Center website. Agricultural management operations such as tillage, fertilization, planting, and harvest for different crops were based on the common practice recommendation and consultation of local farmers in the watershed. The watershed was delineated into 25 subbasins (Fig. 1) and 625 HRUs based on the land use, soil and topographic conditions for SWAT modeling and calibration (Qiu and Wang, 2014).

A long-term streamflow gaging and water quality monitoring station in the watershed (N1 at the outlet of subbasin 12) as shown in Fig. 1, i.e. the Reaville gaging station (Station number 01398000) at the intersection of Reaville Road and Neshanic River, has been maintained by U.S. Geological Survey and NJDEP. Its daily streamflow and periodical grab-sampled water quality data including *FIB* (fecal coliform and *E. coli*) concentration data were used to calibrate and validate the SWAT model. In addition, more intensive water quality monitoring including *FIB* concentration was conducted at seven locations across the watershed (FN1, SN1, UNT1, N1, TN3, TN3a, and UNT2 at the outlets of subbasins 4, 6, 7, 12, 17, 19, and 21, respectively) from June to November in 2007 through a local watershed restoration planning project resulting ina total of 21 monitoring events on fecal coliform and *E. coli*. in each of the seven locations. The methods about water quality sampling and analysis can be found in Rutgers Cooperative Extension (2010). The fecal coliform and *E. coli* concentration data obtained from these monitoring activities were also utilized to calibrate and validate the SWAT model.

2.4 *FIB* source characterization and input set-up in SWAT

2.4.1 Livestock

The livestock in the watershed included cows, horsed, poultry, and sheep, but were dominated by the presence of cows and horses, which were selected as representative livestock for this watershed where cows referred to a combination of beef and dairy cattle. The number of livestock in the watershed was based on the total number of livestock for Hunterdon County obtained from the 2007 agricultural census data (NASS, 2007), which were distributed to the watershed according to the total areas of agricultural lands in the watershed. It was estimated the watershed supported 560 cows and 408 horses annually. Manure production, dry manure production, fecal coliform loading was calculated based on typical amount of animal waste for each kind of livestock estimated by ASAE (2003). *E. coli* loading was estimated to be 62.5 percent of fecal coliform from respective livestock (IDNR, 2006). It was estimated that a cow generated 1.02 x 10^{11}cfu fecal coliform and 6.04 x 10^{10} *E. coli* and a horse 4.14 x 10^{8} fecal coliform and 2.59 x 10^{8} *E. coli* per day.

The pathways for livestock manure to get into streams were set up in the model through three ways: grazing on pasture, manure application to croplands, and direct deposit into streams. This study assumed that cows and horses were grazed on pasture from May to October and fed with hay during the off-grazing season. Although two rounds of agricultural land use inventory were conducted by driving through the major roads in the watershed, only the sighting, not the specific number of livestock in the watershed was recorded in each location. Thus, the estimated total number of livestock were distributed to pasture HRUs in the watershed based on the spatial distribution of livestock and pasture obtained through agricultural land use inventories with the following assumptions: either cows or horses were distributed to a HRU following the majority type of livestock sighted around that HRU (i.e. pasture in a subbasin) and no HRU had both cows and horses; the same grazing density were applied to each type of livestock across the watershed. Based on the estimated total number of livestock and available pasture, the resulting grazing densities were 4.5 cows per ha and 1.7 horses per ha. Daily dry matter intakes were assumed to be 2.5 percent of mature body weights (Rinehart, 2006).

Applying manure helps reduce or eliminate the need for commercial fertilizers. Manure can be applied in four different ways: surface broadcast followed by disking; broadcast without incorporation; injection under the surface; or irrigation. It was difficult to get detailed data on how manure was applied in the watershed. This study assumed that manure was broadcasted to corn HRUs during April followed by disking tillage at the application rate of 45 Mg/ha (Mg is tonne) to fulfill the nitrogen requirement (Santhi et al., 2006). Based on the manure application rate, the amount of manure generated and stored during the off-grazing season would be applied to 85 ha corn fields, which is 11.5 percent of total corn fields. Cow and horse manures were applied to adjacent corn HRUs based on the spatial distribution pattern of livestock obtained through the agricultural land use inventories.

Direct access to streams allows livestock to deposit manure directly into streams. It was assumed that horse owners did not allow their horses to access stream due to fear of waterborne disease, so there was no direct deposit of horse manure into streams. In the watershed, there was 20 percent of pasture that allowed cows to have direct access to stream. It was further assumed that cows would only spend 2 percent of grazing time in streams and therefore 2 percent of cow manure during grazing period will be modeled as a point source to be directly deposited into the streams.

2.4.2 Wildlife

The wildlife in the watershed included deer, raccoon, rodent, geese, and duck. Deer and goose were considered for this study because of their dominance in wildlife in the watershed. Although New Jersey's Landscape Project mapped the habitats for the rare and imperiled wildlife species, there was no inventory for density distribution of common wildlife at the county level in New Jersey. Historical hunting reports were utilized to quantify wildlife population and density. New Jersey's white-tailed deer herd was a major wildlife species and the estimated annual population during 1984 to 2006 ranged from 120,000 to 200,000, or 5.3 to 8.8 per km^2 (NJDEP, 2008). Approximately, 64,000 deer were harvested annually from about 12,945 km^2 of deer habitat in New Jersey. One square kilometer deer habitat yielded on average 1.5 antlered bucks and 3 antlerless deer (NJDEP, 2010a). The deer density was assumed to be 7.7 deer per km^2 across the whole watershed. The total number of deer in the watershed was estimated to be 608 heads. Canada geese eat small grain such as corn and soybean; and prefer to stay on mowed and fertilized turf grass. There are two types of geese in New Jersey, the resident giant Canada geese and seasonally migrating interior Canada geese. The population of resident geese was estimated to be approximately 98,000 in New Jersey, i.e. four geese per km^2 (NJDEP, 2010b). Consider seasonal migration during winter as well as hatching and growing of resident young Canada geese, the geese density in the watershed was considered to double the density of resident geese, i.e. eight geese per km^2, which resulted in 668 geese in the watershed.

The estimate of the quantity of manure generated by deer and goose was based on the per head manure production in the Salt Creek Watershed TMDL study (WHPA, 2004) and the fecal coliform counts in manure were based on the estimates from the Beeds Lake Franklin County *FIB* TMDL study (IDNR, 2006). A deer generated 5×10^8 cfu fecal coliform and 3.13×10^8 *E. coli* and a goose 4.9×10^{10} fecal coliform and 3.06×10^{10} *E. coli* per day. It shall be noted that a goose generates much more *FIB* than a deer or horse. The amount of *FIB* generated by a goose is almost a half of the amount by a cow.

The pathway for *FIB* contained in wildlife manure to enter into streams was implemented in the SWAT model through continuous grazing operations. Deer were assumed to living on forest, while geese on lawns located in low-density residential, commercial, institutional and transportation urban area. The deer and goose manure deposition rates on these lands were estimated by dividing the quantity of manure generated by their total habitat areas.

Since the low-density developments were the dominant type of urban lands in the watershed, the *FIB* loadings from geese through grazing on lawns also approximated the *FIB* loadings from urban runoff. There were other *FIB* sources in urban areas such as pet feces, other urban wildlife, sanitary sewer cross-connections, and ineffective solid waste collection. These sources were ignored in this study since those sources were mostly related to higher development density and there was no accumulation rate available for *FIB* (USEPA, 2000).

2.4.3 Failing septic systems

Although many households in the watershed relied on septic systems for sewer and wastewater treatment, there was no inventory of those systems and their operational status in the watershed. There were 2,696 households located in the low density and rural residential areas in the watershed: 1,508 were in sewer service areas (SSAs) and 1,188 were in the non-SSAs. Assuming one-fifth of the households in SSAs and all households in non-SSAs relied on septic systems, about 1,490 households were likely using septic systems for on-site wastewater treatment.

No study clearly estimated how many septic systems failed or did not properly function in the watershed. Generally, septic system failure occurs in older homes. Improper maintenance also increases the failure rate of septic systems. Virginia Department of Environmental Quality (2002) estimated the failing rate of septic systems based on the construction dates of homes. Failing rates were estimated to be 40, 20, and 5 percent for above 30, 10-30, and less than 10 year old systems, respectively. Several studies found that 30 percent of all septic systems were either failing or not functioning. Based on the construction ages of the housing units in the watershed, a failing rate of 30 percent was assumed for failing septic systems in the study, which resulted in 447 failing septic systems in the watershed. Only failing septic systems close to streams likely have direct impact on water quality. Of the 447 potentially failing septic systems, 164 septic systems were located within the 200-meterbuffer zone of the streams and were assumed to have direct impacts on water quality.

The estimated *FIB* loadings from failing septic systems were based on the following assumptions: (1) average number of persons served by each system is 2.8; (2) septic system effluent discharge rate of 70 gallons per person per day; and (3) concentrations in septic tank effluents were 1 x 10^6cfu per 100mL fecal coliform, and 6.3 x 10^5 cfu per 100mL *E. coli* based on Indiana's Salt Creek *E. coli* TMDL study (WHPA, 2004). The total loads of effluents from failing septic systems entering streams in the watershed were estimated as 2.433 x 10^{11} cfu fecal coliform, and 1.533 x 10^{11} cfu *E. coli* per day. The effluents from these failing systems were incorporated into SWAT as point source directly discharged into the streams in each subbasin.

2.5 Model calibration and validation

2.5.1 Hydrology and sediment calibration and validation

Streamflow calibration was performed at annual, monthly and daily time step using the streamflow data observed from the Reaville gaging station. The calibration period was from 1997 to 2002 and the validation period from 2003 to 2008. The model evaluation indicators NSE, Coefficient of determination (R^2) and mean relative error (D) were used for calibration and validation.NSE indicates the fitting of observed and simulated data and ranges between $-\infty$ and 1.0 (1 inclusive), with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance (Moriasi et al., 2015). R^2 describes how much of the observed dispersion is explained by the simulation and ranges from zero to one. A value of zero means no correlation at all whereas a value of one means that the dispersion of the simulation is equal to that of the observation (Krause et al., 2005). D compares the mean of the simulated data to the observed data. The value of zero indicates no deviation, a negative value indicates underestimation and a positive value overestimation. A sensitivity analysis was first performed to determine the most influential parameters for model calibration. In this study, a sensitivity analysis was executed using the Latin-Hypercube One-Factor-At-a-Time (LH-OAT) approach embedded in ArcSWAT. The identified sensitive parameters were used for calibration until average observed and simulated surface runoffs were within 15 percent and R^2 and NSE greater than 0.5. Similarly, base flow was calibrated until the simulated base flow is within 15 percent of the observed base flow, and surface runoff was continually verified as the base flow calibration variables also affect surface runoff. Sediment calibration was based on the total suspended solids (TSS) measurements at the same station. The key model parameters for calibrating TSS were the universal soil loss equation land-cover and management factor. Calibration for sedimentation in uplands involved adjusting the support-practice factor. Calibration for channel-sediment routing processes in streams involved adjusting the channel-cover factor, channel-erodibility factor, linear factor, and exponential factors for channel-sediment routing. Sediment calibration was conducted such that simulated levels of concentrations in TSS matched the observed concentration levels. The detailed calibration procedures were described in Qiu and Wang (2014).

2.5.2 *FIB* calibration and validation

FIB calibration is a challenging task because of the difficulty of representing the spatial and temporal distribution of *FIB* sources (Coffey et al., 2010). Due to great uncertainties surrounding the spatial and temporal distributions of *FIB* sources, the calibration focused on adjusting release rates from sources, that is, only bacteria wash-off and die-off coefficients were calibrated, while other parameters such as the fraction of manure applied to land areas that has active colony forming units and bacteria partition coefficient between solution and soil particulates, were set to their default values in SWAT. The wash-off fraction, die-off factor for bacteria in soil solution, die-off factor for bacteria adsorbed to soil particles, die-off factor for bacteria on foliage, and die-off factor for bacteria in streams were calibrated for both *E. coli* and fecal coliform. Die-off coefficients for *E. coli* and fecal coliform vary in the literature. Fecal coliform is considered less persistent compared to *E. coli* (Sadeghi and Arnold, 2002), though its die-off coefficients were found to be much lower in some studies (Baffaut, 2004). A conservative estimation was made for fecal coliform for planning purpose in which the die-off coefficients of fecal coliform were assumed to be the same as those of *E. coli*.

The most commonly used model evaluation indicator for *FIB* calibration and validation is NSE. In addition to NSE, other model evaluation indicators such as percent bias (PBIAS), and Root Mean Square Error-observation standard deviation ratio (RSR) were calculated to assess the performance of the SWAT model in simulating *FIB* concentrations in this watershed. PBIAS represents how smaller or larger the simulated values than observed values (Giri et al., 2012). The optimal value of PBIAS is zero. A low-magnitude value indicates accurate model simulation. Positive values indicate model underestimation bias, and negative values model overestimation bias (Gupta et al., 1999).RSR depicts the ratio of root mean square error (RMSE) to standard deviation of the observed data. RSR varies from zero to a large positive value. A value of zero indicates zero RMSE or residual variation and therefore perfect model simulation. The lower RSR, the lower the RMSE, and the better the model simulation performance (Moriasi et al., 2015).

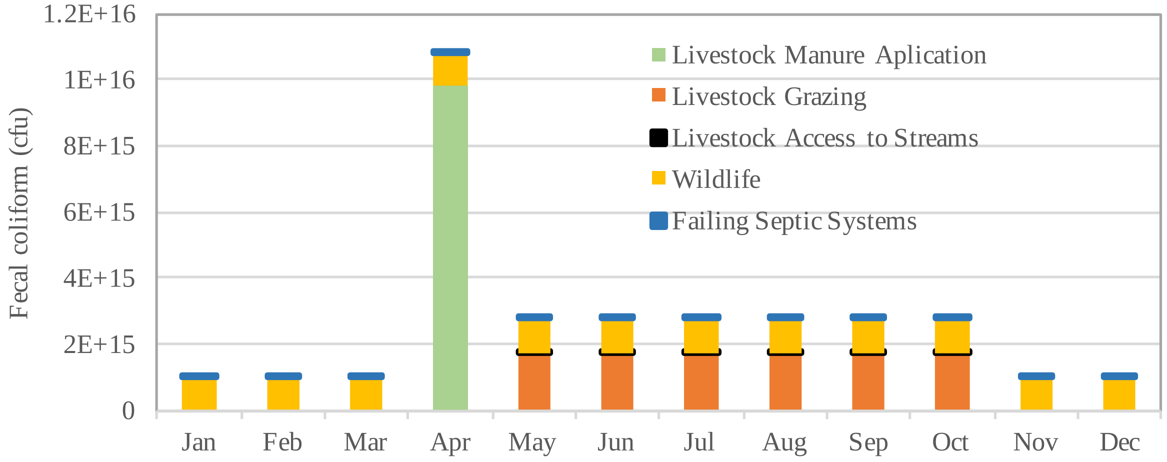
3 Results

3.1 Source characterization

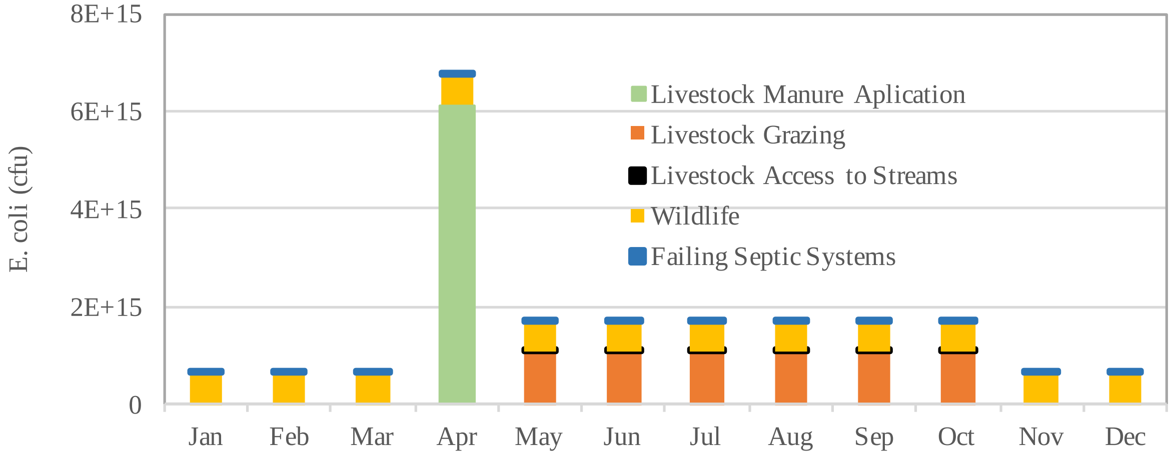
Table 1 summarizes five *FIB* sources and their total source loadings to the watershed. The highest *FIB* loadings to the watershed came from the wildlife with 1.21 x 10^{16} cfu per year in fecal coliform and 7.54 x 10^{15} cfu per year in *E. coli*, which was then followed by the livestock grazing on pasture and livestock manure applications to corn fields. These three sources were modeled as non-point sources in the SWAT model; and most of them would be died off on-site or attached to soils and vegetation and eventually died off on their pathways to streams. Failing septic systems generated only 8.88 x 10^{13} cfu in fecal coliform and 5.60 x 10^{13} cfu in *E. coli*. and cow manure deposited into streams 4.15 x 10^{13} cfu in fecal coliform and 2.60 x 10^{13} cfu in *E. coli* per year, but both could have much more detrimental effects on water quality since they were directly discharged into streams and were modelled as point sources.

Table 1 *FIB* sources and their pathways and estimated source loadings in Neshanic River Watershed.

FIB Sources	Modelled Pathways	Model Setup	Period	Source Loadings (cfu/year)	
				Fecal Coliform	*E. coli*
Livestock	Cattle and horses manure application to corn fields	Non-point Source	April	9.78×10^{15}	6.11×10^{15}
	Cattle and horses grazing on pasture	Non-point Source	May to October	1.04×10^{16}	6.49×10^{15}
	Cattle manure direct deposit into streams	Point Source	May to October	4.15×10^{13}	2.60×10^{13}
Wildlife	Deer continuously grazing in forest; Geese continuously grazing on lawns	Non-point Source	January to December	1.21×10^{16}	7.54×10^{15}
Septic Systems	Failing septic system discharges as continuous fertilization operations	Point Source	January to December	8.88×10^{13}	5.60×10^{13}



a. Fecal coliform



b. *E. coli*

Fig. 2 The estimated monthly *FIB* source loadings in Neshanic River Watershed.

The *FIB* source loadings to the watershed varied significantly across different months. Fig. 2 presents the estimated monthly *FIB* source loadings to the watershed. The highest monthly *FIB* loadings (1.08 x 10^{16} cfu in fecal coliform and 6.74 x 10^{15} cfu in *E. coli*) occurred in April due to the application of livestock manure to selected corn fields in the watershed. The least amount of *FIB* loadings (1.01 x 10^{15}cfu in fecal coliform and 6.33 x 10^{14} cfu in *E. coli* per month) occurred from November to March, during which there were only two *FIB* sources: wildlife and failing septic systems. From May to October, significant amount of *FIB* loadings was added to the watershed because of livestock grazing on pasture and their access to streams during the grazing and the *FIB* source loadings were 2.75 x 10^{15} cfu in fecal coliform and 1.72 x 10^{15} cfu in *E. coli* per month.

3.2 Calibration and validation

3.2.1 Streamflow and Sediment

The streamflow was calibrated at annual, monthly and daily time steps from 1997 to 2002 and validated from 2003 to 2008. Out of 26 parameters tested, the top ten most influential parameters based on the sensitivity analysis were channel effective hydraulic conductivity, initial SCS Curve Number II value, base flow alpha factor, Manning’s “n” value for main channel, surface runoff lag, snow pack temperature lag factor, shallow aquifer for return flow to occur, soil evaporation compensation factor, maximum plant leaf area index, and maximum canopy storage. For simplicity, the monthly flow calibration and validation results are summarized here. NSE, R2, and D were 0.69, 0.72, and -5.83 percent, respectively, for monthly flow during the calibration period, and 0.68, 0.69, and -3.18 percent, respectively, during the validation period. Based on Moriasi et al. (2015), the simulation of streamflow was considered to be satisfactory. The observed instantaneous TSS concentrations were visually compared to the simulated TSS daily concentrations. The simulated TSS concentrations captured the changes in all observed TSS concentrations except onein January 1998 during the calibration period. The observed TSS concentrations are comparable to the simulated concentrations during the validation period with a few exceptions on a few low-flow days. The detail description of streamflow and sediment calibration and validation results was presented in Qiu and Wang (2014).

3.2.2 *FIB*

The *FIB* calibration period was from 1997 to 2002 and the validation period from 2003 to 2008. The calibrated value for the wash-off fraction for persistent bacteria, die-off factor for bacteria in soil solution, die-off factor for bacteria adsorbed to soil particles, die-off factor for bacteria on foliage, and die-off factor for bacteria in streams are presented in Table 2.

Table 2 The calibrated parameter values for simulating *FIB* concentration in Neshanic River Watershed.

Model process	Parameter	Description	Value used
E. coli	WOF_P	Wash-off fraction for persistent bacteria	0.25
	WDPQ	Die-off factor for persistent bacteria in soil solution at 20°C (1/day)	0.10
	WDPS	Die-off factor for persistent bacteria adsorbed to soil particles at 20°C. (1/day)	0.01
	WDPF	Die-off factor for persistent bacteria on foliage at 20°C (1/day)	0.20
	WDPRCH	Die-off factor for persistent bacteria in streams (moving water) at 20°C. (1/day)	0.40
Fecal coliform	WOF_LP	Wash-off fraction for less-persistent bacteria	0.25
	WDLPQ	Die-off factor for less-persistent bacteria in soil solution at 20°C (1/day)	0.10
	WDLPS	Die-off factor for less-persistent bacteria adsorbed to soil particles at 20°C. (1/day)	0.01
	WDLPF	Die-off factor for less-persistent bacteria on foliage at 20°C (1/day)	0.20
	WDLPRCH	Die-off factor for less-persistent bacteria in streams (moving water) at 20°C. (1/day)	0.40

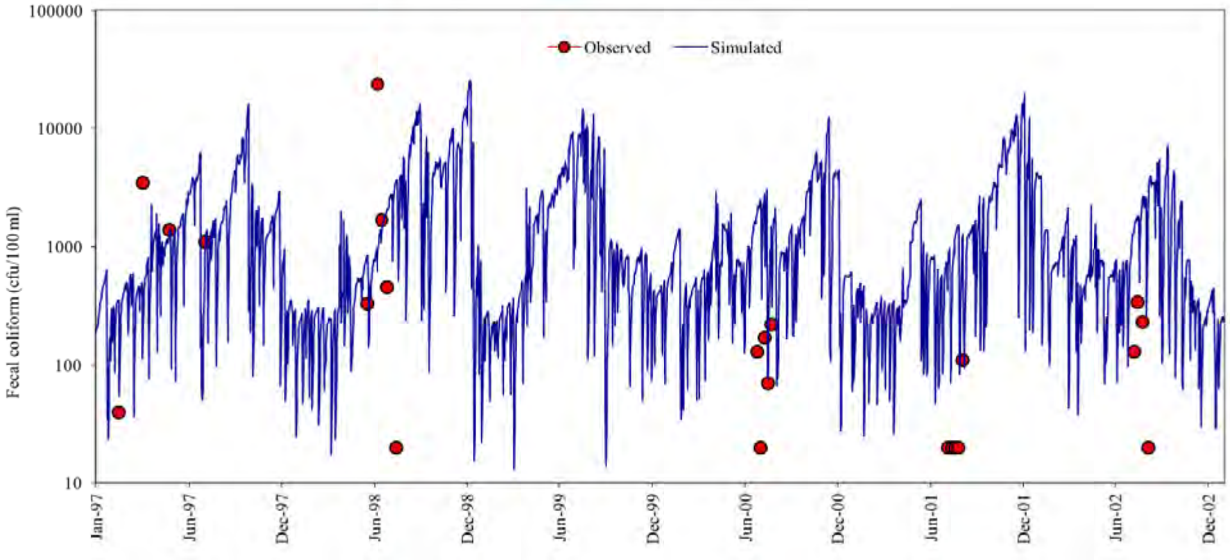
The capacity of the SWAT model in simulating *FIB* contamination was also evaluated using three model evaluation indicators. The calibration was based on 23 observations of fecal coliform concentration and 14 observations of *E. coli* concentration at N1 during 1997-2002 period. NSE, PBIAS and RSR were -0.11, 13.81, and 1.05 for fecal coliform and -28.92, -360.63 and 5.47 for *E. coli*, respectively, during the calibration period. These values especially PBIAS indicated that the SWAT model was well calibrated for modeling fecal coliform but not for *E. coli*.

Table 3 presents the NSE, PBIAS, and RSR values at all seven monitoring stations in the watershed during the validation period. These values at N1 were based on 49 observed concentrations, among which 28 monitoring events were conducted by NJDEP/USGS at frequency of roughly 5 or 6 times per year from 2003 to 2008 and 21 from June to November in 2007 through a local watershed restoration planning project. The NSE, PBIAS and RSR values at N1 were -0.30, 24.11, and 1.14 for fecal coliform and were -0.12, 90.16, and 1.06 for *E. coli*, respectively. The values of three model evaluation indicators at the other six monitoring stations were only based on the 21 monitoring events in 2007 conducted through the local watershed restoration planning project. The NSE, PBIAS, RSR based on all monitoring events in all seven monitoring stations were -0.24, 42.49, and 1.11for fecal coliform and were -0.10, 73.71, and 1.05 for *E. coli*, respectively.

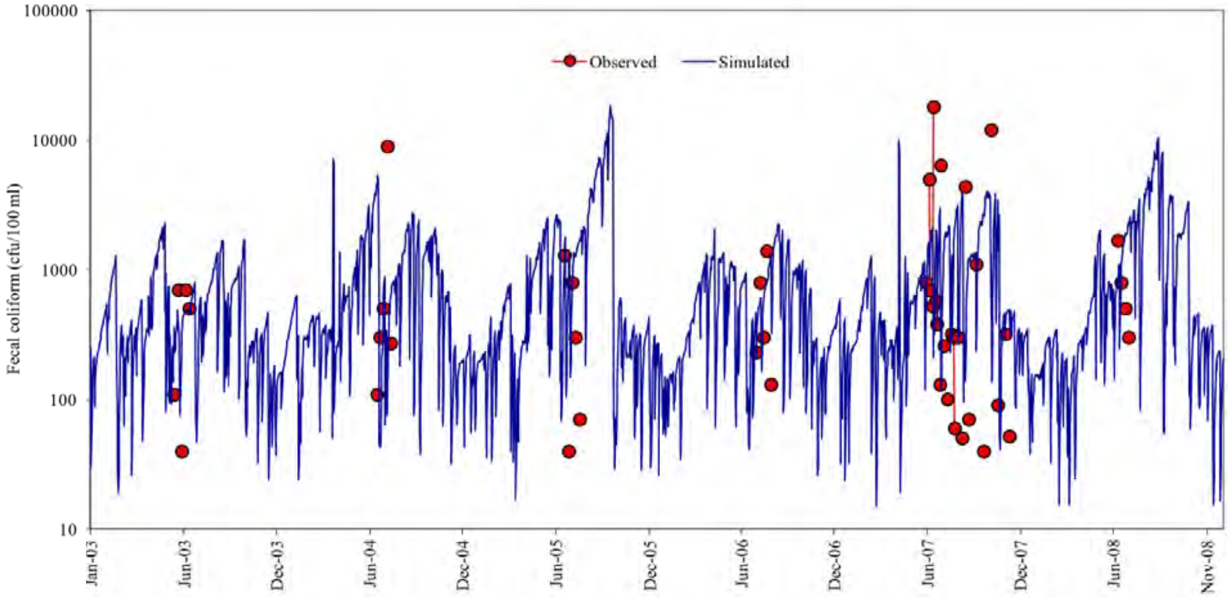
Table 3 The values of model evaluation indicators NSE, PBIAS and RSR for validating fecal coliform and *E. coli* at seven monitoring stations in Neshanic River Watershed

Monitoring	Fecal Coliform				*E. coli*			
Stations	N	NSE	PBIAS	RSR	N	NSE	PBIAS	RSR
N1	49	-0.30	24.11	1.14	49	-0.12	90.16	1.06
FN1	21	-0.30	72.43	1.14	21	-0.14	84.06	1.07
SN1	21	-0.72	1.45	1.31	21	-0.13	62.53	1.07
TN3	21	-0.86	-30.45	1.37	21	-3.54	-124.93	2.13
TN3a	21	-1.17	-29.29	1.47	21	-0.78	0.12	1.33
UNT1	21	-0.19	84.82	1.09	21	-0.18	93.53	1.09
UNT2	21	-0.20	75.74	1.09	21	-0.12	87.90	1.06
All	174	-0.24	42.49	1.11	175	-0.10	73.71	1.05

Most of previous SWAT modeling studies used NSE to evaluate the model performance in simulating *FIB* transport. The reported NSEs ranged from -2.2 to 0.52 by Parajuli et al. (2009) and -0.94 to 0.47 by Niazi et al. (2015). Despite the great uncertainties in the spatial and temporal distributions of *FIB* sources and the small number of grab samples, these NSE values except at TN3 were very close to zero and in the range of what reported in literature. The PBIAS value at N1, the main station for validation was 24.11, which implied a satisfactory validation according to Moriasi et al. (2015). Fig. 3 visually compared the simulated and observed fecal coliform concentration during the calibration period 1997-2002 (a) and the validation period 2003-2008 (b). There was some unevenness between the simulated and observed fecal coliform concentration during the calibration period, i.e. most of the observed concentrations were on the higher end of the simulated concentration in 1997 and 1998 and on the lower end in 2000, 2001 and 2002 as shown in Fig. 3(a). However, both the simulated and observation fecal coliform concentration matched better during the validation period; the simulated concentrations were comparable to most observed fecal coliform concentrations.



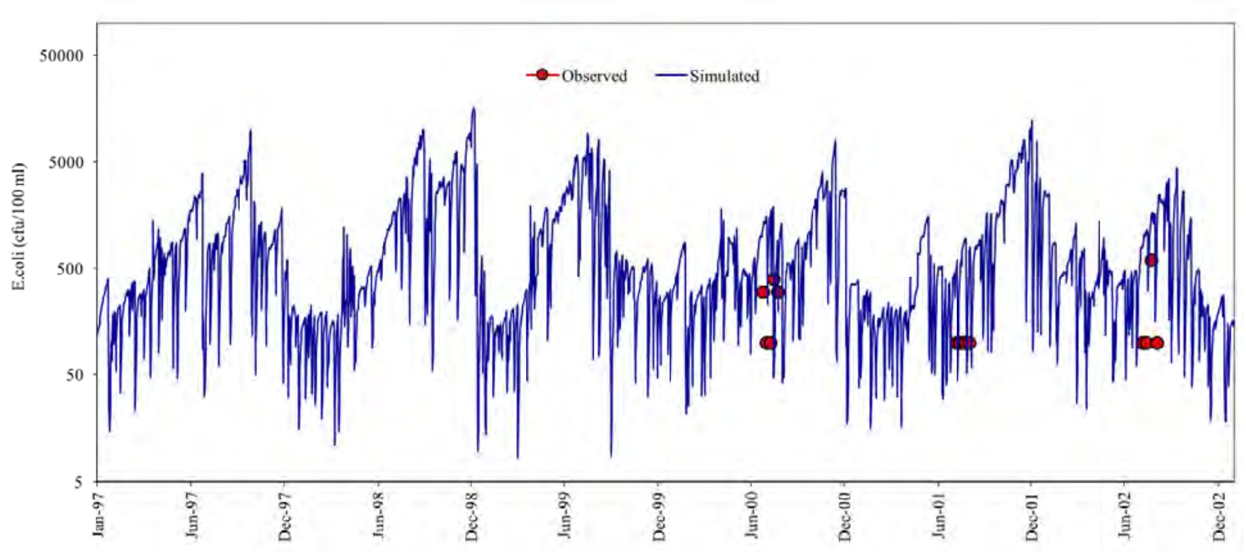
a. During the calibration period 1997-2002



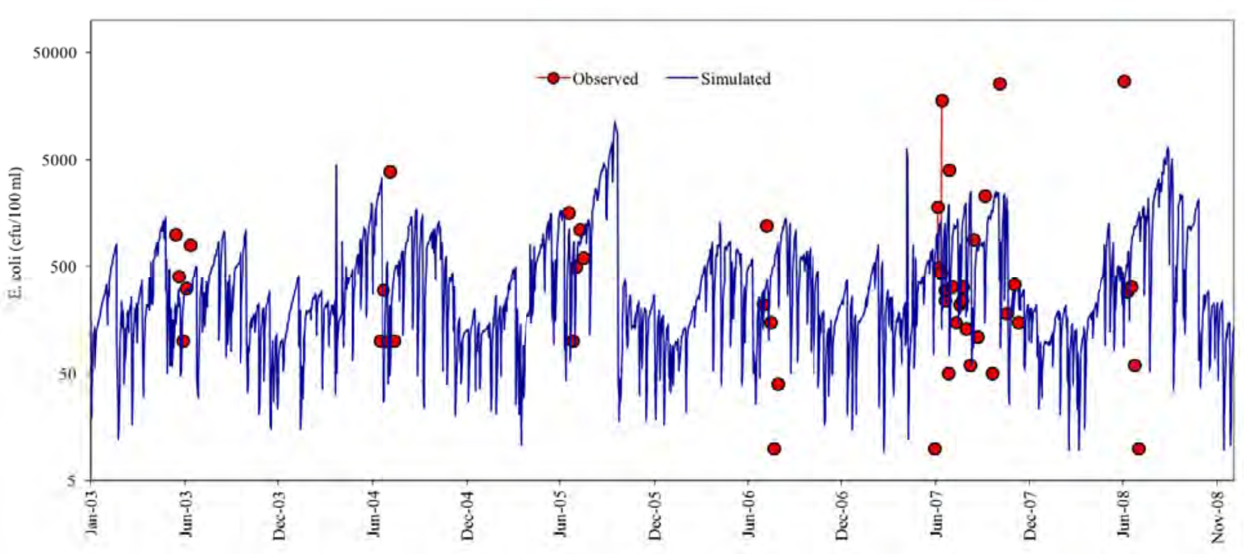
b. During the validation period 2003-2008

Fig. 3 Comparison between the simulated and observed daily fecal coliform concentration during the calibration (a) and the validation (b) periods at the Reaville station (N1) in Neshanic River Watershed.

Fig. 4 visually compared the simulated and observed *E. coli* concentration during the calibration period 1997-2002 (a) and the validation period 2003-2008 (b). As shown in Fig. 4, similar observations were found when comparing the simulated and observed *E. coli* concentrations during the calibration and validation periods. It should be noted that the model predicted daily averages, whereas the observations were point-in-time grabs. Because the observations are not daily averages, they are likely to exhibit greater variability than model predictions.



a. During the calibration period 1997-2002



b. During the validation period 2003-2008

Fig. 4 Comparison between the simulated and observed daily *E. coli* concentration during the calibration (a) and the validation (b) periods at the Reaville station (N1) in Neshanic River Watershed.

3.3 Relative contribution of *FIB* sources to water quality

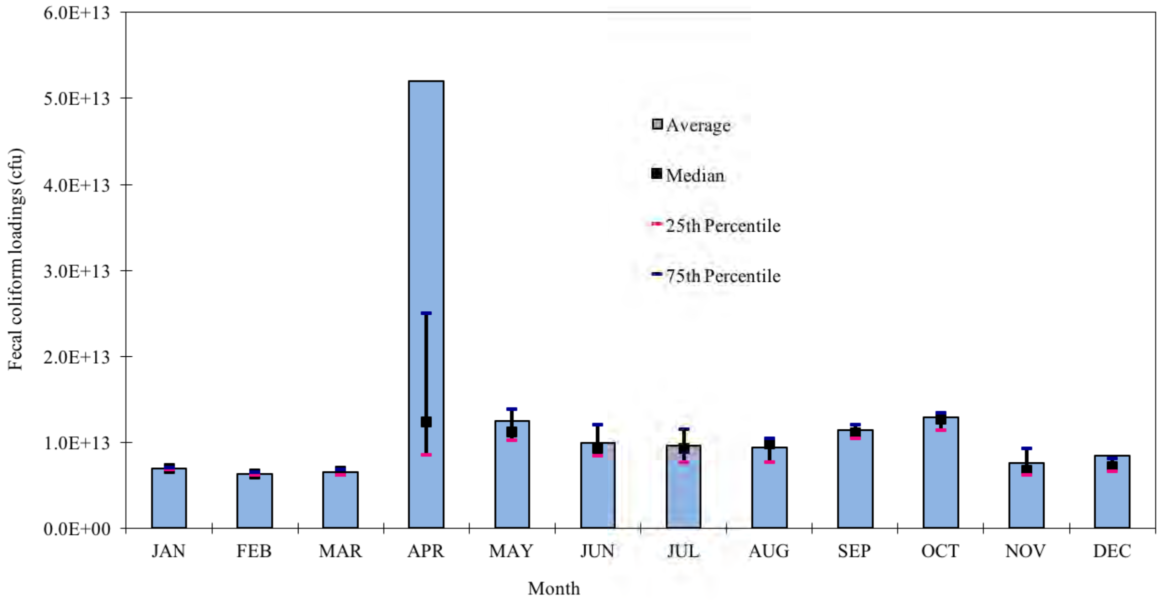
Human and animal wastes are *FIB* sources in the Neshanic streams. Although there are five *FIB* sources as characterized in Section 3.1, some *FIB* would die-off and fail to reach the watershed outlet because of various physical and biological processes onsite, during their pathway to the streams and within streams. Table 4 presents the source contribution of average annual loadings of fecal coliform and *E. coli* to water quality at the Neshanic River Watershed outlet. The bacteria contributions were estimated as the differences of the total amount of *FIB* reaching at the watershed outlet between the baseline modeling scenario that took account of all *FIB* sources and alternative modeling scenarios that removed certain *FIB* sources. Failing septic systems were the largest source for *FIB* and contribute almost half of the *FIB* loadings to water quality degradation at the watershed outlet. The second largest source of *FIB* was manure applied to selected corn fields, which accounts for about 31 percent of the annual *FIB* loadings reached to the watershed outlet. Livestock direct access to streams contributed about 19 percent of the annual *FIB* loadings at the watershed outlet, which made it the third largest source of *FIB*. Livestock grazing on pastures contributed about 2 percent of the *FIB* loadings at the watershed outlet. Wildlife including geese and deer generated significant amount of *FIB* to the watershed, but was just a minor contributor to the *FIB* loadings at the watershed out as it was modeled as non-point sources and most of *FIB* died off or was retained on the landscape or in the streams.

Table 4 Source contributions of the annual loadings to water quality at the Neshanic River Watershed outlet Sources.

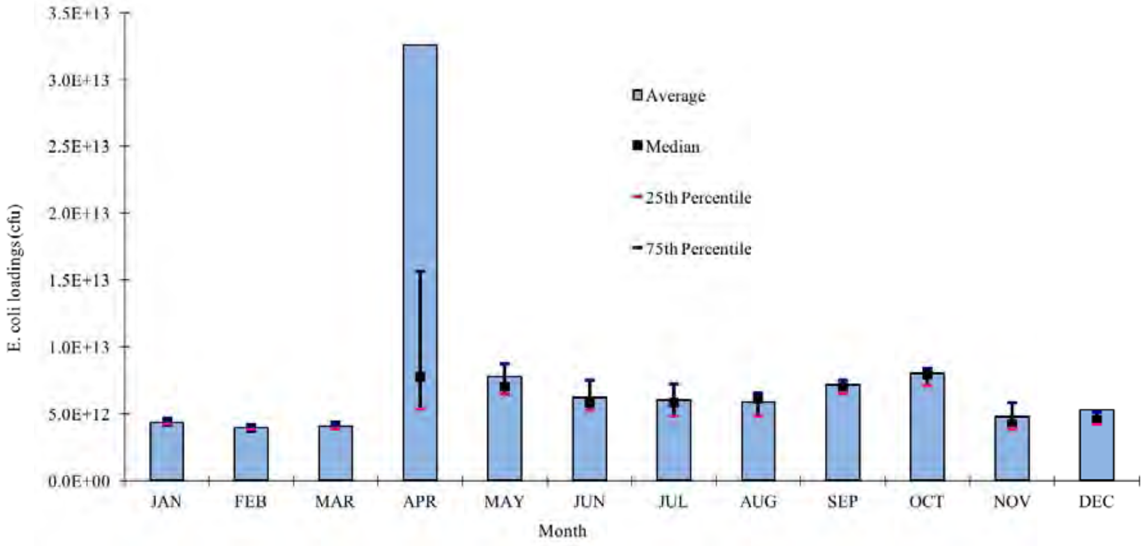
Sources	Fecal Coliform		*E. Coli*	
	Loading (cfu/year)	Contribution (%)	Loading (cfu/year)	Contribution (%)
Failing septic systems	7.20×10^{13}	45.94	4.54×10^{13}	46.09
Manure application	4.91×10^{13}	31.34	3.08×10^{13}	31.25
Livestock access to streams	2.96×10^{13}	18.90	1.85×10^{13}	18.81
Livestock grazing	3.85×10^{12}	2.45	2.41×10^{12}	2.45
Wildlife	2.15×10^{12}	1.37	1.37×10^{12}	1.40
Total	1.57×10^{14}	100.00	9.84×10^{13}	100.00

3.4 Seasonal pattern of *FIB* loadings

Fig. 5 presents the seasonal pattern of the total fecal coliform (a) and *E. coli* (b) loadings that reached to the watershed outlet based on the monthly *FIB* loadings during the modeling period 1997-2008. The figure compared the average, median, the 25 and 75 percentile values of the monthly fecal coliform and *E. coli* loadings. The seasonal patterns for both fecal coliform and *E. coli* loadings at the watershed outlet were similar. The *FIB* loadings reached to the watershed outlet from April to October were generally much higher than in other months because the higher *FIB* source loadings during those months as discussed in Section 3.1. The average *FIB* loadings in April were the highest, i.e. four to eight times higher than the average monthly values from May to October. The high average *FIB* loadings in April were mostly attributed to livestock manure application to selected corn fields in the watershed. The monthly *FIB* loadings decreased from May to August and went up in September and reached to a new peak in October. Such variation in the monthly *FIB* loadings reached to the watershed outlet might be related to the storm pattern in the study area. The frequent and severe storm events in May helped carry more *FIB* to the streams. The higher *FIB* loadings reached to the watershed outlet in September and October might be due to the wash-off effects of the *FIB* accumulated during the summer period. *FIB* loadings were generally low during the cold season from November to March because of less active *FIB* source loadings as discussed in Section 3.1.



a. Fecal Coliform



b. *E. coli*

Fig. 5 Monthly variation in Fecal Coliform and *E. coli* loadings that reached tothe Neshanic River Watershed outlet from 1997 to 2008.

4 Discussions

Given uncertainties in representing *FIB* sources spatially and temporally and a small number of grab samples in multiple locations for model calibration and validation, the SWAT model reasonably simulates the fate and transport of fecal coliform in Neshanic River Watershed. The model evaluation indicator PBIAS for fecal coliform at the N1 station (the most important calibration station among the seven monitoring stations) was 13.81 for calibration and 24.11 for validation, which are considered tobe satisfactory. However, the values of other model evaluation indicators are not satisfactory. The most commonly used NSEs are all negative for all seven stations, although they are very close to zero and arein the range of NSEs reported by other studies. One possible reason could be that this study used an older version of SWAT model that had simpler overland and stream transport process that did not consider the hyporheic exchange of bacteria transport across the sediment-water interface during the in-stream processes as identified by Kim et al. (2017). SWAT model that incorporates complete understanding of *FIB* transport processes would help improve the model performance.

In this study, the SWAT model generally performed better when simulating fecal coliform than *E. coli* as evidenced by the model evaluation indicators. A possible reason could be the lack of *E. coli* data for *FIB* source characterization from some sources. The study applied a conversion rate of62.5 percent to estimate *E. coli* loading from fecal coliform loads based on IDNR(2006). Coffey (2015) converted the simulated fecal coliform output to *E. coli* concentrations based on a translator equation developed by VDEQ (2002) for comparing the simulated results to the observed ones to evaluate whether the *E. coli* water quality standard would be achieved. Either conversion would introduce a systematic bias into the modeling results, which affect the model performance. Such biases could be reduced or eliminated by developing better data sources for *FIB* modeling.

This study identified wildlife as only a minor *FIB* contributor to the water quality degradation measured at the watershed outlet as it was modeled as a nonpoint source. However, wildlife could easily be detrimental to water quality since wildlife could move around in landscape and directly deposit its manure to waterbodies and therefore be a point source that directly transport *FIB* into waterbodies. Given the fact that the total *FIB* loadings from wildlife especially geese were about 136 times higher than from the failing septic systems in the watershed, the results would be quite different if wildlife directly deposit its manure to the waterbodies in the watershed. Therefore, it is essential to keep geese and other wildlife away from waterbodies and therefore minimize their impacts on water quality through various watershed management practices.

The analysis on the seasonal variability of *FIB* loadings that reached to the watershed outlet showed that *FIB* loadings to the streams from April to October were generally higher than other months. The highest *FIB* loadings were in April and in October. The high *FIB* loadings to the streams in spring including April, May and June has been generally recognized and understood and most of mandatory monitoring on *FIB* in streams is conducted in spring and summer. However, not enough attention was given to the high *FIB* loadings in the fall. Cho (2016a) developed a new bacteria subroutine for SWAT and introduced critical temperatures as a parameter to simulate the onset of bacteria growth and die-off for understanding the improved understanding of the seasonal variability of bacteria in the streams. Such development in SWAT would help better understand the seasonal variability of *FIB* in streams. Future *FIB* monitoring may also need to be expand to early spring like April and late fall like October to fully understand the *FIB* fate and transport in watersheds for public health protection.

5 Conclusions

This study assessed the SWAT modeling capability of simulating the fate and transport of fecal coliform and *E. coli* and their temporal variations in Neshanic River Watershed, a sub-urban watershed with mixed land uses in central New Jersey. The study specifically demonstrated the complicity of characterizing various *FIB* sources associated with suburban land uses, which often were simplified or even ignored by other SWAT applications. Despite the great uncertainties in spatial and temporal representation of *FIB* sources, limited number of grab samples for model evaluation and the use of a relatively older model, SWAT satisfactorily simulated the fate and transport of fecal coliform in the watershed. Various model evaluation indicators have been used to assess the model performance in simulating *FIB* fate and transport in watersheds, but there were no consistent criteria in using them. More *FIB* calibration and validation work are needed tohelp develop a set of criteria values for assessing the modeling capacity in simulating the *FIB* fate and transport in watersheds that are similar to the criteria values for assessing the modeling capacity in simulating streamflow and the fate and transport of sediment and nutrients in watersheds as done by Moriasi et al. (2015).

Biophysical models like SWAT are promising tools to understand the *FIB* fate and transport in watersheds, but the *FIB* simulation is still an emerging science. Like other empirical applications in simulating *FIB* concentration in watersheds, this study contributes to the knowledge base of understanding the SWAT modeling capacity in simulating the *FIB* fate and transport in watersheds. Such knowledge will help develop better simulation model for watershed mangers and policymakers to use for effectively controlling *FIB* and thereby reducing their health and environmental risks.

Acknowledgement

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