Title: Incorporating heterogenous estuaries into the Soil and Water Assessment Tool (SWAT+)

Abstract

1. Introduction

1. Coastal estuaries threated by land-use and climate change

Estuaries are critical zones for biodiversity, fisheries, tourism, livelihoods, water quality and nutrient cycling (e.g., Jänes et al., 2022; Pendleton, 2010). However, with changes in climate, land-use, and coastal water elevation, estuaries face increasing environmental degradation, including water quality threats from the landscape – such as excess nutrients, sediments, and pathogens, ultimately leading to accelerated eutrophication (Bricker et al., 2008; Freeman et al., 2019; Paerl and Paul, 2012; Robins et al., 2016). At the turn of the century, a survey of almost one hundred estuaries along the east and west coast of the conterminous United States revealed 78% of the estuarian surface area was already experiencing eutrophic conditions (Bricker et al., 2008). The environmental stressors put on estuaries is further exacerbated by the rapid human population growth in coastal regions: between 1970 and 2010, the majority of U.S. population growth (52%) was concentrated in coastal counties (45%, or 50.9 million people; NOAA, 2013). Urbanization has been a focus of addressing estuarian pollution, however, in many estuaries agriculture is a more prominent source of nutrient and sediment pollution (Bricker et al., 2008; Freeman et al., 2019; Hole et al., 2002).

Estuarine coastal managers need specific information to help address the water quality issues unique to their estuary. Both land management (e.g., Murphy and Sprague, 2019) and climate (e.g.,Yang et al., 2016) have been shown to be critical components to the severity of water quality issues. However, making regional generalizations about land-management and climate characteristics to address water quality issues proves to be difficult and less informative for localized management decisions (Bricker et al., 2008; Liang et al., 2020; Murphy and Sprague, 2019). Biogeochemical mechanisms for nutrient transport and response in watersheds and estuaries can vary even within the same region, due to causes such as variation in watershed transport capacity, climatic patterns, and algal species (Anderson et al., 2021; Fraterrigo and Downing, 2008; Goyette et al., 2019; Pinckney et al., 2001) Hence, in many instances scientists and resource managers have been focusing on addressing each system's specific conditions that lead to its unique water quality issues and response.

Environmental model coupling has become a common framework for addressing individual watershed and estuarine water quality issues by including the links between watershed, river, and estuary (Linker et al., 2002; Medellín-Azuara et al., 2017; Robins et al., 2016; Santiago-Collazo et al., 2019). One prominent example of coupling models for a watershed -estuary system is in the Chesapeake Bay. The coupled models were first used in the *1987 Chesapeake Bay Agreement* to help validate the need for a 40% nutrient reduction goal by the year 2000 (Linker et al., 2002) and continue to be used and improved upon today (Chesapeake Bay Program, 2020a, 2020b). Many other regions have undertaken similar environmental model coupling to understand basin-riverine-estuary-coast dynamics, such as: Mobile Bay, Alabama (Estes et al.,

2015), St. Louis Bay estuary, Missouri (Liu et al., 2008), Guadalupe Bay, Texas (Arismendez et al., 2009), the Seine River and estuary, France (Laruelle et al., 2019), and the Gironde Estuary, France (Lajaunie-Salla et al., 2017), and along the Iberian coast in Spain (Brito et al., 2015; Campuzano et al., 2016; Sobrinho et al., 2021).

No one framework will be able to achieve representation of all physical processes and meet every goal for its application. Hence, there exist many modeling applications that are suitable for use to represent a system as comprehensive and complex as the watershed to the coast. Modeling has trended towards more complex spatial and process representations, supported by the rise of computing power (Ganju et al., 2016). However, there remains extensive possibility with simpler model representations, especially for decision support within the policy and management realms. Simpler simulations can help with comprehension of results and can provide equally as robust prediction as more complex simulations (Ganju et al., 2016; Ménesguen et al., 2007). Studies comparing simplified and more complex models of the same system (e.g., food webs, watersheds) demonstrate that even simple models can capture the dynamics of system well, with different levels of complexity needed depending on the system dynamics (Orth et al., 2015; Raick et al., 2006). Additionally, simple models are less prone to over-fitting, a problem that remains with complex ecological models with increasing flexibility (Bell and Schlaepfer, 2016).

The goal of this study is to simplify a watershed-estuary representation within a single modeling framework. Our study site is Old Woman Creek (OWC), an estuary located in northern Ohio in the Lake Erie drainage basin. We employ the latest version of the Soil and Water Assessment Tool, SWAT+, to simulate both the watershed and a representation of the estuary. We calibrated our model to daily discharge and water quality data (phosphorus, sediment). We validated our simulated estuary approach using the outputs from a hydrodynamic model and soil core data within the estuary. We coordinated three model--review and input sessions with a subset of potential end-users. The final modeling framework is a helpful tool for end-users in land-management and climate adaptation and can be tested and applied in other estuary and wetland systems.

2. Methods

Old Woman Creek watershed and estuary

Old Woman Creek watershed (HUC 04100012 03 04) and estuary is situated in northern Ohio in the Great Lakes Drainage Basin (Figure 1). The basin is approximately 71 km^2 and drains directly to Lake Erie. The primary land-use in the watershed is agricultural row crop (54%), followed by forested (27%), pasture (11%), and urban land-uses (8%). From years 2011-2020, Old Woman Creek received an average of 1090 mm of precipitation per year (min – 910 mm; max – 1230 mm). Normal daily temperatures ranged from an average annual minimum of -19°C to an average annual maximum of 34°C. The Old Woman Creek watershed is on the 303d list of impaired waters for impairments to aquatic life use (OEPA, 2005, 2004). In order to improve the aquatic life use classification, the focus of the Old Woman Creek total maximum daily loads

(TMDLs) are on sediment and nutrients, with a particular focus on phosphorus because of its role as a limiting nutrient for algal blooms in freshwater systems (OEPA, 2005).
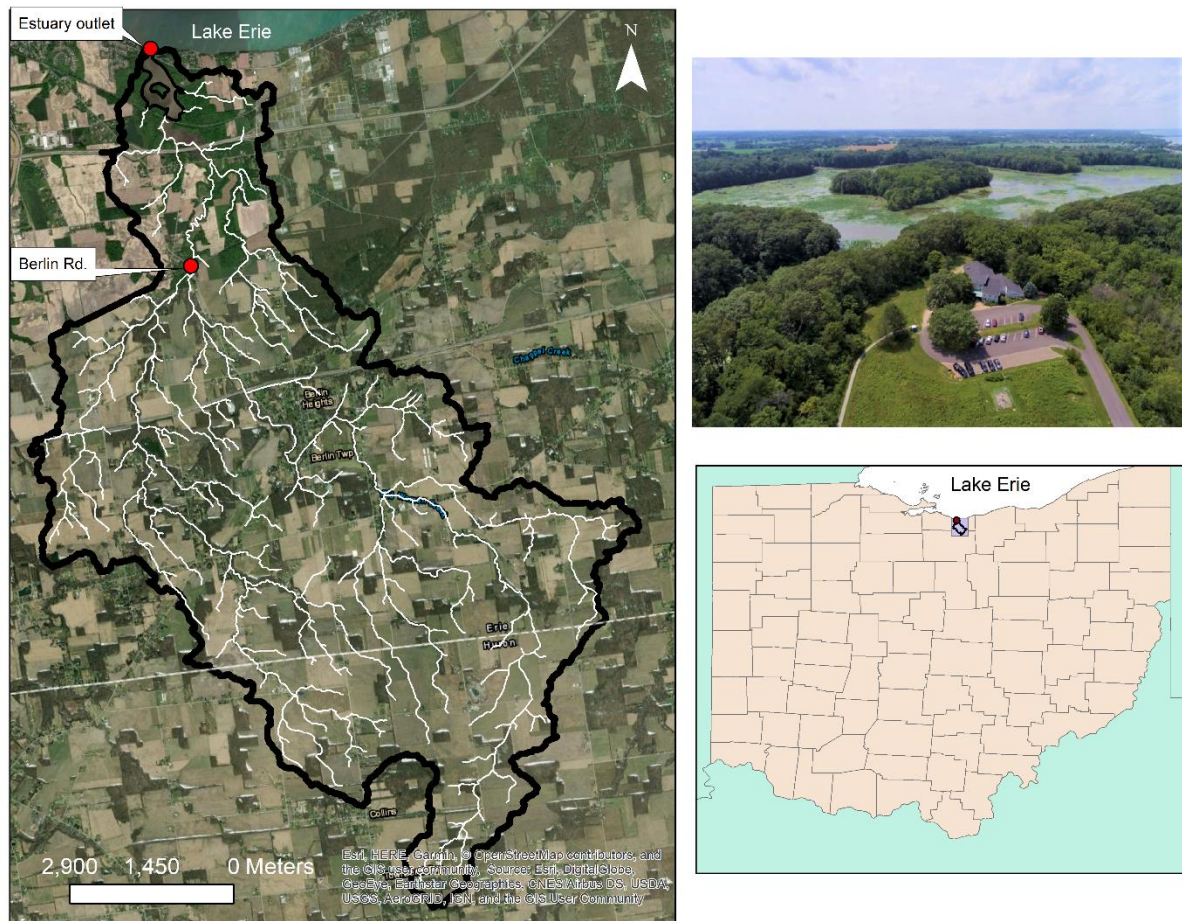

Figure 1. Old Woman Creek watershed (left, bottom right) and estuary (top left). Location of the calibration gauges are labeled.

At the outlet of the Old Woman Creek watershed is the Old Woman Creek estuarine wetland (latitude: 41°22′39″, longitude: −82°30′3″), which is formally managed by one of thirty National Estuarine Research Reserves in conjunction with the Ohio Department of Natural Resources. The estuary is approximately 61 ha in size is separated from Lake Erie by a permeable sand barrier that can be broken during hydrologic events and on occasion human interference. The estuary is greatly influenced by the conditions of Lake Erie. During barrier break events, which occur mainly through differentials in water height between the estuary and Lake Erie, water can rapidly flow into or out of the OWC estuary. Water levels greatly affect the type of vegetation that can grow in the estuary. In years of extremely high-water levels, the estuary is mainly open water with little vegetation growing. In years with shallower water levels, a greater variety of vegetation patches could be found in the different depth areas, including American water lily (*Nymphaea odorata*), yellow lotus (*Nelumbo lutea*), cattail (several species and hybrids of *Typha*), and reed (several species of Phragmites spp.). In recent years, the reed patches have disappeared due to rising water levels in Lake Erie (Ju and Bohrer, 2022; Kayastha et al., 2022).

SWAT+

In this study, we employed the Soil and Water Assessment Tool for use in building the Old Woman Creek watershed and estuary model. SWAT is a physically based watershed model that runs at the daily time-step and requires, at-minimum, inputs of land-use and land cover, soil type, and topography (Arnold et al., 2012). SWAT is widely used in the Midwest region because of its ability to represent complex agricultural land-management and predict nutrient and sediment loss well (Gebremariam et al., 2014). We used the latest version of SWAT, SWAT+ (version 60.5.5, see SI for source code modifications), which is considerable update to the previous SWAT 2012. The advantage of SWAT+ lies in its flexibility in linking spatial objects (Bieger et al., 2017), which was particularly suitable for the configuration of the estuary into unique vegetation patches.

The OWC-SWAT+ model was built using 10-m resolution elevation data (USGS NHDplus, 2020), county- based soils data (SSURGO, 2020), 30-m resolution gridded land use data (NASS-CDL, 2017). Historical climate data was derived from two sources: the NOAA meteorological station at the OWC NERR (NERRS, 2021) and the CoCoRaHS station at Berlin Heights (OH-ER-11). Temperature data was collected from the OWC NERR meteorological station (NERRS, 2021) and precipitation data was combined from the OWC NERR and a CoCoRaHS station at Berlin Heights (OH-ER-11). Precipitation data from the OWC NERR was used from 2009 until the CoCoRaHS station came online in March 2012. Daily distribution of a rainfall event at the OWC NERR was used to gap fill the CoCoRaHS data when a sample precipitation total represented multiple days.

The model was calibrated and validated to eight years of daily observed data. We used eight years of daily discharge data at Berlin Rd. (USGS #04199155) and five years of daily water quality data at both Berlin Rd. and the outlet of the estuary (Figure 1). Water quality data was analyzed at Heidelberg University National Water Quality lab (NWQL). Data below the NWQL minimum detection limits were removed. Daily water quality data comes from a 5-year study in which phosphorus retention for Old Woman Creek was estimated (OCM, 2023). The model was run with a five-year warm-up period (2009-2012) and simulated the baseline years of 2013-2020. Calibration years for discharge were 2013-2017 and for water quality 2015-2017. Validation years for discharge were 2018-2020 and for water quality 2018-2019.

a. Agricultural management

The majority of OWC land-use is row-crop agriculture. Hence, we focus primarily on refining this data to be representative of management in the watershed and accurately reflect the hydrology and nutrient losses from row-crop fields in Old Woman Creek.

Management in Old Woman Creek was determined using a combination of multiple sources, including a 2016 report on agricultural management and BMPs in the WLEB (CEAP, 2016), Erie Soil and Water Conservation District data, and in consultation with members of the OWC potential end-user group.

Rates of grassed waterways and filter strips were determined using the CEAP report (CEAP, 2016, Apostel et al., 2021). Grassed waterways were allocated in the model to intercept runoff from 21% of agricultural fields and filter strips to intercept runoff from 35% of agricultural fields. Grassed waterways were implemented based on field slope: taller and narrower grassed waterways were implemented on high slopes and shorter and wider grassed waterways on low slopes (Table SX).

Tile drainage was implanted on all poorly drained soils (USDA soil class C and D) as well as moderately drained soils (USDA soil class B) with less than 2% slope. The total rate of tile drainage in the OWC-SWAT+ model was on 76% of cropland.

In the OWC-SWAT+ model, four crop rotations of corn-soy, corn-soy-rye, con-soy-wheat-rye, and corn-soy-wheat-soy were implemented. The tillage scenarios used on top of these scenarios were: conventional tillage, rotational tillage, reduced tillage, and no-till. The combination of crop rotation and tillage created seven unique management scenarios that were implemented into the model (Table 1). Rates of implementation were determined using the Erie Soil and Water Conservation tillage transect data (Erie SWCD, 2021). The year 2016 had the most land surveyed in the dataset (47% of cropland area) and hence was used in conjunction with expert advice from the Erie Soil and Water Conservation district to estimate the rates of various types of tillage. From the tillage transect, we focused on matching the rates of no-till and conventional tillage at 60 and 21%, respectively. Rates of rotational and reduced tillage were then estimated at 15% and 4%, respectively.

Table 1. Rates of management scenarios implemented on total row cropland

Management scenario	Percent of row crop land
Corn Soy - Full tillage	21
Corn Soy - Reduced tillage	4
Corn Soy - Rotational no-till	15
Corn Soy - Full no-till	40
Corn Soy - Full No-Till W/ Rye Cover Crop	10
Corn-Bean-Wheat/Double Crop Beans	9
Corn Bean Wheat Full No-Till W/Cover Crops	1

  b. Soft data

Old Woman Creek is situated on the eastern border of the Western Lake Erie Basin. However, it has been documented to behave differently in terms of main nutrient forms from agricultural loss than some of the nearby basins (HTLP, 2018). For instance, soluble phosphorus concentrations from OWC is below the Lake Erie targets, which many neighboring watersheds struggle to achieve (Martin et al., 2021, HTLP, 2018, GLWQA 2015). Additionally, there is a dearth of modern studies on the watershed to characterize more recent landscape processes and behavior. For instance, OWC's goal is to reduce sediment loading by 66% to improve water quality and be removed from the 303d list of impaired waters (OEPA, 2005). However, few recent studies exist

on sediment loss from the landscape in OWC. Previous studies have estimated sediment loss using the MUSLE equation as well as extensive sediment sampling across the watershed. Both studies found net soil erosion on average to range from 0.5 ton/ha/yr (Matisoff et al., 2002a) to 1.1 ton/ha/yr (Evans and Seamon, 1997). In this study, the net erosion rate from (whole basin Agricultural fields) was ___ ton/ha/yr. However, it is important to note this model is calibrated for the 2011-2020 period and these studies were done closer to 2000. In 2005, when creating the OWC TMDL for sediment, the Erie SWCD estimated no-till was closer to a rate of 40% on cropland acres (OEPA, 2005). The push for conservation tillage has been successful in this watershed, with the most recent estimate of no-till acres at 60% based on data taken by the Erie Soil and Water Conservation District (Table 1). Hence, it would be expected the management in this study would reflects a lower sediment loss from the watershed than previous studies.

Old Woman Creek estuary representation and calibration

Reasoning and implementation

Insert schematic

(Villa et al., 2022) demonstrated a statistically significant effect of microtopography on the rates of phosphorus (P) accumulation in estuary soils. Hence, to accurately represent rates of P accumulation, we implemented the estuary as a series of parallel reservoirs with each representing microtopographic variation (shallow, intermediate, deep) within the estuary. We used two data sources to calibrate the reservoirs as separate objects: the first being data from a hydrodynamic simulation within the estuary (DG-SWM, cite) and sediment cores (Villa et al., 2022).

From the DG-SWM data, we were able to obtain estimations of hydrologic properties (e.g., volume, residence time, Table SX). During the calibration period (2013-2020), OWC estuary was in a period of transition from shallower water levels to higher water levels caused by an increase in the water elevation in Lake Erie. Hence, we used simulations from 2017 and 2019 to represent the final result of the decadal trend. We split discharge from Old Woman Creek into each reservoir, with volume of flow proportional to the fraction of the total volume informed by (DG-SWM, microtopography analysis)

Soil core data from the estuary informed the rates of sedimentation and phosphorus accumulation within each depth patch for years within 2010-2020 (Villa et al., 2022). Nine coring stations were located at 3 locations (outflow, backflow, mid-estuary) each with 3 microtopographic levels (shallow, intermediate, deep). Rates of sediment accretion (mm yr^{-1}) and total phosphorus accumulation (g m^{-2} yr^{-1}) were calculated at each coring location and dated within a coring segment using the distribution of 210Pb activity in the core profile and the constant-rate-of-supply (CRS) model (Appleby and Oldfield, 1978).

End-user engagement

As environmental modeling becomes increasingly complex and sustainability remains a pressing issue, it is critical to be engaged with end-users to ensure the model is both representative of the system and can address the questions that need answered (Ganju et al., 2016; Miller et al., 2011;
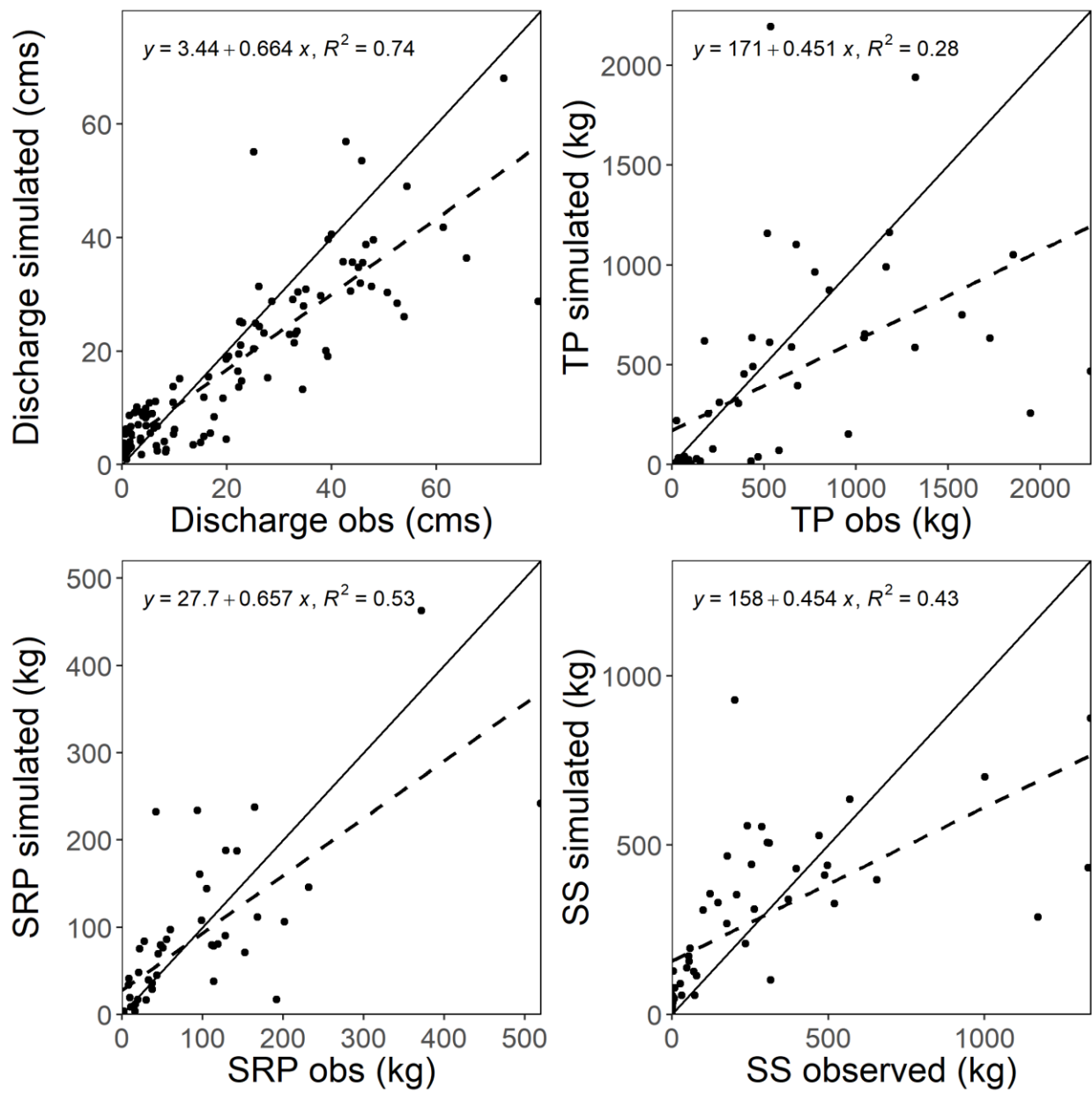
Robins et al., 2016; e.g., Kalcic et al., 2016). This project gathered a group of potential end-users to engage with the OWC-SWAT+ model development process and create land-use scenarios of interest. The project engaged 16 potential end users, representing local government (1), federal/state government agencies (8), non-profit (2), community groups (1), soil and water conservation districts (1), and farmer/producer within the watershed/county (3). Three meetings were held during fall of 2021 and spring and fall of 2022. The purpose of the meetings was to introduce potential end-users to the model and allow feedback on model inputs/development. Attendees provided feedback on adjusting management inputs, importance of different water quality issues in OWC, and provided knowledge of and access to extensive data available for the watershed and estuary.
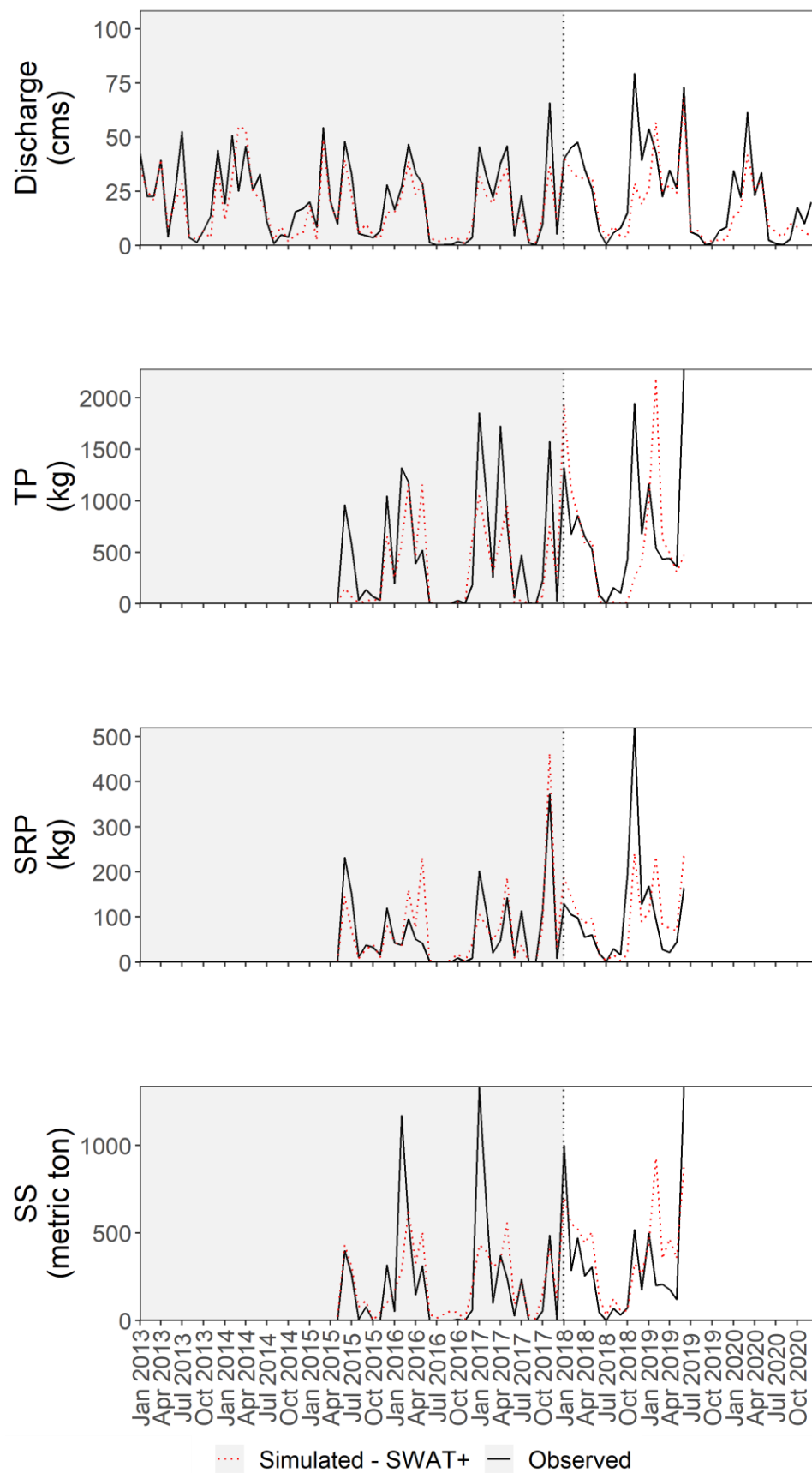
3. Results

Watershed calibration

The calibrated watershed model had an area of 71 km^2 containing 9409 HRUs, 39 subbasins, and 3 reservoirs.

Berlin Rd. calibration

$y = 3.44 + 0.664\,x,\ R^2 = 0.74$

$y = 171 + 0.451\,x,\ R^2 = 0.28$

$y = 27.7 + 0.657\,x,\ R^2 = 0.53$

$y = 158 + 0.454\,x,\ R^2 = 0.43$

 Table 1. Performance measures for OWC-SWAT+ at Berlin Rd. Bolded values are considered satisfactory by published standards for watershed models.

	Calibration (2013-2017)		Validation (2018-2020)	
	NSE	Pbias	NSE	Pbias
Discharge	**0.74**	**-14**	**0.63**	-22
Total phosphorus	**0.48**	-32	-0.50	**-14**
Soluble phosphorus	**0.60**	**4**	**0.37**	**-3**
Sediment	0.40	**-6**	0.42	24

Sediment

Crop yields

4. Discussion

Sediment

Septics

5. Conclusions

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Supplemental Information

Old Woman Creek hosts one township in the watershed, Berlin Heights, with a population of 714 people. Berlin Heights does not have a central sewage system and relies solely on septic systems for wastewater treatment. The septic systems pose a water quality threat because of both a lack

of maintenance and antiquated technology. A study done by Erie County Health Department estimated approximately 50% of septic systems in Berlin Heights are failing (ECGHD, 2009).