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Assessing the Impact of Climate and Land Use Change on Water Resources in Schuylkill River Watershed

A Thesis

Submitted to the Faculty

of

Drexel University

by

Suna Ekin Sahin

In partial fulfillment of the

requirements for the degree

of

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Abstract

Assessing the impact of climate and land use change on water resources in the Schuylkill River watershed
Suna Ekin Sahin

The Schuylkill River watershed located in southeastern Pennsylvania caters to various services including supplying drinking water to the cities, providing water for power generation, recreation, transportation, irrigation, and supporting ecosystems. Changing climate and land use patterns are likely to impact the water resources by influencing precipitation, evapotranspiration, soil moisture, and infiltration rates at a local scale. This study attempts to build a hydrologic model to assess the impact of climate and land use change on water resources in the region. The hydrologic model was created within the STELLA modeling environment. The STELLA model was calibrated for three years, from 2007 to 2010, by comparing daily recorded stream flow with the model prediction for stream flow. Downscaled future climate change scenarios were gathered from the Localized Constructed Analogs (LOCA) from 2020 to 2040 for the Representative Concentration Pathways (RCP) 4.5 and RCP 8.5 emission scenarios. Three regional land use change scenarios were developed based on historical land use and land cover change trends. The calibrated STELLA model was then run under projected climate and land use scenarios to analyze the effect of those changes on water resources. Results of these simulations indicate that daily streamflow objectives are met 67.68% -76.85% of the time for the time period between 2040-2040 under the RCP 4.5 emission scenarios, and 67.17% -

75.55% of the days under the RCP 8.5 emission scenarios in the Schuylkill River watershed. The impact of land use and land cover change on water resources was found to be insignificant for this region.

1. INTRODUCTION

1.1. BACKGROUND

Impacts of climate change, higher water demand as a result of increasing population, and rapidly changing land use and land cover is intensifying the vulnerability of water resources in many watersheds around the world. Precipitation and temperature patterns are changing as a result of an increase in anthropogenic greenhouses gases in the atmosphere (IPCC Panel, 2014). Moreover, frequency, intensity and spatial changes in precipitation events may cause an increase in magnitude and frequency of extreme events such as floods and droughts. Studies conducted on a global scale indicate that surface temperature change is projected to exceed 2 °C at the end of the 21st century under the RCP 8.5, comparatively high greenhouse gases emission scenario (IPCC Panel, 2014).

Several studies attempted to analyze the impact of climate change on water resources at the basin and sub-basin scale by using various hydrological models. Jin et al. (2018) investigated the impact of climate variability on flows of the Volta River system in West Africa by using the Integrated Catchment Model (INCA). The result of the study indicated a significant increase in flow during wet seasons which may result in more frequent floods in the region. Similarly, Christensen et al. (2004) used Variable Infiltration Capacity (VIC) to simulate streamflow in the Colorado River basin under climate change. The finding of this study suggested a drastic decrease in performance of water resources and a significant decrease in hydropower output in the basin. Additionally, the reservoir system performance in the Colorado River Basin was found to be highly sensitive to the variability due to the climate change. Aich et al. (2014) used the Soil and Water Integrated Model (SWIM) to simulate the streamflow under climate change in four African river basins. The result of the study suggested an increase in flood frequency and intensity for all four river basins in the continent. Zhang et al. (2016) simulate the hydrologic processes under climate change scenarios through SWAT model for Xin river basin in China. The result of the study revealed the low streamflow conditions in the basin are likely to follow historical patterns whereas the high streamflow conditions tend to increase drastically in the 21st century. The recent regional and local scale studies that investigate the impact of climate change on hydrology in the North America (Demaria, Palmer, & Roundy, 2016; Kopytkovskiy, Geza, & Mccray, 2015; and Shamir et al., 2015) predict an increase in low streamflow conditions, a decline in precipitation events in during warm seasons, and an increase in temperature which might increase amount of water loss due to evaporation from lakes and reservoirs. Additionally, changes in land use and land cover alter hydrologic processes such as infiltration, groundwater recharge, base flow, and runoff in watersheds (Lin, Hong, Wu, Wu, & Verburg, 2007).

1.2. MOTIVATION

Watersheds provide many services and benefits to society and the economy. These services include supplying water for various purposes such as drinking, irrigation, transportation, energy generation, and recreation. Water resources management policies are designed to allocate available water resources to meet the highest priority demands in a watershed, given uncertainty and variability in many factors, such as seasonal flow trends, droughts, floods, and groundwater level. All of these factors are driven by precipitation, evaporation and temperature rates.

The gap between available water resources and demand is expected to expand due to changes in population, economic development, and climate change (Vörösmarty, Green, & Salisbury, 2000). Conventional water resource management practices may not be adequate to overcome uncertainties related to the future availability of water resources and extreme events. Traditional water resource management approaches include designing, building, and operating infrastructures such as reservoirs, dams, spillways, and water supply systems. The design of these infrastructures is made under the assumption that the hydrological cycle and natural systems fluctuate within an unchanging envelope of variability (Milly et al., 2008). In other words, the prevalence of an event that has a certain magnitude can be estimated from historical records. However, with the increase in more intense events, this approached, based on assumed stationary of the frequency distribution of different precipitation and drought events, is dead (Milly et al., 2008) and therefore, new water resource management strategies are needed (Demaria et al., 2016; Milly et al., 2008).

As mentioned in the previous section, the possible effect of climate change on water resources differs from region to region due to the unique characteristic of each basin, and, therefore these impacts need to be investigated on local scales to develop a holistic approach to overcome uncertainties associated with the availability of water resources. For these reasons, this study attempts to assess the impacts of land use and climate change on water resources on a sub-watershed level to support water resources managers in developing adaptive policies.

The Schuylkill River watershed, one of the sub-watersheds located in the Delaware River Basin, has been chosen to be the area of this case study. A report from the Delaware River Basin Commission (DRBC) (2018) summarizes the probable shift in regional weather patterns in the Delaware River Basin. The study predicted that there would be fewer but more intense storms during in the winter months which might cause a potential increase in flood events and increase in temperatures which will directly affect the evapotranspiration rates and therefore bring about extended drought cycles. If the runoff in the basin decreases as a result of those changes in weather patterns, energy generation activities dependent on the water resource availability might be disrupted, water supplies might become inadequate to meet the demands in the basin, and recreational activities might be disrupted. In contrast, if the runoff increases, the frequency of flooding events might increase, the reservoir capacities and operational policies might need to be revised.

Although the DRBC report provides coarse information about probable changes in regional climate patterns, the impact of climate change on water resources has not been precisely examined. Furthermore, to develop a robust and resilient solution to the water resources management challenges, studies with higher spatial resolution than the DRBC report are necessary to investigate the local effects of climate and land use change. From this point of view, this study aims to investigate the possible effect of changing precipitation and temperature patterns on water resources in the Schuylkill River watershed with respect to current watershed management policies.

1.3. OBJECTIVE

The overall aim of this study is to assess the impacts of climate and land use changes on water supply in the Schuylkill River watershed in Pennsylvania. A hydrologic model simulating existing watershed management policies was built in the modeling environment, STELLA. The model was run under different climate and land use change scenarios. The projected streamflow in the Schuylkill River watershed indicates potential responses of the watershed to changes in land use and climate in terms of water resources availability. The findings of the study can be used to guide short- and long-term water resources planning decisions. The specific objectives of this study are to:

- Build a water resources model for the Schuylkill River watershed in STELLA
- Simulate historical streamflow data within the Schuylkill River watershed by calibrating model runs with historical streamflow measured at specific locations by USGS gages
- Simulate streamflow from 2020 to 2040 by running the model under a scenario of both climate and land use change
- Analyze current and future simulations of streamflow to determine possible water resources availability in the future

2. DESCRIPTION OF STUDY AREA

2.1. SCHUYLKILL RIVER WATERSHED

The Schuylkill River watershed located in southeastern Pennsylvania encompasses nearly 2,000 square miles and constitutes eleven counties. The major cities located in the basin are Pottsville, Reading, Pottstown, Norristown, and Philadelphia. Schuylkill River watershed is the drinking water source of approximately 1.75 million people (Philadelphia Water Department, 2010). Drinking water needs of nearly 80 percent of these people are met from surface water supplies downstream of Pottstown. The largest drinking water consumer in the basin is the Philadelphia Water Department (PWD) providing drinking water for approximately 40% of the population of Philadelphia through the Schuylkill River watershed. The PWD delivers drinking water to the city through two intakes, Belmont and Queen Lane, located on the lower portion of the Schuylkill River.

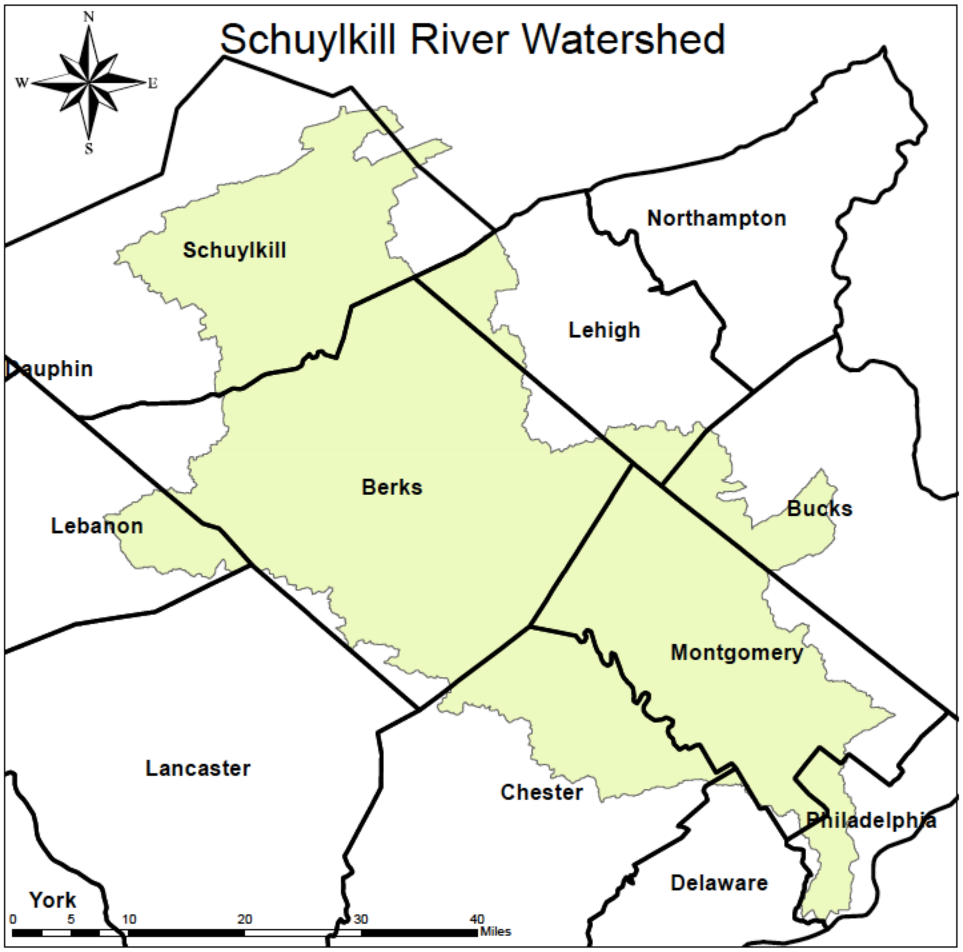


Figure 1. Schuylkill River Watershed and Counties

2.2. WATER CONSUMPTION

Total withdrawals in the basin are divided into four categories, drinking water, power sector demand, mining and industrial water demand (Philadelphia Water Department, 2010).

The power sector is responsible for the largest withdrawal in the Schuylkill River watershed. Annual average withdrawals for the power sector are 330 CFS, accounting for 41% of the total withdrawals in the watershed. However, only 16.3% of power sector demand is consumptive use meaning that 83.7% of withdrawn water is returned to the watershed (Philadelphia Water Department, 2010).

The drinking water sector has the second highest water demand in the watershed. Annual potable water demand is 248 CFS accounting for 31% of the total withdrawals. The consumptive use of potable water demand is estimated to be 15% meaning that more than half of the water return to the watershed as treated wastewater (Philadelphia Water Department, 2010).

Mining and industrial water demand account for 7% and 4% of total water withdrawal respectively (Philadelphia Water Department, 2010).

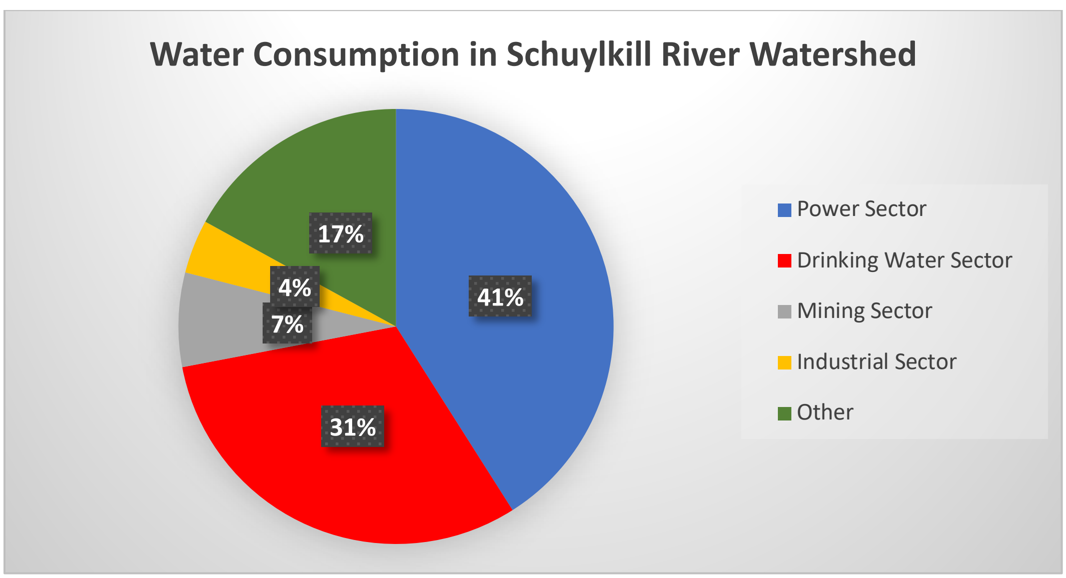


Figure 2. Percentage of Water Consumption in Schuylkill River Watershed

2.3. RESERVOIRS

The Schuylkill River watershed hosts four major reservoirs: Blue Marsh Reservoir, Still Creek Reservoir, Ontelaunee Reservoir, and Green Lane Reservoir.

Blue Marsh Reservoir, the largest water body in the basin, is located on the Tulpehocken Creek and is owned and operated by the Army Corps of Engineers. Green Lane Reservoir, located headwaters of the Perkiomen Creek, is owned and operated by Aqua America, Inc. Still Creek Reservoir is located near the headwaters of the Little Schuylkill River and owned by Tamaqua Water Authority. Ontelaunee Reservoir, owned and operated by Reading Water Authority, is located north of the City of Reading. Alongside being used for recreational purposes, the Ontelaunee Reservoir supplies drinking water to the City of Reading.

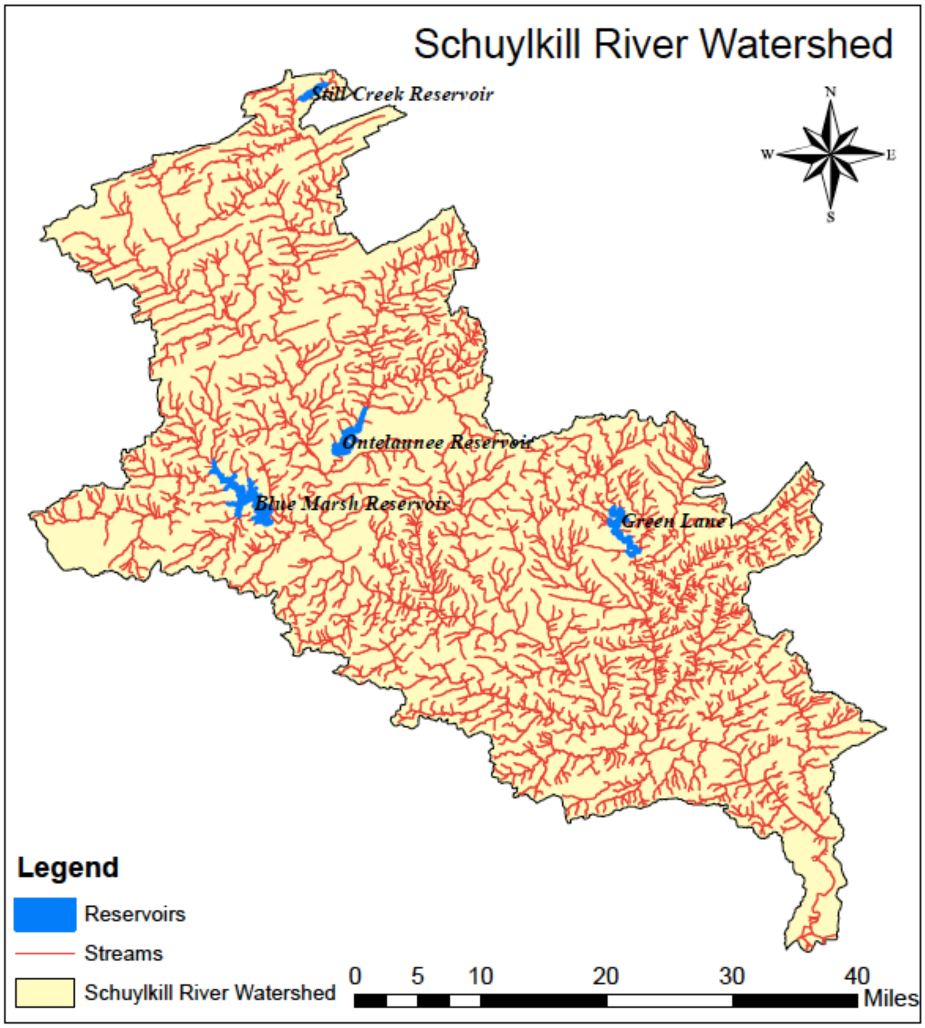


Figure 3. Tributaries of Schuylkill River Watershed

2.4. LAND COVER

In order to estimate the land use in the Schuylkill River watershed the most recent National Land Cover Dataset (NLCD, 2011) was obtained from United States Geological Survey (USGS) website. The NLCD has 21 land cover categories of which Schuylkill River watershed includes 14 categories: high and low intensity residential, agricultural pasture/hay and row crops, commercial/industrial/transportation, deciduous forested, evergreen forested, mixed forested, open water, quarries/strip mines/gravel pits, transitional, urban/recreational grasses, emergent herbaceous wetlands, and woody wetlands. These categories were reclassified to represent major land cover classes: developed, agricultural, forested, water, and other. In 2011, the Schuylkill River watershed was 27% developed land, 41% forest land, and 29% agricultural land. Figure 4 displays the most recent land cover data in the basin. The lower part of the basin is dominated by developed land cover whereas the upper and central part of the watershed is dominated by forest and agricultural land respectively.

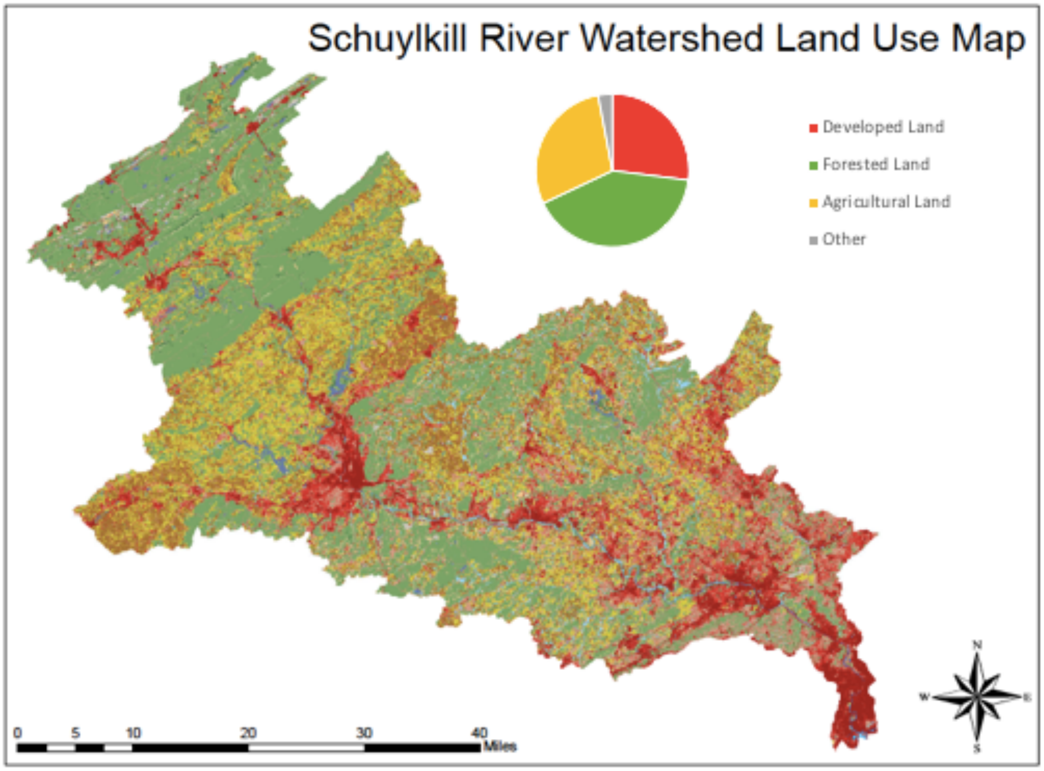


Figure 4. Land Use Classes (2011) in the Schuylkill River Watershed

2.5. CLIMATE

The climate of the Schuylkill River watershed is generally humid. The mean annual temperature in the watershed is 52°F. The average temperatures during winter and summer are 31°F and 72°F, respectively (Biesecker, Lescinsky, & Wood, 1968). The topography and elevation affect the precipitation trends in the watershed. The annual precipitation at the mountain regions in the watershed is 45-50 in/yr whereas it decreases to 43 in/yr at the plain regions (Pennsylvania Department of Conservation and Natural Resources, 2001). Flows of rivers and streams depend on the local precipitation rates within the

Schuylkill River Basin. Evaporation is also an important factor affecting water availability in the basin. On average in Pennsylvania, 50% of annual precipitation is returned to the atmosphere through evaporation and transpiration by the plants, 20% turns into stormflow and augments rivers and streams during rainfall and snowmelt events, and 30% recharges groundwater aquifers by infiltration (Fleeger, 1999).

2.6. WATERSHED MANAGEMENT AND POLICY IN THE SCHUYLKILL RIVER WATERSHED

There are four watershed management policies related to streamflow conditions in the Schuylkill River watershed including (1) Delaware River Basin Commission (DRBC) directed releases from Blue Marsh Reservoir, (2) minimum release criteria from Blue Marsh Reservoir, (3) drought demand restrictions in Pennsylvania, and (4) consumptive use replacement policy for Limerick Generation Station (LGS).

With 219 square miles of drainage area, the Blue Marsh Reservoir is the largest water body located in the Schuylkill River watershed. Tulpehocken Creek, a tributary to the Schuylkill River, hosts the Blue Marsh Reservoir. The flow of the Schuylkill River is governed by releases from the Blue Marsh Reservoir. The reservoir is owned and operated by the Army Corps of Engineers. The primary objectives of the operational policy of Blue Marsh Reservoir are providing flood control, water supply, and low flow augmentations. The secondary objectives are recreation and providing water quality control.

The Delaware River Basin Commission (DRBC) has purchased 8,000 acre-feet of water supply storage of Blue Marsh Reservoir to be utilized for water quality control, water supply, low flow augmentation, and downstream water quality enhancements. The Army Corps of Engineers uses the remaining 6,621 acre-feet for water quality control and meeting release requirements for recreation, fish, wildlife, and water supply. Under normal conditions, the operational objectives of Blue Marsh Reservoir are providing a water supply for the Western Berks Water Authority, flood control on the lower portion of Schuylkill River watershed at, and water quality control for the Delaware River. DRBC may request additional releases depending upon the streamflow conditions at the downstream of the Blue Marsh Reservoir (US Army Corps of Engineers, 1996).

2.6.1. DRBC Directed Releases from Blue Marsh Reservoir

DRBC directs releases from storage in Blue Marsh Reservoir to control salinity in the Delaware estuary. DRBC monitors flow conditions of the Delaware River at Trenton and Montague. DRBC considers dissolved oxygen level, temperature, and flow conditions as stream quality control parameters. When the stream flow conditions fall below 400 cubic feet per second (CFS), dissolved oxygen below 4 mg/l, and temperature above 86 degrees- Fahrenheit at these points, DRBC may request additional releases from Army Corps Engineers from

Blue Marsh to enhance the stream water quality (US Army Corps of Engineers, 1996).

2.6.2. Conservation Releases from Blue Marsh Reservoir

Conservation release indicates the minimum amount of water that must be released from the reservoir at all times. The Blue Marsh Reservoir must release 41 CFS per day for the conservation of Tulpehocken Creek, and 18 CFS per day for meeting water demand for Western Berks Water Authority, whose water intake structure is located approximately one mile downstream of the Blue Marsh Reservoir. In total, the daily conservation release criterion for Blue Marsh Reservoir is 59 CFS (US Army Corps of Engineers, 1996).

2.6.3. Consumptive Use Replacement Policy for Limerick Generation Station

The Limerick Generation Station (LGS) is a nuclear power plant located on the Schuylkill River at Limerick, PA. LGS is owned and operated by Exelon Corporation. The power plant has two generation units each having a maximum 3,515 megawatts power (Delaware River Basin Commission, 2012). Each generation unit is cooled through a cooling tower with the circulation of water. Water required for the cooling process is withdrawn from the Schuylkill River through two intakes, one on the Perkiomen Creek and one on the Schuylkill River. The Schuylkill River intake is located downstream of Pottstown and Perkiomen Creek intake is located downstream of Graterford. Water withdrawn through those two intakes is used for consumptive and non-consumptive needs at LGS.

When the streamflow conditions fall to 560 CFS at USGS gage 01472000 Pottstown and 210 CFS at USGS gage 01473000 Graterford, the LGS is obligated to supplement water to the Schuylkill River watershed with the equal amount of water lost due to evaporative cooling process (consumptive use) plus a 3% raise to replace the water lost during transportation of water from release location to intake location via open channels (Exelon Generation Company, 2012). This augmentation water need is met through three water resources which have been contracted by LGS: Still Creek Reservoir, Wadesville Mine Pool, and Bradshaw Reservoir. Still Creek Reservoir is located in the headwaters of the Little Schuylkill River, and the manager and operator of the reservoir is the Tamaqua Area Water Authority. Being an active open pit mine, Wadesville Mine Pool is operated by Reading Anthracite and located in the headwaters of the Schuylkill River. Bradshaw Reservoir is designed to regulate releases of water transmitted by Point Pleasant Pumping Station from the Delaware River to East Branch Perkiomen Creek and Neshaminy watersheds. When the streamflow conditions at Pottstown and Graterford exceed the policy triggers, supplementary releases are deactivated. In addition to the augmentation policy, LGS has an obligation to maintain streamflow conditions above 10 CFS on the East Branch Perkiomen Creek. The streamflow rate on the East Perkiomen Creek is observed through USGS gage 01472620 Dublin.

2.6.4. Drought Demand Restrictions in Pennsylvania

Drought management is the responsibility of the Office of Water Resources Planning at the Department of Environmental Protection in Pennsylvania. The policymakers take into account five drought indicators namely precipitation, streamflow, groundwater level, soil moisture, and reservoir storage information on a regular basis. These drought indicators are monitored through distributed recording stations across each county in Pennsylvania. If the three or more indicators reach drought trigger, the Department of Environmental Protection (DEP) will request the Pennsylvania Emergency Management Agency (PEMA) to convene a meeting to review and evaluate the data to decide if formal drought declaration is necessary (Department of Environmental Protection, 2016).

Table 1. Drought stages and % of voluntary restrictions

Drought Phase	**% of Voluntary Restrictions**
Drought Watch	5%
Drought Warning	10%
Drought Emergency	Prohibition of non-essential water uses – 15% reduction or lower

Pennsylvania has three drought phases: drought watch, drought warning, and drought emergency. The drought watch and drought warning include voluntary water conservation from the consumptive uses whereas the drought emergency restricts the non-essential water uses. Table 1 presents the necessary percentage reductions for each drought phases. Drought declarations are issued, and drought restrictions are implemented on a county by county basis (Department of Environmental Protection, 2015).

3. SIMULATION TOOL

3.1. STELLA SOFTWARE

Structural Thinking Experimental Learning Laboratory with Animation (STELLA) is an object-oriented, graphical modeling software package designed by Barry Richmond and commercialized by High Performance Systems ("ISEE systems," n.d.). STELLA software was chosen as the modeling environment for this project since it offers numerous advantages for water resources modelers. STELLA software does not require proficiency in computer programming; thus, it allows the participation of non-programmers in the modeling process and minimizes the startup time for model development (Palmer, 2010). It is convenient to work with large datasets since it allows developers to link other programs suitable for data storage such as Microsoft Excel. Another feature distinguishing STELLA from other water resources modeling software is that users can define the variable names in the complex systems which make the software easy for model modifications. Besides, the model developers can create multiple sectors to simplify complex systems. If desired, these sectors can run exclusively from the model. Furthermore, the software has numerous interfaces which facilitate model generation, modification, and presentation mode. The presentation mode permits modelers to explore how changing specific parameters would affect model results instantly.

In STELLA, each icon simulates a process and has unique features which specify how it can be linked with other objects in the software. The simulation of a system is developed by the selection of appropriate icons that represent components of the system. The interaction between objects is established by connectors, and then the functional relationships between elements are defined. STELLA consists of five major icons: stocks, flows, converters, connectors, and sectors displayed in Figure 5.

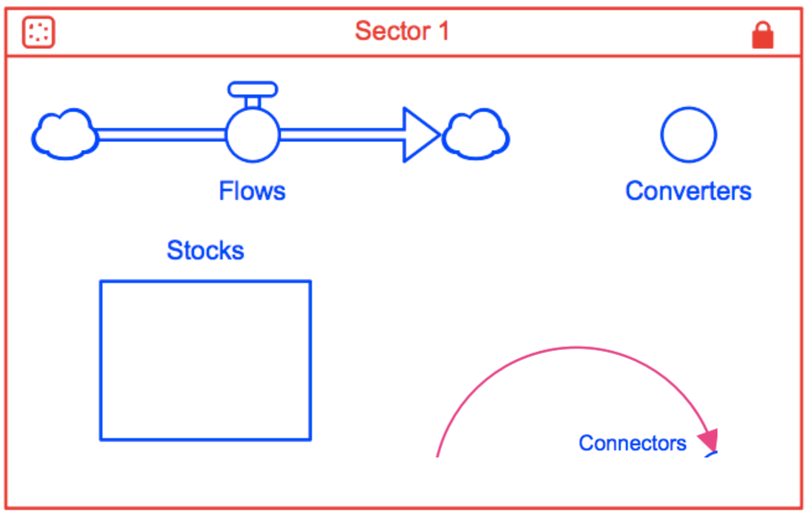


Figure 5. An example of a sector with the Modelling Icons of STELLA

Stocks are the state variable representing system components that can accumulate or deplete over time. Components whose values are measured as rates are represented through flows in the modeling environment. Also, information exchanges between and among stocks are controlled by flows (Ouyang, Zhang, Leininger, & Frey, 2015). Converters represent constant value or functions over time. Connectors are used to establish cause and effect relationships among modeling elements (Palmer, 2010). Sectors help users organize their models by allowing users to cluster icons in the modeling interface. In addition, a ghost icon is a tool that is used to create a copy of an existing stock, flow, or converter. The ghost tool allows programmers to use the original stock, flow, or converter in another sector or area in the model such that the visual complexity of models can be decreased ("ISEE systems," n.d.). The copy of the element created with ghost tool is not a new or separate variable. It is a shortcut of the original variable. The ghosted variable appears at the model view interface with the same name and shape as original copy yet the with dotted lines.

3.2. HYDROLOGIC MODELING WITH STELLA

Hydrological models have recently been applied to better understand and predict the behavior of hydrological systems in response to water resources management challenges (Devia, Ganasri, & Dwarakish, 2015).

The primary concept of hydrologic modeling in STELLA is the continuity principle which requires conservation of the amount of water in a system. Conservation of mass in a system is described by differences between inflow and outflow in one-time step. STELLA automatically creates a continuity equation for mass balance for stocks based on inflows and outflows to stocks. Table 2 displays the icons of STELLA commonly used in the hydrologic model and their specific objectives.

Table 2. Icons of STELLA and Their Objectives in Hydrologic Modeling

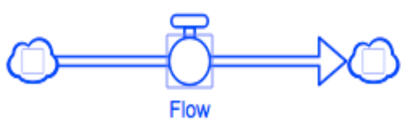
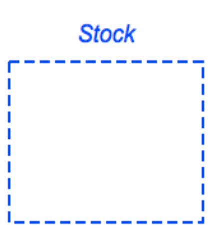
Icons of STELLA	Objectives of Icons in Hydrologic Modeling
	-Represent reservoirs
	- Represents time series inputs from excel such as precipitation
	-Represent inflows to reservois, outflows from reservoir -Codes equations and if/else statements
	-Build cause and effect relationship between variables
	-Representation of a shortcut of "*Stock*" variable created by ghost tool

Figure 6 illustrates components of a very simple example of a reservoir operation and how the continuity concept is applied to simulate a reservoir in the STELLA modeling environment.

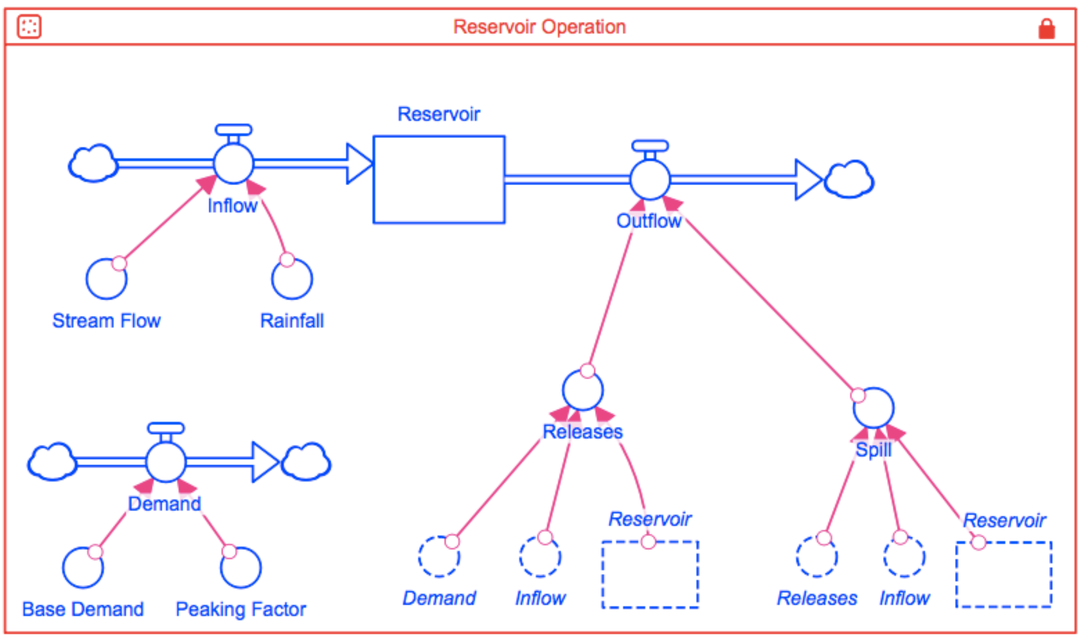


Figure 6. Example of a basic reservoir model in STELLA

Equations 1-4 displayed below show the continuity equation for mass balance of the reservoir illustrated in Figure 6. Equation 1 states that the volume of water stored in the reservoir at the current time step is the sum of its value in the previous time step and the differences between inflow and outflow rates at the current time step.

$$Resevoir\ (t) = Resevoir\ (t - dt) + [Inflow * dt - Outflow * dt] \quad (1)$$

$$Inflow = Streamflow + Direct\ precipitation\ onto\ reservoir \quad (2)$$

$$Outflow = Releases + Spill \quad (3)$$

$$Demand = Base\ Demand * Peaking\ Factor \quad (4)$$

Typically, in hydrological models, inflows to the reservoirs are influent stream flows and rainfall whereas outflows from the reservoirs are governed by reservoir operation rules such as releases based upon demands in the watershed and spills controlled by the capacity of the reservoir and evaporation. Such variables that affect inflow and outflow rates are simulated through converters and cause-and-effect relationships between flows and converters built by connectors as shown in Figure 6.

Controlled releases from the reservoir are programmed through IF ELSE THEN statements in the modeling environment. Equation 5 implies that if the volume of water stored in the reservoir plus the amount of water entering the reservoir is adequate to meet the specified demand, then the reservoir releases an equal amount of water to demand. Otherwise, the reservoir releases volume of water in the reservoir at the current time step along with the inflow to meet the demand.

$$Release = \ IF\ Reservoir + Inflow \geq$$
$$Demand\ THEN\ Demand\ ELSE\ Reservoir + Inflow \tag{5}$$

Similarly, Equation 6 states that when the volume of water in the reservoir plus inflow minus the amount of demanded water from the reservoir is greater than the reservoir capacity, then the reservoir dumps the excess amount of water. When the volume of water in the reservoir plus inflow minus the amount of demanded water is lower than the storage capacity of the reservoir, then the spill calculation is not activated, and the excess of water beyond demand is stored in the reservoir.

$$Spill = IF\ Reservoir\ Storage + Inflow - Releases \geq$$
$$Reservoir\ Capacity\ THEN\ Reservoir\ Storage + Inflow - Releases -$$
$$Reservoir\ Capacity\ ELSE\ 0 \tag{6}$$

Release and spill equations are a basic representation of reservoir operation policies. More complex reservoir operating procedures such as the space rule, the pack rule, the hedging rule (Lund, 1999) can be incorporated with STELLA.

4. METHODOLOGY

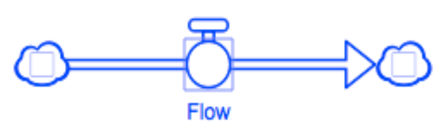
4.1. DESCRIPTION OF THE MODEL

The STELLA model can be used to code watershed management policies and reservoir operation rules to simulate observed stream flow of the Schuylkill River as well as its tributaries. A baseline model was built and validated against the stream flow conditions measured by USGS gages at specific locations. After validation, the baseline model was run under climate change and land use scenarios described further in *Section 4.3*.

The baseline model simulates fifty years of streamflow in the Schuylkill River from 1960 to 2010 using a daily time step and the mass balance approach which takes into account inflows, outflows, demands, withdrawals, and discharges in the watershed.

Components of the Schuylkill River watershed model and their representation through STELLA icons are shown in Table 3.

Table 3. Elements of the Schuylkill River Watershed Model and Icons Representing the Elements in STELLA

Elements of Schuylkill River Watershed Model	Icons Representing Each Element in the Model
• Blue Marsh Reservoir • Wadesville Reservoir • Bradshaw Reservoir	
• Spill Rules • Demand Rules • Release Rules • Unit Conversions	
• USGS Gages • River Confluences • Inflows to Reservoirs • Outflows from Reservoirs	

The STELLA model includes two main parts, Blue Marsh Reservoir simulation, and Schuylkill River flow simulation. The Blue Marsh Reservoir simulation is programmed to simulate three watershed management policies defined in the Water Control Manual of Blue Marsh: (1) seasonal storage elevations, (2) flood control, and (3) conservation releases. DRBC directed releases from Blue Marsh Reservoir were not included in the model since these releases are triggered by the streamflow conditions in the Delaware River.

Figure 7 depicts the sectors constituting the Blue Marsh Reservoir simulation in STELLA. A detailed explanation of each sector of the Blue Marsh Reservoir simulation portion of the model is given in *Section 4.1.2*.

The Blue Marsh Reservoir simulation was connected to the Schuylkill River flow simulation as an inflow to Tulpehocken Creek. Figure 8 displays a schematic of Schuylkill River flow simulation. The connection of Blue Marsh Reservoir simulation to the Schuylkill River flow simulation is highlighted with the black circle in Figure 8.

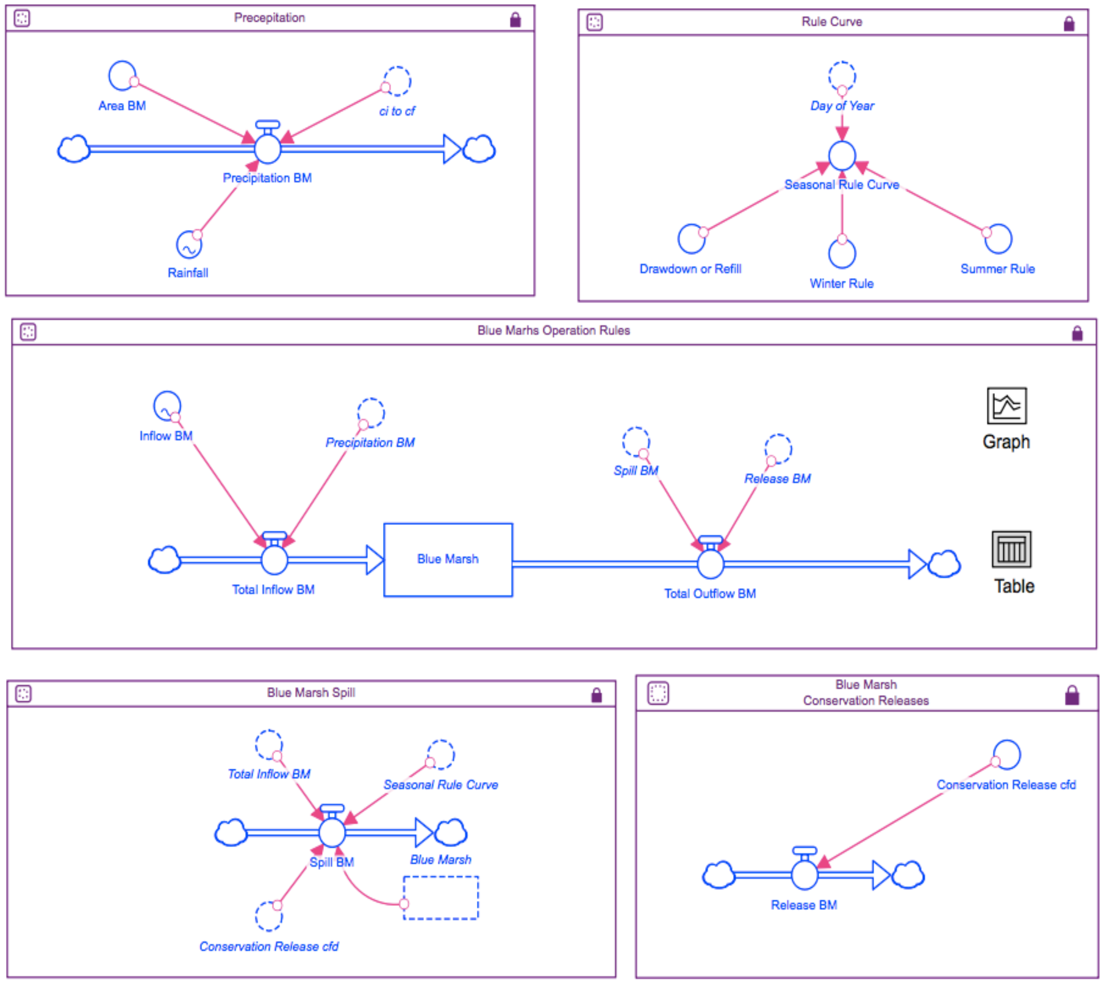


Figure 7. Blue Marsh Reservoir Simulation portion of the STELLA model

The Schuylkill River flow simulation portion of the model is a replica of the Schuylkill River watershed map, featuring two reservoirs, Wadesville, and Bradshaw, and twenty-seven nodes, representing existing USGS gages and confluences in the watershed. Wadesville and Bradshaw Reservoirs were programmed to simulate augmentation policies regarding LGS. Still Creek, Ontelaunee, and Green Lane Reservoirs are three additional reservoirs located in the watershed. They are omitted from the model due to lack of historical inflow and reservoir storage data required to calibrate and validate simulation results. The Schuylkill River flow simulation portion of the model is too big to fit on a single page. For this reason, the smaller representation of the Schuylkill River watershed model is added to illustrate the main portion of the model (Figure 8).

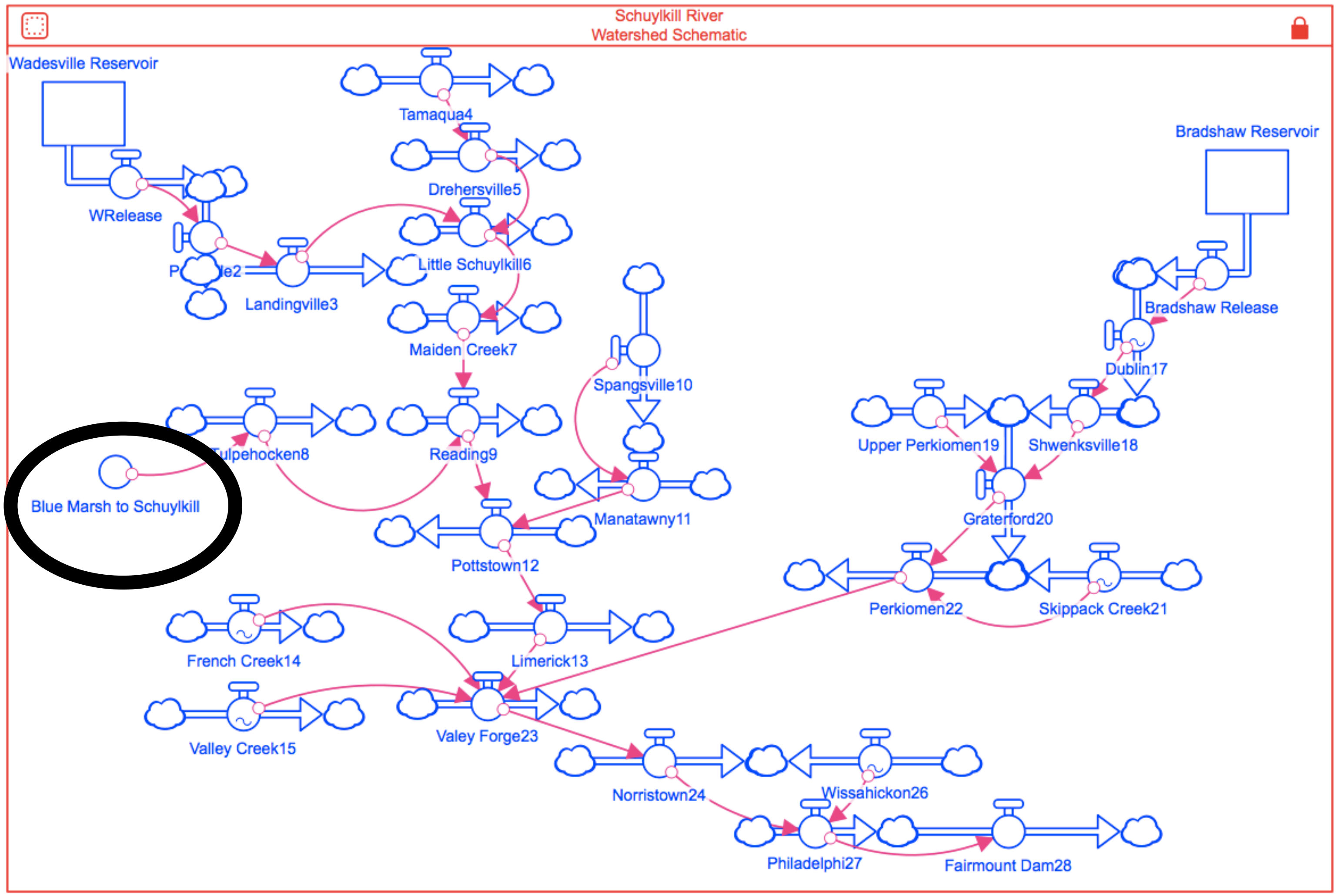


Figure 8. Schematic of Schuylkill River Flow Simulation Portion of the STELLA Model

4.1.1. Schuylkill River Flow Simulation

4.1.1.1. Calculation of Inflows

Inflow to the Schuylkill River flow simulation portion of the model is the total of the flow rate of each tributary to each of the twenty-seven nodes. The flow rates of a few tributaries in the basin are recorded by USGS gages; however, data records for those gauges are not available for the simulation period of the model. The majority of the streams in the basin are ungaged. Two different methods were used to calculate inflow to the nodes in the STELLA model. These methods were the use of Delaware River Basin Streamflow Estimator Tool (DRB-SET) and calculation of runoff based on composite curve number method and calculation of base flow. The reason behind employing two methods is flow estimation for ungaged streams was based on the DRB-SET tool for the years 1960 to 2010. Therefore, the inflow for future events is not available from the DRB-SET tool and instead was estimated by calculation of runoff based on the composite curve number method and base flow. Table 4 shows the objective of each inflow calculation method.

Table 4. Objective of Inflow Calculation Methods

Method used to calculate inflow	Objective of the method
DRB-SET Tool	-Simulation and validation of historical stream flow rates (1960-2010) through existing reservoir operation rules and active watershed management policies
Runoff based on composite curve number and base flow	-Simulation and calibration of historical stream flow rates (1960-2010) through existing reservoir operation rules and active watershed management policies -Simulate the stream flow rates under projected climate and land use change scenarios (2020-2040)

In addition to the influent stream data, cumulative consumptive water use was calculated for each node and added as an input to those nodes. Annual average daily discharge values (D) and annual average daily withdrawal values (W) reported to the state were gathered from the Schuylkill River Hydrology and Consumptive Use Report (2010) and subtracted to derive cumulative consumptive water use (CCW) for each node. Equation 7 displays how cumulative consumptive water was calculated in the model.

$$CCW = D - W \quad (7)$$

A negative value of CCW indicates a consumptive loss at nodes whereas a positive value of CCW indicates a gain.

4.1.1.1.1. DRB-SET Method

DRB-SET is a tool developed by the U.S. Geological Survey (USGS) for the simulation of streamflow at a daily time step for ungauged stream locations in the Delaware River Basin from 1960 to 2010. The DRB-SET tool calculates the flow of desired ungauged streams by selecting an appropriate stream gage with similar basin characteristics to the desired one (Stuckey & Ulrich, 2015). The characteristics of the desired stream are identified through a website, StreamStats version 4, developed by USGS. StreamStats version 4 interoperates with the DRB-Set Tool. Once the watershed is delineated on the StreamStats website, the basin characteristics of the desired stream are automatically inserted into the DBR-Set Tool. Then, the tool assigns an appropriate stream gage to calculate the average daily flow of the desired stream. The assigned stream gage is referred to as the reference stream gage. Selection of an appropriate reference stream gage is based on the following two criteria:

1) The ungauged stream and reference stream gage need to have a strong correlation with respect to streamflow conditions
2) The reference stream gage needs to have similar hydrologic features and basin characteristics as the ungaged stream

Alternatively, stream gage selection can be made manually, or the closest gauge can be assigned as a reference stream gage manually.

4.1.1.1.2. Runoff Based on Composite Curve Number and Baseflow

The composite curve number is a method used to calculate the amount of runoff produce during and after precipitation events based on hydrological soil type and land use type (NRCS, 1986).

The Schuylkill River watershed was divided into sub-watersheds based on the drainage areas of the nodes in the STELLA model. The curve number of each node was calculated based on land use type and soil type corresponding to each drainage area in the ArcGIS software. The amount of runoff produced was calculated based on the curve numbers for each node (Amur, 2018). Appendix A.1 shows the list of nodes in the STELLA model along with the corresponding drainage area, the current curve number derived based on the most recent land use and land cover data.

The amount of baseflow, that is the flow from groundwater to surface water, for each node was calculated on a daily time step based on available water storage values (field capacity) and hydrological parameters, including precipitation, evapotranspiration, and soil moisture content (Hawkins, 2015). A detailed description of the method for calculating curve number, runoff, and base flow can be found in Amur (2018).

The total inflow to each node is the sum of baseflow and runoff generated after precipitation events.

4.1.1.2. Demand Deliveries from the Schuylkill River Watershed

There are three demand nodes included in the Schuylkill River watershed Model: LGS Demand at Schuylkill River, LGS Demand at Perkiomen Creek, and City of Philadelphia Demand. Each demand node was separated to the individual sectors and programmed to take daily withdrawals.

4.1.1.2.1. Limerick Generation Station Demand

LGS has two water intake locations in the Schuylkill River watershed to satisfy non-consumptive and consumptive water demand at the power plant. The intakes are located on the Perkiomen Creek and Schuylkill River. Schuylkill River intake is located downstream of Pottstown and the Perkiomen Creek intake is located downstream of Graterford. The decision as to which intake is used relies on a mechanism associated with proprietary costs. In order to simplify the intake selection process for the simulation, two thirds of the total demand of LGS was assumed to withdraw through Limerick Perkiomen Demand sector (Figure 9), and one third of the demand was assumed to be withdrawn through Limerick Schuylkill Demand sector (Figure 9).

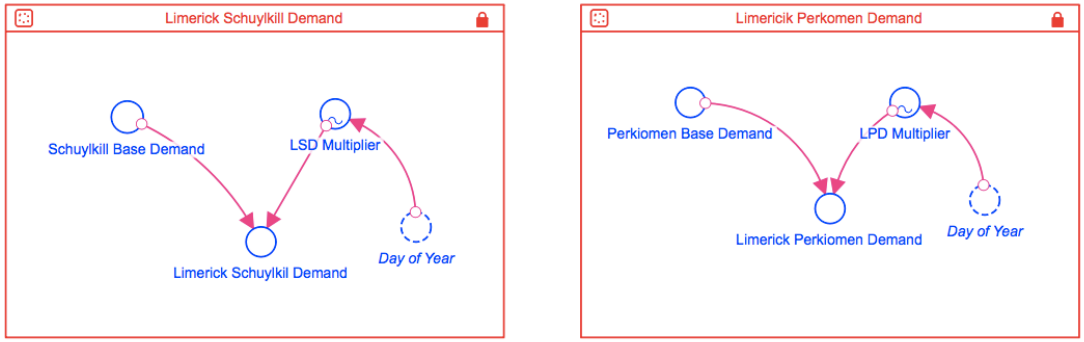


Figure 9. Limerick Schuylkill Demand and Limerick Perkiomen Demand Sectors

The steps explained below were followed to assign the demand patterns of the Limerick Schuylkill Demand sector shown in Table 5 (Hesson, 2013):

1) Monthly average of daily average cooling water withdrawals is multiplied by two-thirds and recorded as estimated daily withdrawals
2) Annual average of recorded value is calculated and assigned as base demand for the sector
3) Recorded estimated daily withdrawals are divided by base demand to derive peaking factors for every month
4) The product of base demand and peaking factors are assigned as calculated average daily withdrawal by month from the Limerick Schuylkill Demand sector

Table 5. Limerick Schuylkill Demand Pattern

Month	Average Daily Cooling Water Withdrawal by Month (CFS)	Limerick Schuylkill Base Demand (CFS)	Limerick Schuylkill Peaking Factor	Calculated Average Daily Withdrawal by Month (CFS)
1	43.6	32.6	0.89	29.04
2	42.7	32.6	0.87	28.49
3	36.4	32.6	0.74	24.24
4	43.0	32.6	0.88	28.68
5	51.0	32.6	1.04	33.99
6	55.6	32.6	1.14	37.04
7	57.5	32.6	1.18	38.34
8	57.5	32.6	1.18	38.36
9	54.6	32.6	1.12	36.42
10	51.4	32.6	1.05	34.26
11	49.0	32.6	1.00	32.64
12	45.0	32.6	0.92	30.02

To assign the demand pattern of Limerick Perkiomen Demand sector (Table 6), the steps explained above were applied. The only exception was the estimated daily withdrawal derived from the monthly average of daily average cooling water withdrawals is multiplied by one-third.

Table 6. Limerick Perkiomen Demand Pattern

Month	Average Daily Cooling Water Withdrawal by Month (CFS)	Limerick Perkiomen Base Demand (CFS)	Limerick Perkiomen Peaking Factor	Calculated Average Daily Withdrawal by Month (CFS)
1	43.6	16.3	0.89	14.5
2	42.7	16.3	0.87	14.2
3	36.4	16.3	0.74	12.1
4	43.0	16.3	0.88	14.3
5	51.0	16.3	1.04	17.0
6	55.6	16.3	1.14	18.5
7	57.5	16.3	1.18	19.2
8	57.5	16.3	1.18	19.2
9	54.6	16.3	1.12	18.2
10	51.4	16.3	1.05	17.1
11	49.0	16.3	1.00	16.3
12	45.0	16.3	0.92	15.0

4.1.1.2.2. Philadelphia Water Demand

Philadelphia Water Department has two water intakes located on the lower Schuylkill River, Queen Lane and Belmont, which are represented through one demand node in the model (Figure 10).

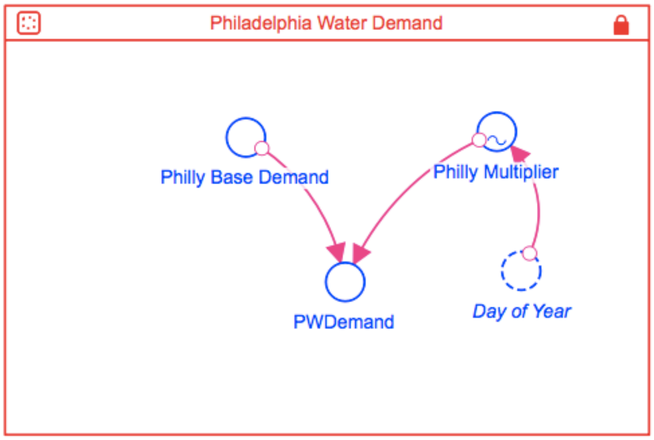


Figure 10. Philadelphia Water Demand Sector

Demand patterns of the Philadelphia Water Demand sector, displayed in Table 7, were calculated based on the following steps (Hesson, 2013):

1) Monthly average daily water withdrawal of PWD is computed based on observed average daily water withdrawal from 2001 to 2010.
2) Average of the monthly average daily withdrawal values from 2001 to 2010 is taken to compute annual monthly average daily withdrawal.
3) Computed annual monthly average daily withdrawal is assigned as base demand for the sector
4) Peaking factor for each month is derived from the calculated base demand value at the previous step

Table 7. Philadelphia Water Demand Pattern

Month	PWD Base Demand (CFS)	PWD Peaking Factor	Calculated Average Daily Withdrawal by Month (CFS)
1	188	1.03	195
2	188	1.04	197
3	188	0.98	186
4	188	0.93	176
5	188	0.93	175
6	188	1.00	190
7	188	1.06	201
8	188	1.07	202
9	188	1.01	191
10	188	0.98	185
11	188	0.97	184
12	188	0.99	188

4.1.1.3. Augmentation Policy-Limerick Generation Station

LGS has a contract with three water suppliers, Still Creek Reservoir, Bradshaw Reservoir, and Wadesville Mine Pool, in the Schuylkill River watershed to replace lost water due to the evaporative cooling process of two generation towers when necessary. DRBC policies state that when the streamflow condition at USGS gage 01472000 Pottstown is forecasted to fall below 560 CFS in three days, LGS must augment streamflow via releases from Still Creek Reservoir or Wadesville Reservoir and augmentation releases are required to continue two days after streamflow conditions have risen above 560 CFS at Pottstown. Additionally, when streamflow measured at USGS gage 01473000 Graterford falls below 210 CFS and LGS uses Perkiomen Creek as the source of water demand, the streamflow is required to be augmented by LGS through releases from Bradshaw Reservoir. At the same time, LGS must preserve, streamflow above 10 CFS at East Perkiomen Creek whose flow condition is recorded by USGS gage 01472620 Dublin.

Streamflow augmentation policy regarding LGS was modeled through Bradshaw Reservoir and Wadesville Reservoir in the simulation. The third water supply, Still Creek Reservoir is used as a backup source to replace lost water due to evaporative cooling processes at LGS. Releases requested from Still Creek Reservoir was simulated through Wadesville Reservoir, and the Still Creek Reservoir was omitted from the STELLA model. Due to lack of inflow data to Wadesville and Bradshaw Reservoirs, these reservoirs are assumed to be full all times to make releases to augment stream flow conditions downstream when necessary.

Augmentation releases from Bradshaw and Wadesville Reservoirs were simulated through two individual sectors as shown in Figure 11.

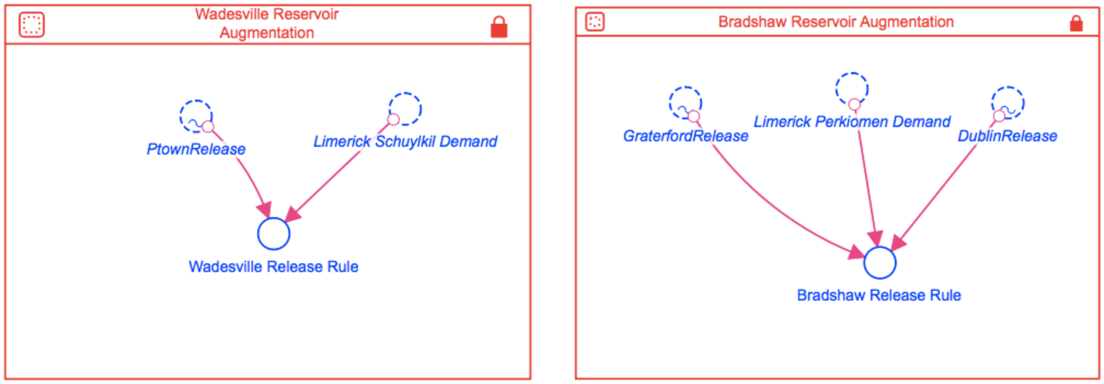


Figure 11. Wadesville and Bradshaw Reservoir Sectors

Wadesville Reservoir was assigned as the augmentation source for Limerick Schuylkill Demand. The reservoir was programmed to make releases on the same day when the stream flow at Perkiomen node falls below 560 CFS and to terminate releases at the same day when stream flow condition at Perkiomen node rises above 560 CFS. The amount of water released from the Wadesville Reservoir is equal to the amount of water withdrawn from the Schuylkill River by LGS on the same day.

The augmentation source for Limerick Perkiomen Demand is Bradshaw Reservoir. Releases from Bradshaw Reservoir depend on the two conditions. If the streamflow at Graterford node is below 210 CFS and streamflow at Dublin node is below 10 CFS, Bradshaw Reservoir releases the same amount of water withdrawn from Perkiomen Creek plus differences between 10 CFS and inflow at Dublin node. If the streamflow at Graterford is less than 210 CFS but Dublin is above 10 CFS then releases from the reservoir is equal the amount of water withdrawn from Perkiomen Creek. If the stream flow at Graterford is more than

210 CFS yet Dublin is below 10 CFS, the reservoir only releases the difference between 10 CFS and inflow at Dublin. Bradshaw Reservoir does not release water if the stream flow at Graterford node is estimated to be above the policy trigger, 210 CFS, and inflow of Dublin node is above 10 CFS.

Programmed releases from Wadesville and Bradshaw Reservoirs are prompted based on the streamflow conditions at policy trigger points all of which are located at the downstream of those reservoirs in the simulation. Yet, the STELLA software does not allow a connection from downstream to upstream nodes when the flow of a downstream node is a function of the upstream node flow. To eliminate a connection error, the simulation of historical streamflow is finalized through two runs of the model. The first run of the model simulates policies regarding Blue Marsh Reservoir. This is because Pottstown node is located downstream of the Tulpehocken node where the releases from Blue Marsh join on the main stem of Schuylkill River. Once the first run of the model is completed simulated streamflow data at Pottstown, Graterford, and Dublin nodes are duplicated to be used for the simulation of LGS augmentation policies and demand deliveries from the Schuylkill River System on the second run.

4.1.2. Blue Marsh Reservoir Simulation

The operation rules of Blue Marsh are simulated through four subsectors and one main sector in the model. The picture of all the sub-sectors and main sectors is shown in Figure 7.

The sub-sectors include calculation of the direct precipitation to the reservoir (Figure 12), rule curve of the reservoir (Figure 13), reservoir spill (Figure 14), and mandatory conservation releases (Figure 15).

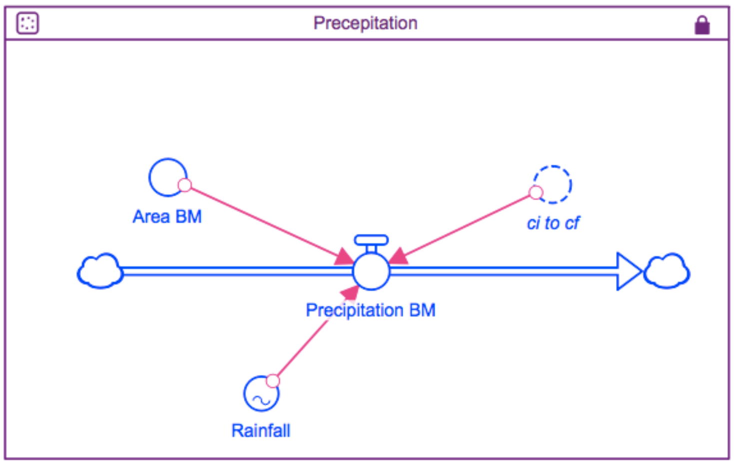


Figure 12. Sub-sector of Blue Marsh Reservoir Simulation Calculating the Direct Precipitation top of the Reservoir

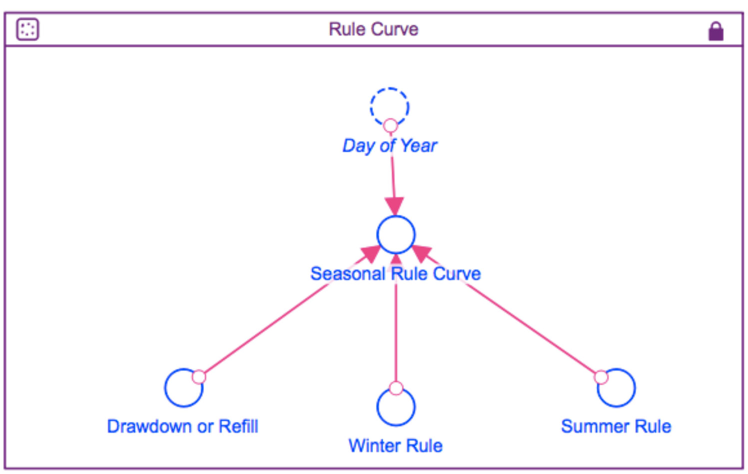


Figure 13. Sub-sector of Blue Marsh Reservoir Simulation Coding Rule Curve of the Reservoir

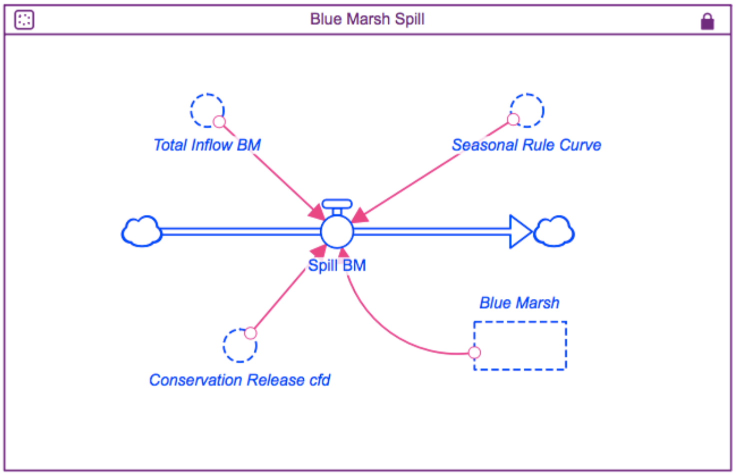


Figure 14. Sub-Sector of Blue Marsh Reservoir Simulation Coding Spill Equation

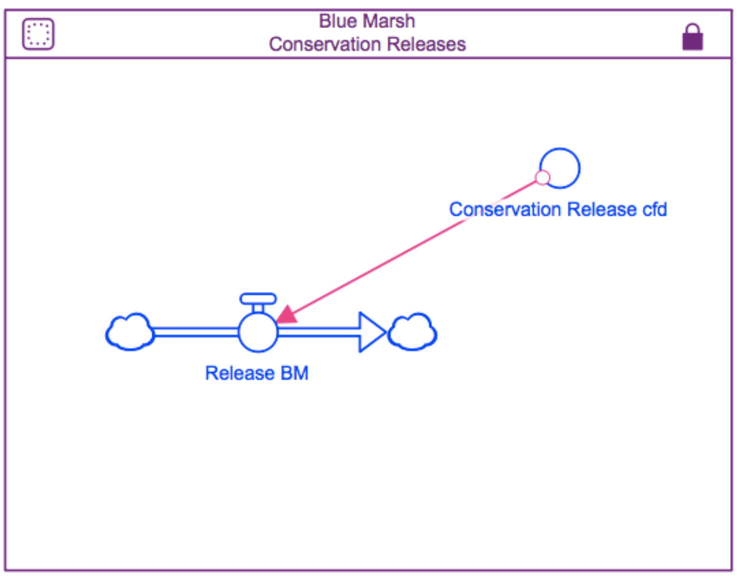


Figure 15. Sub-Sector of Blue Marsh Reservoir Simulation Coding Conservation Releases

All these sectors are connected with the main sector (Figure 16) either as an inflow or outflow of the reservoir.

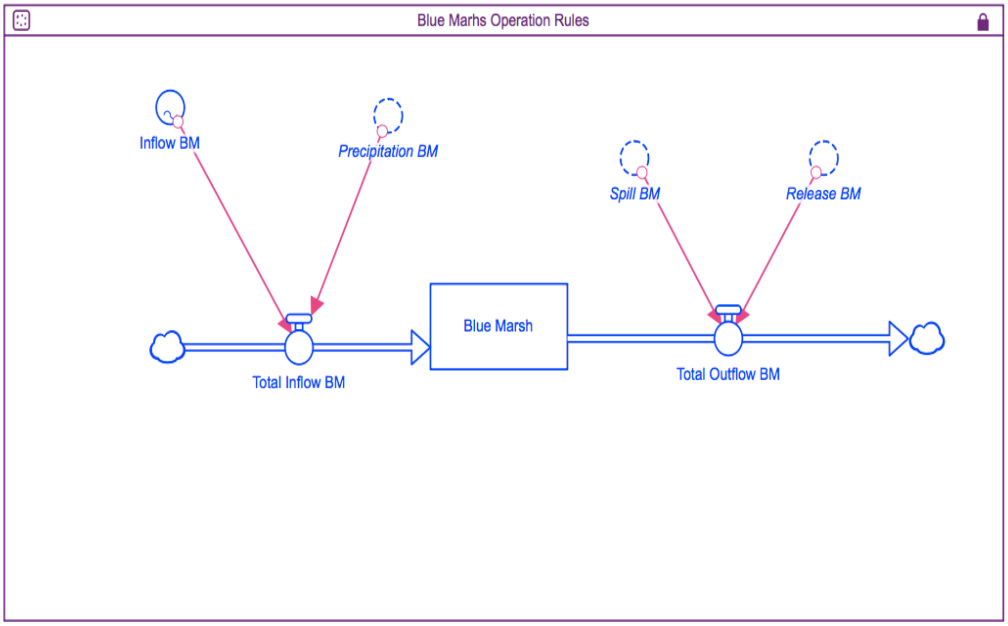


Figure 16. Main sector of Blue Marsh Reservoir Simulation

The reason behind this is that the Blue Marsh Reservoir simulation sectors follow a mass balance approach which accounts for change in storage as illustrated in Equation 8.

$$Change\ in\ Storage = \sum inflows - \sum outflows \quad (8)$$

Inflows to the reservoir are direct precipitation onto the reservoir and the total influent streamflow to the reservoir. Outflow from the reservoir is governed by the Blue Marsh Reservoir operation rules defined in the Water Control Manual of Blue Marsh including seasonal reservoir spills and conservation releases. Spill rules are designed to dump water from a reservoir when the reservoir capacity is full. The spill and release rules of Blue Marsh Reservoir are described in detail at the *Section 4.1.2.1* and *Section 4.1.2.3*.

The change in storage indicates the difference between total inflows to the reservoir and total outflows from the reservoir. If the difference between inflows and outflows is negative, the reservoir storage level decreases otherwise more water stored in the reservoir and the storage level increases. The mass balance equation of Blue Marsh Reservoir is defined and displayed in Equation 9.

$$\begin{aligned} &Change\ in\ storage = [initial\ reservoir\ storage] + \\ &[direct\ precipitation\ onto\ reservoir + influent\ stream\ flow] - \\ &[conservation\ releases + reservoir\ spill] \end{aligned} \quad (9)$$

Blue Marsh Reservoir is located on the upstream of the confluence point of Tulpehocken Creek and the Schuylkill River main stem. Therefore, once the coding of Blue Mash operation rules was complete, the outflow node of Blue Marsh Reservoir was connected to the Schuylkill River System portion of the model. This connection is at the Tulpehocken node which represents the confluence point of Tulpehocken Creek and Schuylkill River in the simulation.

4.1.2.1. Seasonal Reservoir Rule Curve for Blue Marsh

A rule curve is used to manage the reservoir operations by dividing the storage volume of a reservoir into different zones based on the objectives of operational policies. Figure 17 displays Blue Marsh Reservoir pool elevations and volumes.

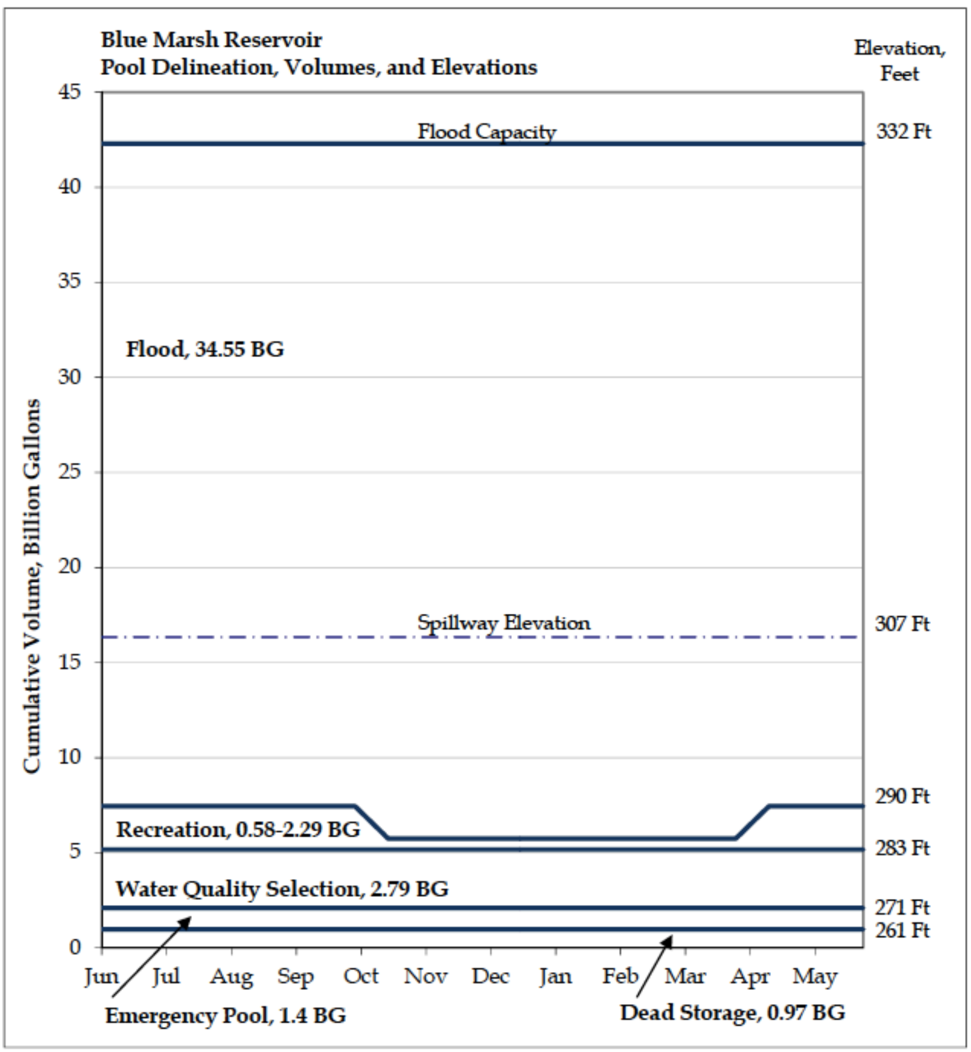


Figure 17. Blue Marsh Reservoir Pool Elevations and Volumes (Hesson, 2013)

The primary objectives of the Blue Marsh Reservoir are to control flooding in the Schuylkill River watershed, supply water to the downstream counties, and meet the low flow augmentation demands. The seasonal rule curve for Blue Marsh reservoir is coded into the model (Figure 13) as described in the Blue Marsh Operational Manual (US Army Corps of Engineers, 1996). The storage level of the reservoir in the simulation should follow the seasonal storage level shown in Table 8.

Table 8. Seasonal Pool Elevations

Pool	Elevation, Feet	Volume Above Dead Storage		Time Period
		Acre-Feet	Billion Gallons	
Summer Pool	290	22,897	7.45	Apr 16 - Sept 30
Drawdown	290-285	-	-	Oct 1 – Oct 15
Winter Pool	285	17,623	5.74	Oct 16 – Mar 31
Refill	285-290	-	-	Apr 1 – Apr 15

4.1.2.2. Inflows to Blue Marsh Reservoir

The primary inflows to Blue Marsh Reservoir are direct precipitation onto the reservoir (Figure 12) and influent streamflow (Figure 16).

Fifty years of daily precipitation data for the dam was downloaded from the online tool, CLIMOD2 which is designed by the Northeast Regional Climate Center. Daily precipitation data (P_{daily}) is multiplied by the surface area of the reservoir (A) to determine the volume of direct precipitation (P_{direct}).

$$P_{direct} = P_{daily} * A \tag{10}$$

Equation 10 presents how the volume of direct precipitation to the reservoir is calculated in the model.

4.1.2.3. Outflows from Blue Marsh Reservoir

The outflows from the Blue Marsh Reservoir are regulated by conservation releases (Figure 15) and reservoir spills from the reservoir (Figure 14). To simulate conservation release criteria, Blue Marsh Reservoir is programmed to release 59 CFS for all time; release of 41 CFS for the conservation of Tulpehocken Creek and water supply release of 18 CFS for the Western Berks Water Authority. The reservoir is assigned to activate spills when the total of inflow and existing storage minus conservation releases is above the seasonal rule curve storage capacities given in Table 8. The amount of water released from the reservoir is equal to the volume of water above the seasonal rule curve. When the volume of water does not exceed the seasonal rule curve, the spills are not activated, and therefore reservoir releases only include conservation releases.

4.2. CALIBRATION AND VALIDATION OF STREAMFLOW AND RESERVOIR STORAGE

The calibration process involved modifying model parameters to generate a good reproduction of historical observations in the study area. The calibration and validation of DRB-SET tool and calculation of runoff based on composite curve number method and baseflow are described in the following sections.

4.2.1. Verification of DRB-SET Tool Method

DRB-SET Tool method was used to simulate historical streamflow rates from 1960 to 2010 through coding existing reservoir operation rules and active watershed management policies.

To examine the performance of the model, daily observed stream flow data from 2007 to 2010 were compared to the simulated stream flow data. The comparison results suggest a good agreement between historical and simulated streamflow by showing a coefficient of determination (R^2) of 0.845. For this reason, no parameter calibration was required.

The visual comparison of model performance showing both simulated and observed streamflow conditions at the USGS gage 0143500 Norristown is displayed in Figure 18.

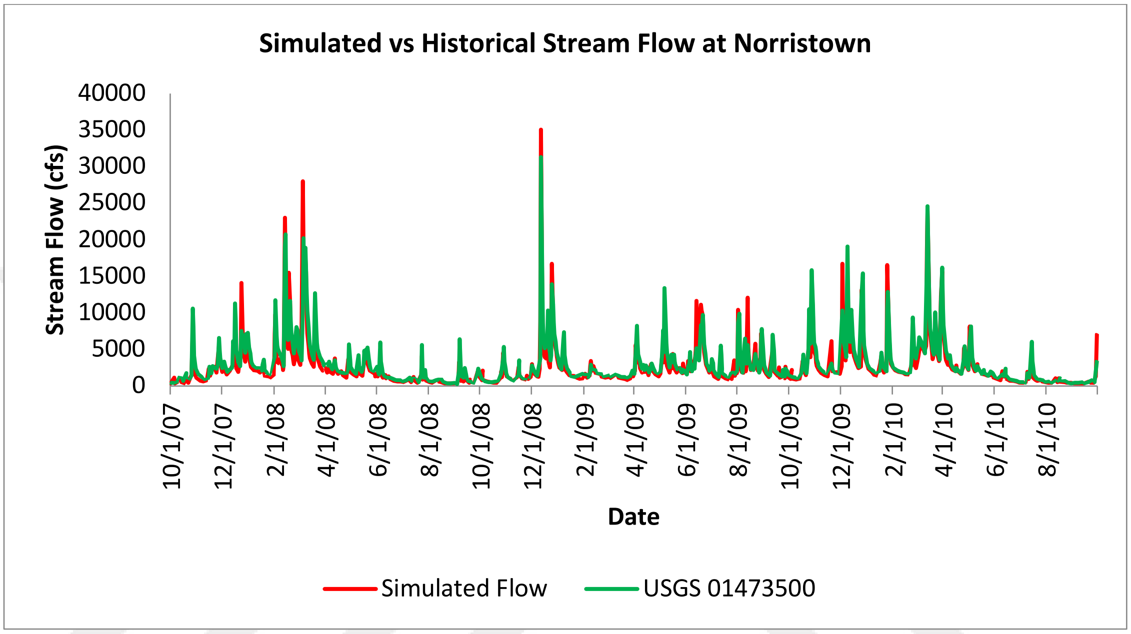


Figure 18. Observed and Simulated Stream Flow for USGS gage 0147350 at Norristown

To verify the simulated storage level of Blue Marsh reservoir, the observed reservoir elevation data were gathered from USGS gage 01470870 Blue Marsh Lake for three years from 2007 to 2010. The model predicts the reservoir storages as a volume rather than an elevation. For the verification purposes, observed elevation data were converted to the storage values with the help of an elevation-storage curve. To estimate the relationship between observed elevation and storage values, annual average elevation and storage data for Blue Marsh Reservoir were downloaded from the USGS web-site. This dataset is available for every water year and can be found in the annual Water-Data Reports. Regression analysis was applied to the downloaded data and relationship between observed elevation and storage values was estimated as shown in Equation 11.

Figure 19 shows the elevation-storage curve for Blue Marsh Reservoir based on the observed data.

$$Storage = 0.0215 * e^{(0.0477*Elevation)} \quad (11)$$

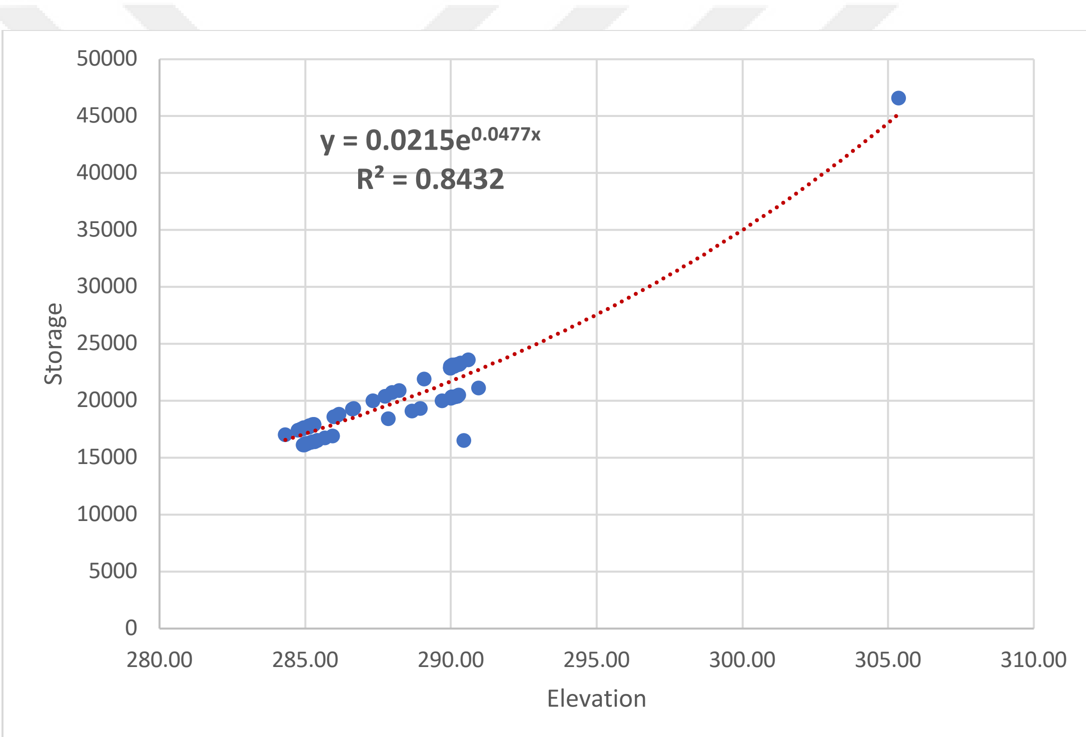


Figure 19. Elevation to Storage Graph for Blue Marsh Reservoir

Once the relationship between elevation and storage values was determined, then the daily observed elevation data were converted to the storage values to be visually compared with the predicted storage values. Figure 20 shows the comparison of observed and predicted storage values for Blue Marsh Reservoir from 2007 to 2010 in a daily time step.

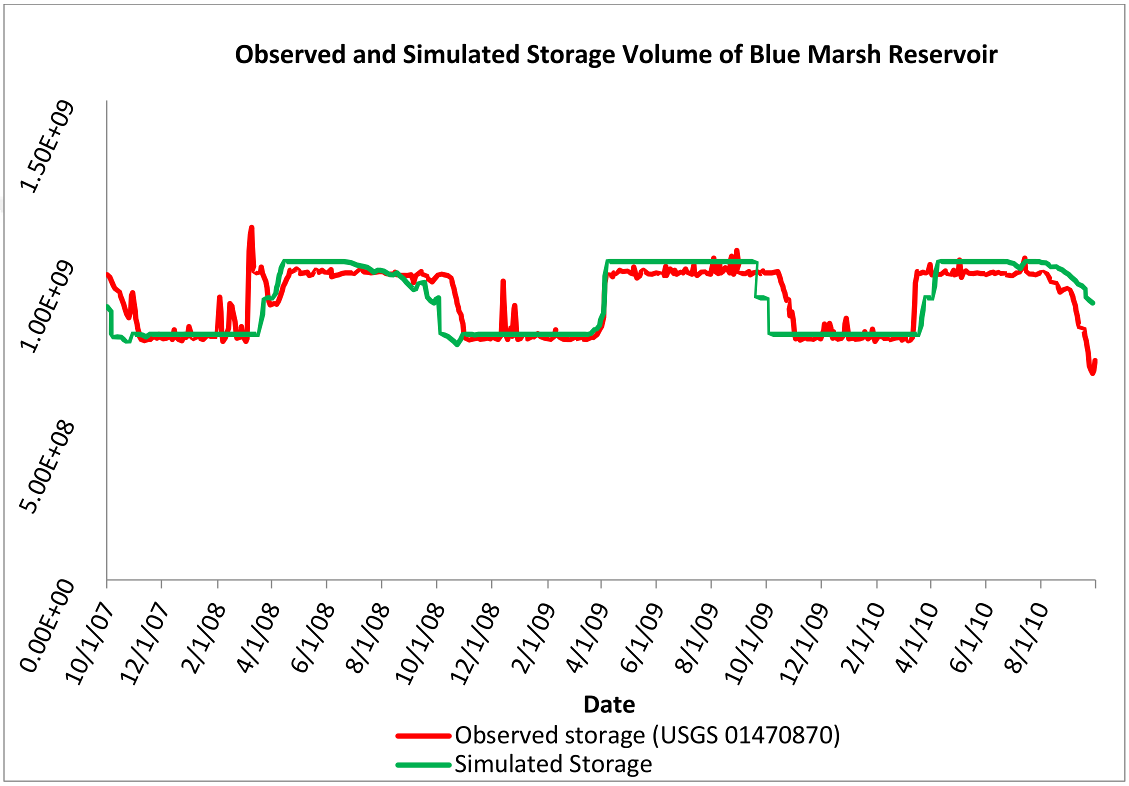


Figure 20. Observed and Simulated Storage Level of Blue Marsh Reservoir

4.2.2. Calibration and Validation of Runoff Based on Composite Curve Number and Base Flow Method

The STELLA model was run with the inflow data calculated by using the baseflow and runoff method without input from the DRB-SET tool from 2007 to 2008 for the calibration of runoff & base flow method. Two model parameters, baseflow rates and initial abstraction values, were adjusted for every node in the STELLA model to minimize the difference between simulated and observed stream flow. Initial abstraction represents the amount of water absorbed before the runoff generated. Baseflow was estimated based on available precipitation, potential evapotranspiration, field capacity, and soil moisture content of the region in a daily time step (Amur, 2018). Baseflow accumulated into a reservoir named baseflow accumulation reservoir which is a hypothetical reservoir built into the model for every node. Baseflow rates indicated the percentage of discharge from the baseflow accumulation reservoir. Baseflow rates are specific to each node and adjusted based on the historical streamflow behavior. Appendix A.2 includes adjusted parameters and corresponding gages.

Once the model base flow rates and initial abstraction values are calibrated, the model runs for another period of time with the calibrated parameters to validate the consistency of these parameters. The calibration and validation results show a good agreement between simulated and observed flow with a coefficient of determination (R^2) of 0.582. Figure 21 shows the visual comparison of simulated and observed flow at USGS gage 01473500 at Norristown and Figure 22 shows simulated and observed storage levels for Blue Marsh Reservoir.

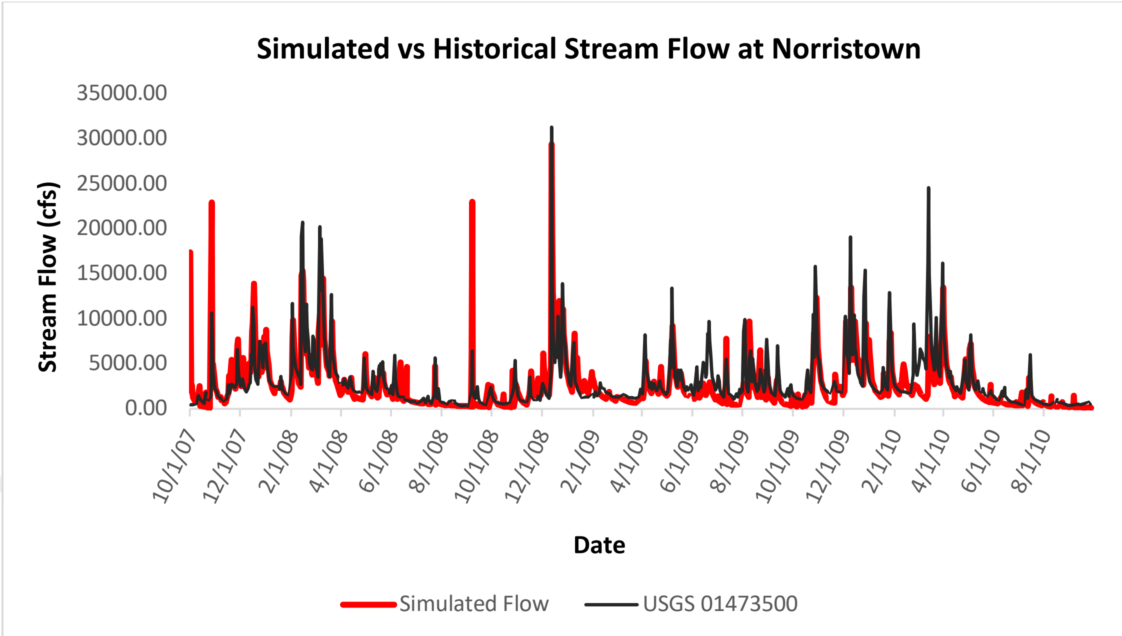


Figure 21. Observed and Simulated Stream Flow for USGS gage 01473500 at Norristown

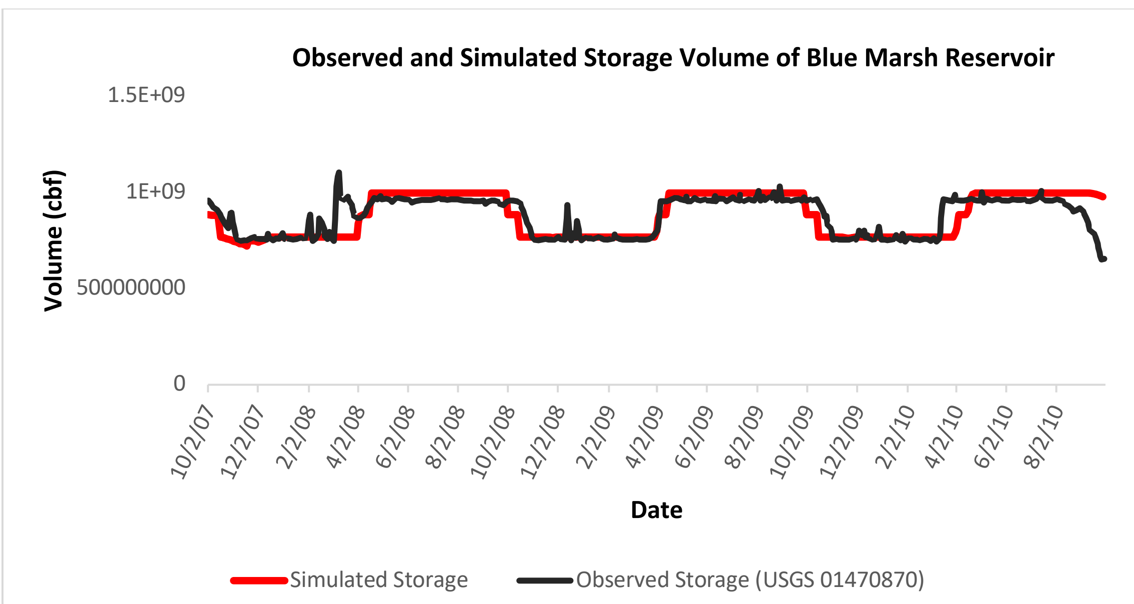


Figure 22. Observed and Simulated Storage Level of Blue Marsh Reservoir

4.3. CLIMATE CHANGE SCENARIO

To simulate the streamflow from 2020 to 2040 and assess the water resources availability, the STELLA model run under two emission, twelve climate change and three land use change scenarios.

4.3.1. Climate Change Projections

The Representative Concentration Pathways is a set of four greenhouse gases concentration pathways: RCP2.6, RCP4.5, RCP6.0 and RCP8.5 (Moss et al., 2010). These pathways were developed as a result of a design process integrating emissions, land use, and socio-economic scenarios (Van Vuuren et al., 2011). The Representative Concentration Pathways (RCP) 8.5 and 4.5 were chosen as the climate change scenarios for this study. RCP 8.5 represents a relatively high greenhouse gas emission pathway in comparison with other three scenarios (Riahi et al., 2011) whereas RCP 4.5 represents a moderate greenhouse gas emission reaching the peak point at 2040 and then decline (Thomson et al., 2011).

Most climate models have coarse spatial and temporal resolution and, therefore, might not provide precise data sets for precipitation and temperature changes on a local scale. Precipitation and temperature are important climate parameters to assess the impact of climate change on water resources because the availability of surface water resources is mostly driven by precipitation, temperature, and evapotranspiration. For this reason, climate model predictions need to be downscaled to a finer spatial resolution to assess the climate change impact on water resources on a sub-watershed level. The RCP 4.5 and 8.5 scenarios were downscaled by using Localized Constructed Analogs (LOCA) statistical downscaling method to obtain finer-resolution climate data set (Amur, 2018). The downscaled data set includes daily precipitation, evapotranspiration, and soil moisture data from 2020 to 2040 for six General Climate Model (GCM) outputs for each emission scenario (Amur, 2018).

4.3.2. Land Use Projections

Land use change has a significant impact on the amount of runoff generated during and after precipitation events. Expansion of impervious areas in watersheds is responsible for decreasing the infiltration capacity of land cover, therefore, increasing the amount of runoff. To assess the impact of land cover change on water resources, the future land cover and land use change projections were incorporated with the STELLA model through the composite curve number method. For this purpose, three land use change scenarios were considered: as-is scenario, sprawl growth scenario, and smart growth scenario were created.

The as-is scenario simulates the case where the population trends and change in the impervious area follow historical trends (Amur, 2018). The sprawl growth scenario simulates the case where the change in the impervious area exceeds the growth of population (Amur, 2018). The smart scenario simulates the case where the change in the impervious area is less than the growth of population (Amur, 2018). Amur (2018) provides further details on the development of land use and land cover projection for the Schuylkill River watershed. Appendix A.3 shows the list of nodes in the STELLA model along with the corresponding drainage areas and projected curve number calculated based on possible land use and land cover changes under three scenarios namely smart growth, as is, and sprawl growth scenarios.

4.3.3. Demand Projections

There are three water demand deliveries coded into the STELLA model of Schuylkill River watershed as described at the *Section 4.1.1.2*. Under the climate and land use change scenarios, Philadelphia water demand was increased based on the projected population for Philadelphia county for 2040. Table 9 shows the projected water demand for Philadelphia water demand sector simulated in the model.

Table 9. Projected Water Demand for Philadelphia Water Demand Sector

Month	PWD Base Demand (CFS)	PWD Peaking Factor	Calculated Average Daily Withdrawal by Month (CFS)
1	188	1.03	195
2	188	1.04	197
3	188	0.98	186
4	188	0.93	176
5	188	0.93	175
6	188	1.00	190
7	188	1.06	201
8	188	1.07	202
9	188	1.01	191
10	188	0.98	185
11	188	0.97	184
12	188	0.99	188

LGS water demand was assumed to remain as is because of the lack of information regarding the capacity of the Limerick Generation Station.

5. RESULTS & DISCUSSION

The model was run for twenty years, from 2020 to 2040, with future climate data projected from twelve GCMs under two emission scenarios (RCP 4.5 and RCP 8.5) and three land use change scenarios. Table 10 shows the climate and land use change scenarios employed for the future streamflow projection of the study.

Table 10. Climate and Land Use Change Scenarios used for

		Emission Scenarios											
		RCP 4.5						RCP 8.5					
Land use change scenarios	Smart Growth	*access*	*bcc-csm*	*bcc-csm-1-1-m*	*canesm2*	*ccsm4*	*cesm 1-bgc*	*access*	*bcc-csm*	*bcc-csm-1-1-m*	*canesm2*	*ccsm4*	*cesm 1-bgc*
	As Is	*access*	*bcc-csm*	*bcc-csm-1-1-m*	*canesm2*	*ccsm4*	*cesm 1-bgc*	*access*	*bcc-csm*	*bcc-csm-1-1-m*	*canesm2*	*ccsm4*	*cesm 1-bgc*
	Sprawl Growth	*access*	*bcc-csm*	*bcc-csm-1-1-m*	*canesm2*	*ccsm4*	*cesm 1-bgc*	*access*	*bcc-csm*	*bcc-csm-1-1-m*	*canesm2*	*ccsm4*	*cesm 1-bgc*

The precipitation, evapotranspiration, soil moisture, field capacity, land use and land cover data, and hydrological soil type were used to generate future streamflow in the Schuylkill River watershed (Amur, 2018).

Flow targets or streamflow objectives indicate the minimum amount of water desired at a specific location. Streamflow objectives were employed to assess the availability of water resources in the Schuylkill River watershed. To analyze the availability of water resources the best-suited stream gage location would be the one located immediately upstream of Philadelphia Water Department intakes. Yet, no such stream gage exists in the Schuylkill River watershed. For this reason, Norristown, the nearest upstream gage, is located ten miles upstream of Philadelphia water intakes was selected as the stream gage to assess the availability of water resources.

The historical streamflow objective for Norristown was calculated for the period of 1990-2010 to assess the availability of water resources. The flow target for Norristown includes maximum potable water demand for PWD, fish passage operation at Fairmount Dam, and a safety factor. At Fairmount Dam in Philadelphia, 100 CFS is required to operate the fish ladder (USACE, 2004). The maximum projected water demand for PWD was estimated to as 285 CFS. In addition to the maximum potable water demand and fish passage operational demand, 100 CFS safety factor was added to the target flow. In total, historical streamflow objective for Norristown is 485 CFS (Hesson, 2013). Table 11 shows the components and the total streamflow objective for Norristown.

Table 11. Historical Flow Target and Its Components for Norristown

Flow Target Component	Flow Target (CFS)
Maximum Drinking Water Demand	285
Fish Passage Operation	100
Safety Factor	100
Total	**485**

The streamflow objective for Norristown was projected to be 491 CFS by 2040. Table 12 displays the component of the flow target for Norristown.

Table 12. Projected Flow Target and Its Components for Norristown

Flow Target Component	Flow Target (CFS)
Maximum Drinking Water Demand	291
Fish Passage Operation	100
Safety Factor	100
Total	**491**

Based on projected population for Philadelphia county, the maximum PWD potable water demand was estimated to increase to 291 CFS by 2040. The fish ladder and safety factor were assumed to be as is in the future. In total, the projected streamflow for Norristown was estimated as 491 CFS.

The streamflow predictions from 2020 to 2040 and flow target at Norristown was compared for twelve different climate change scenarios (Figure 23- 31).

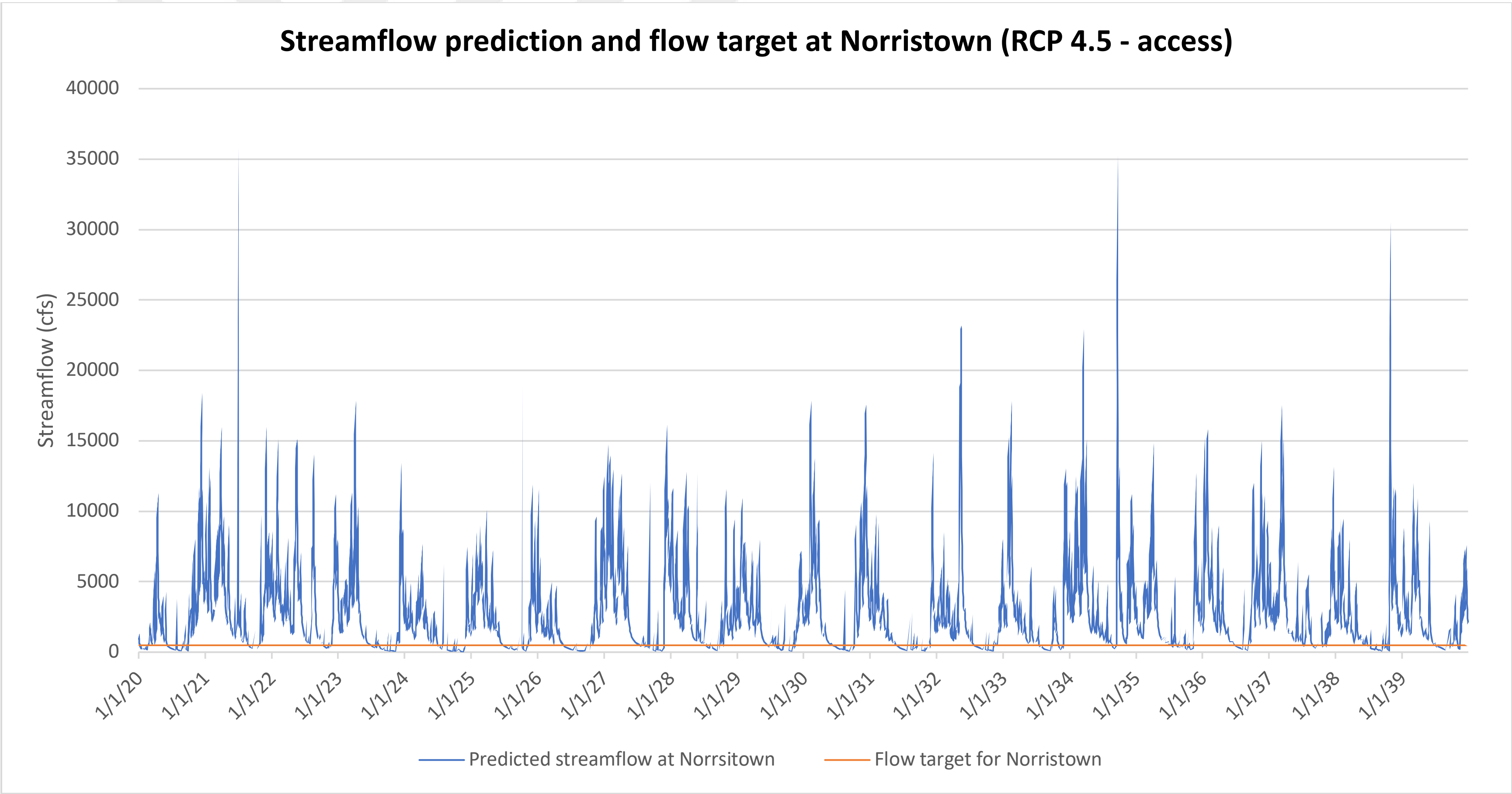


Figure 23. Predicted Future Streamflow from 2020 to 2040 and Flow Target at Norristown Under RCP 4.5 Emission Scenario and GMC Output of *access*

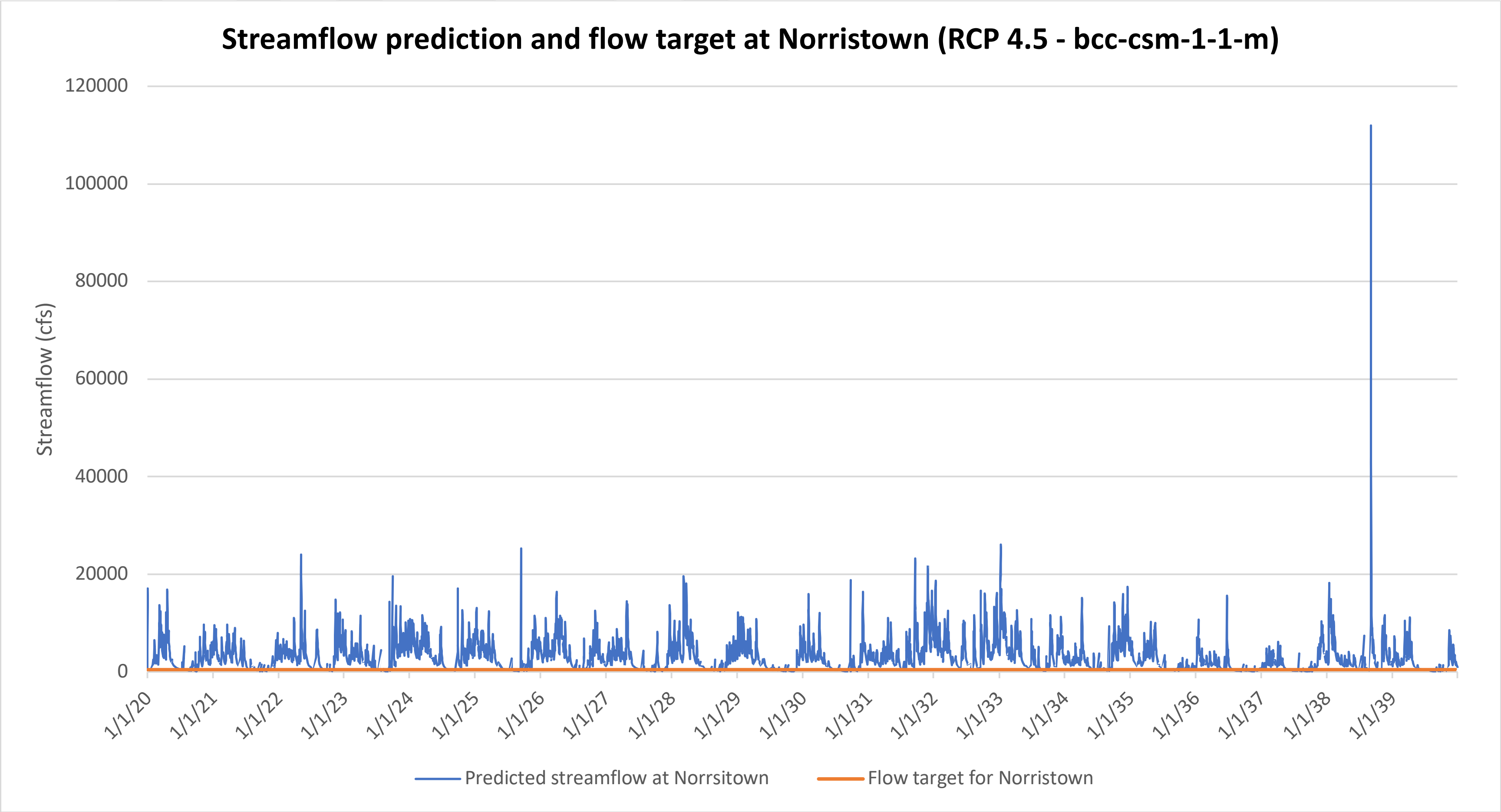


Figure 24. Predicted Future Streamflow from 2020 to 2040 and Flow Target at Norristown Under RCP 4.5 Emission Scenario and GMC Output of *bcc-csm-1-1-m*

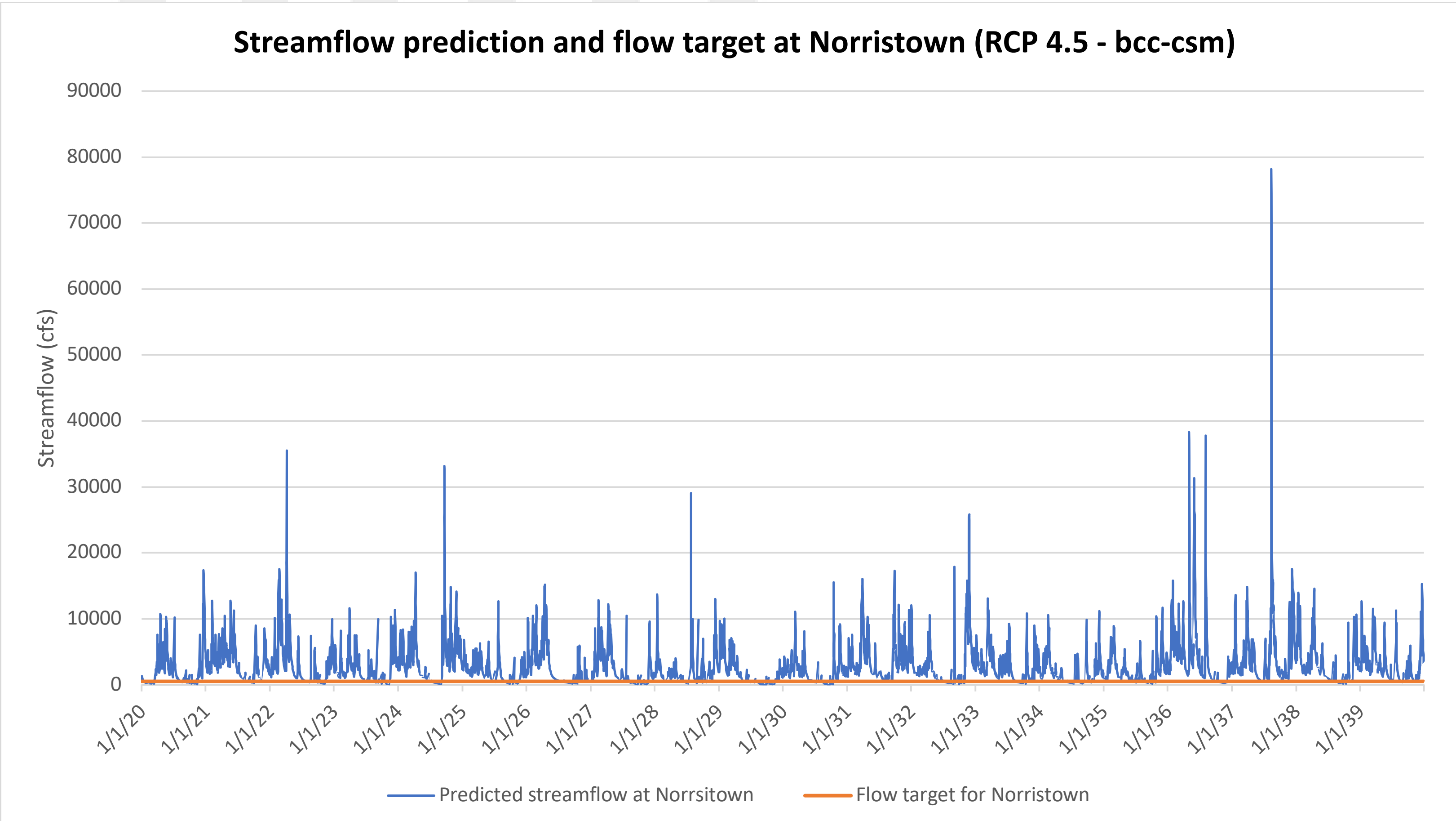


Figure 25. Predicted Future Streamflow from 2020 to 2040 and Flow Target at Norristown Under RCP 4.5 Emission Scenario and GMC Output of *bcc-csm*

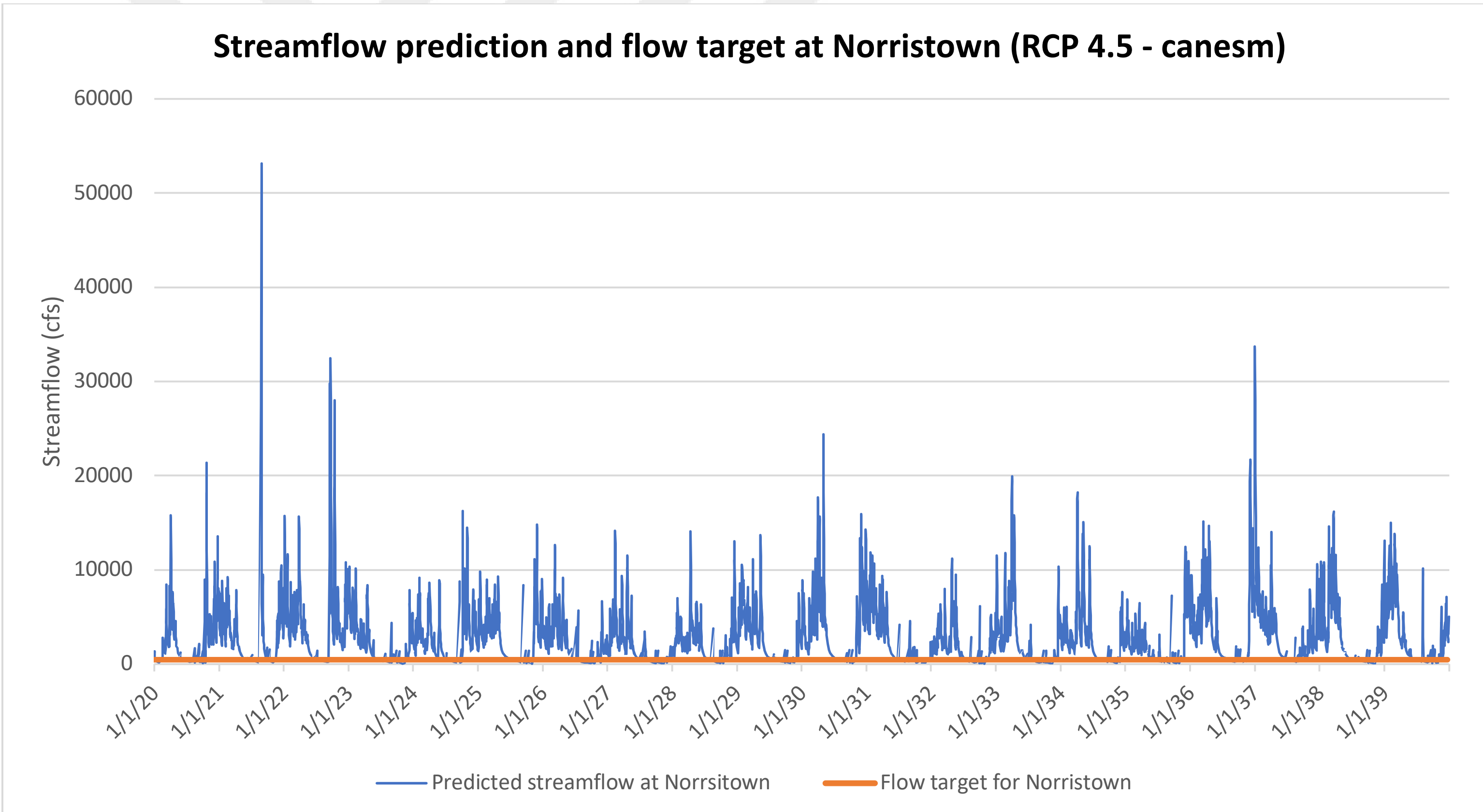


Figure 26. Predicted Future Streamflow from 2020 to 2040 and Flow Target at Norristown Under RCP 4.5 Emission Scenario and GMC Output of *canesm*

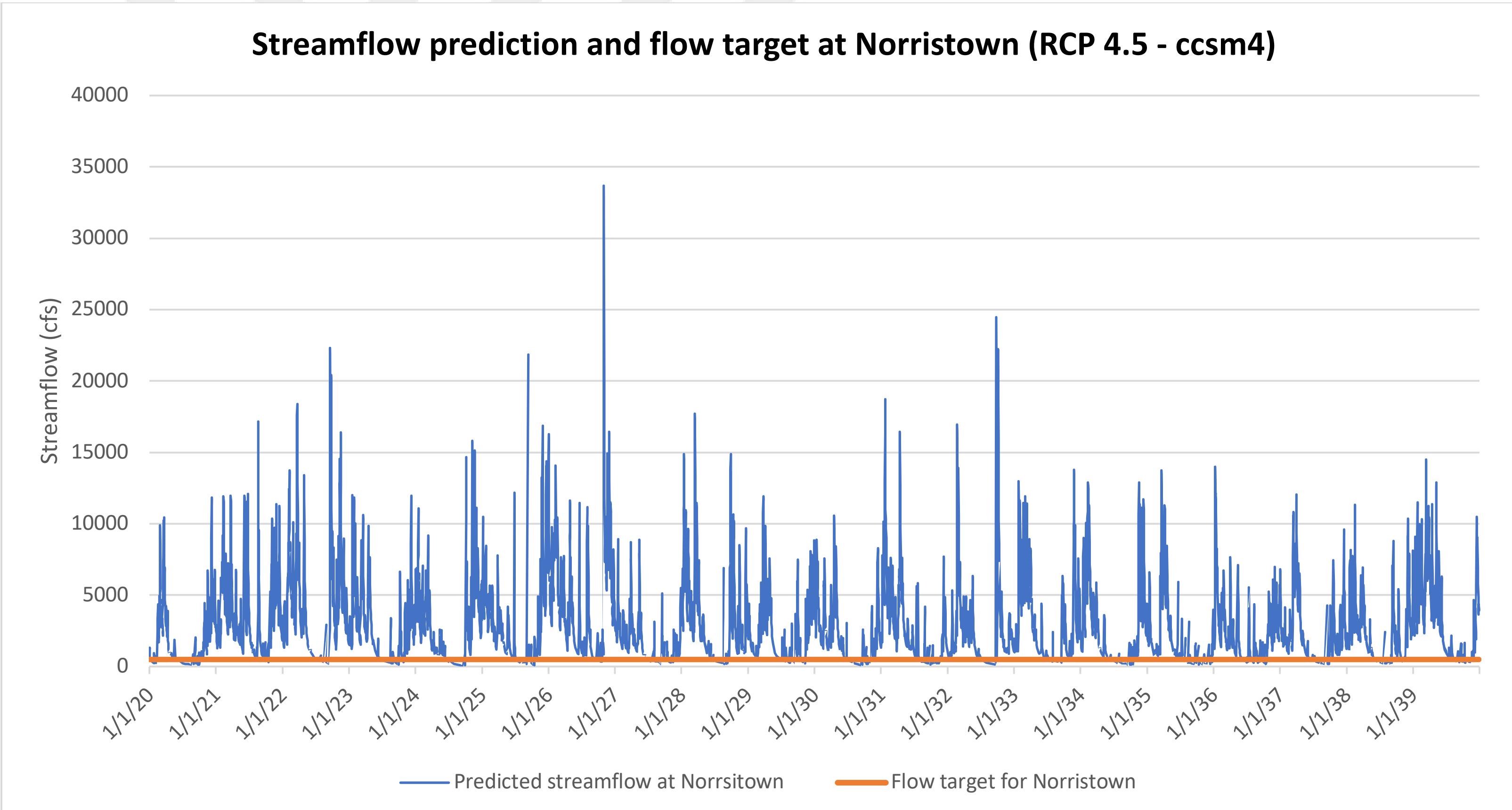


Figure 27. Predicted Future Streamflow from 2020 to 2040 and Flow Target at Norristown Under RCP 4.5 Emission Scenario and GMC Output of *ccsm-4*

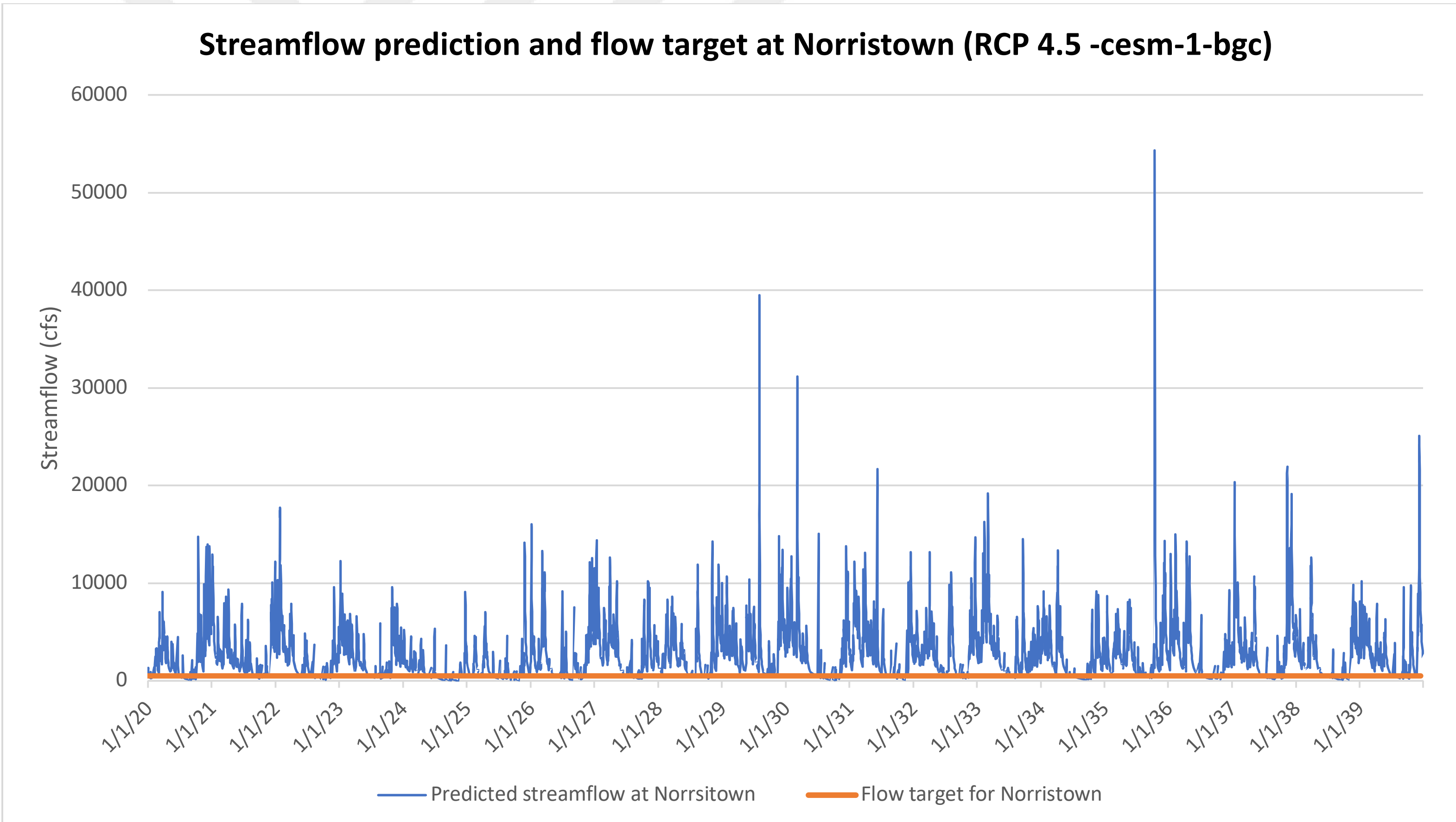


Figure 28. Predicted Future Streamflow from 2020 to 2040 and Flow Target at Norristown Under RCP 4.5 Emission Scenario and GMC Output of *cesm-1-bgc*

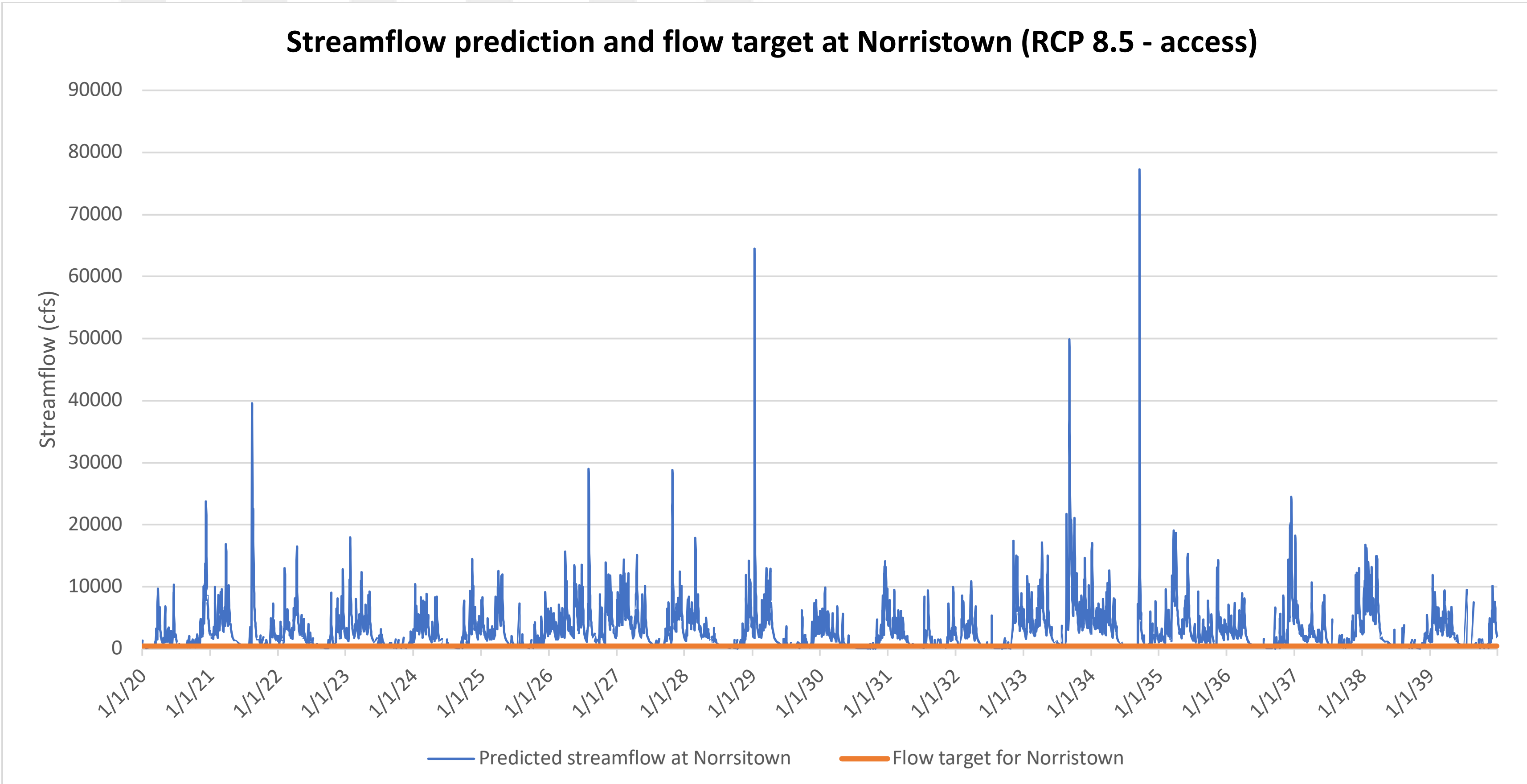


Figure 29. Predicted Future Streamflow from 2020 to 2040 and Flow Target at Norristown Under RCP 8.5 Emission Scenario and GMC Output of *access*

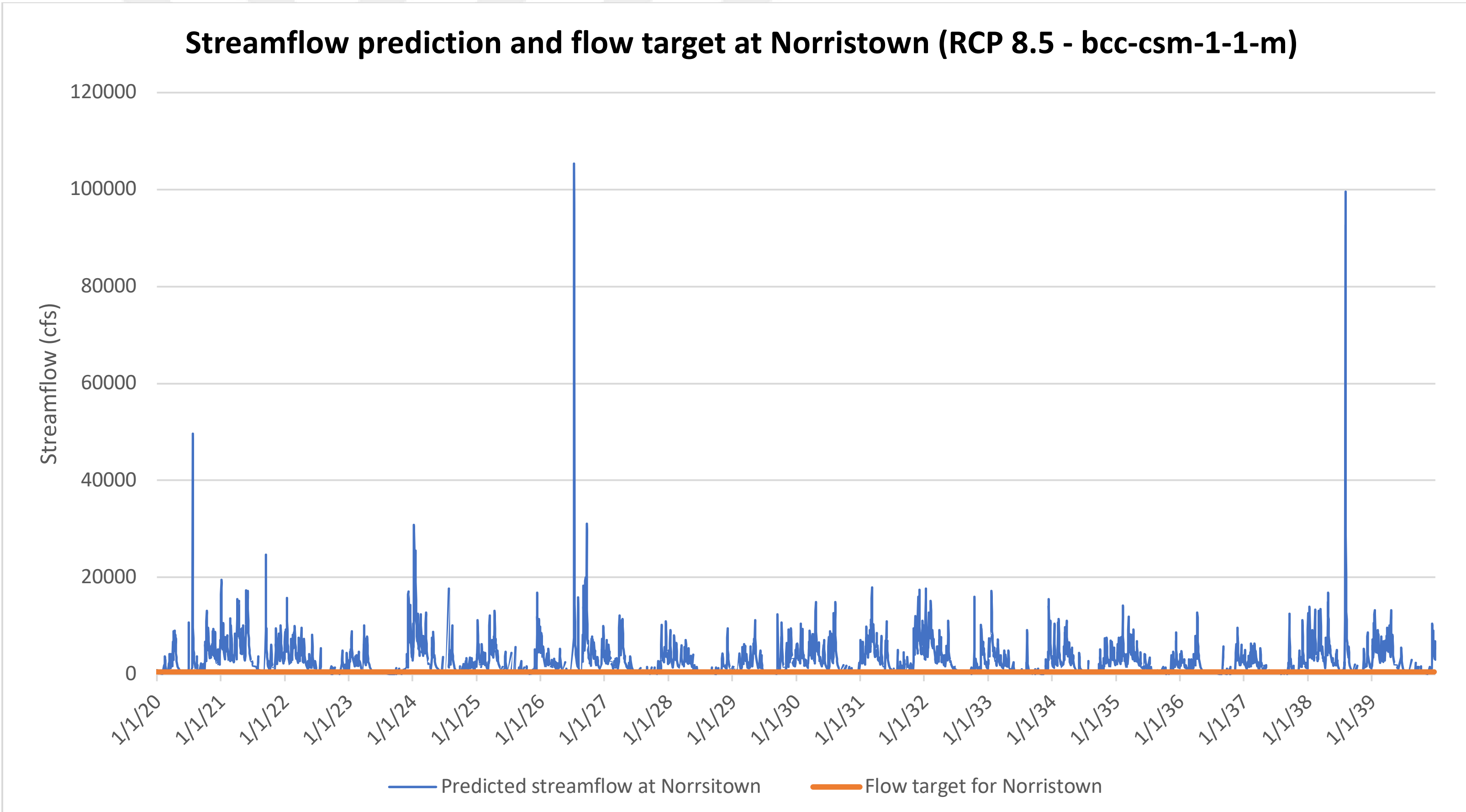


Figure 30. Predicted Future Streamflow from 2020 to 2040 and Flow Target at Norristown Under RCP 8.5 Emission Scenario and GMC Output of *bcc-csm-1-1-m*

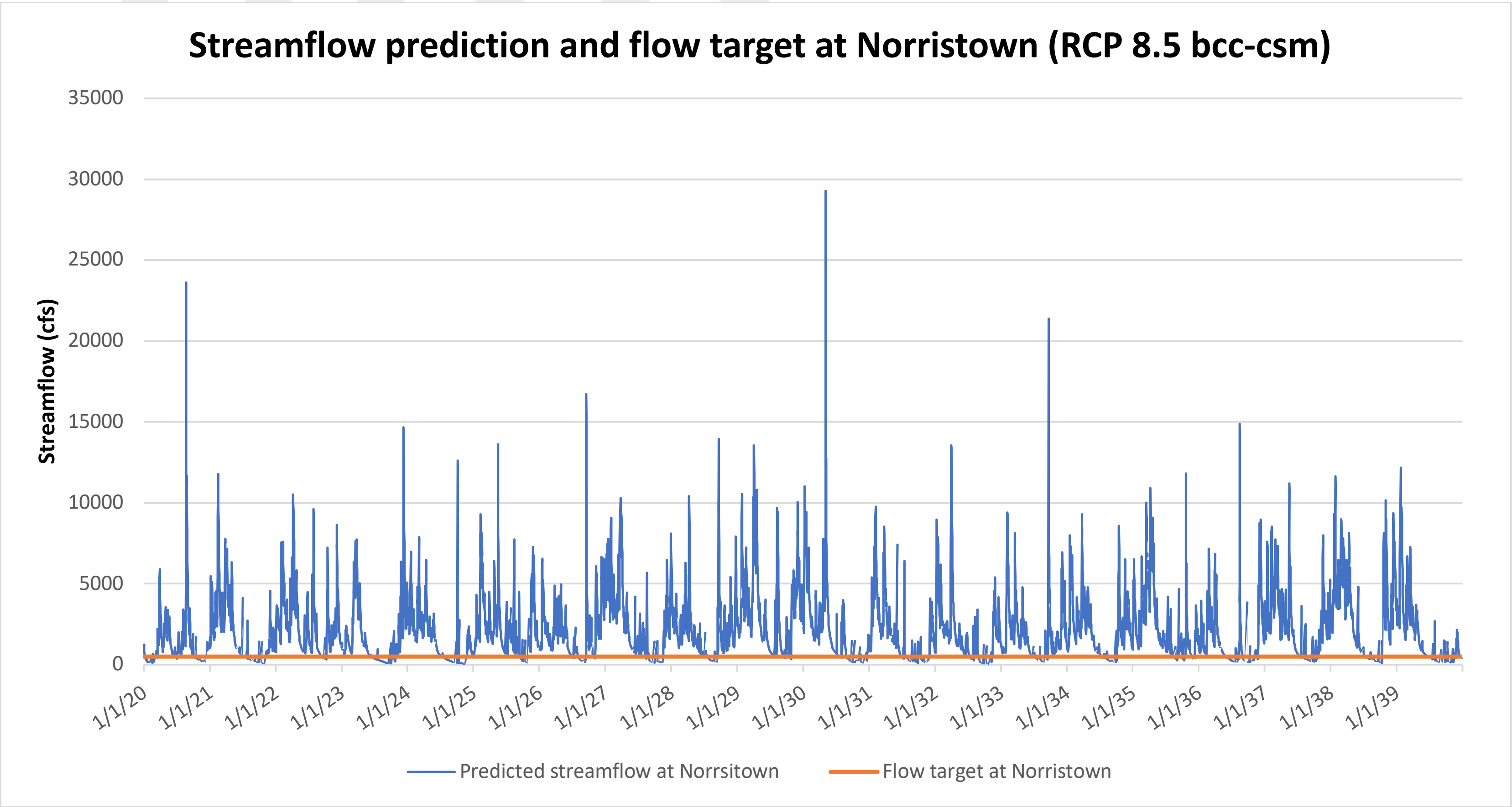


Figure 31. Predicted Future Streamflow from 2020 to 2040 and Flow Target at Norristown Under RCP 8.5 Emission Scenario and GMC Output of *bcc-csm*

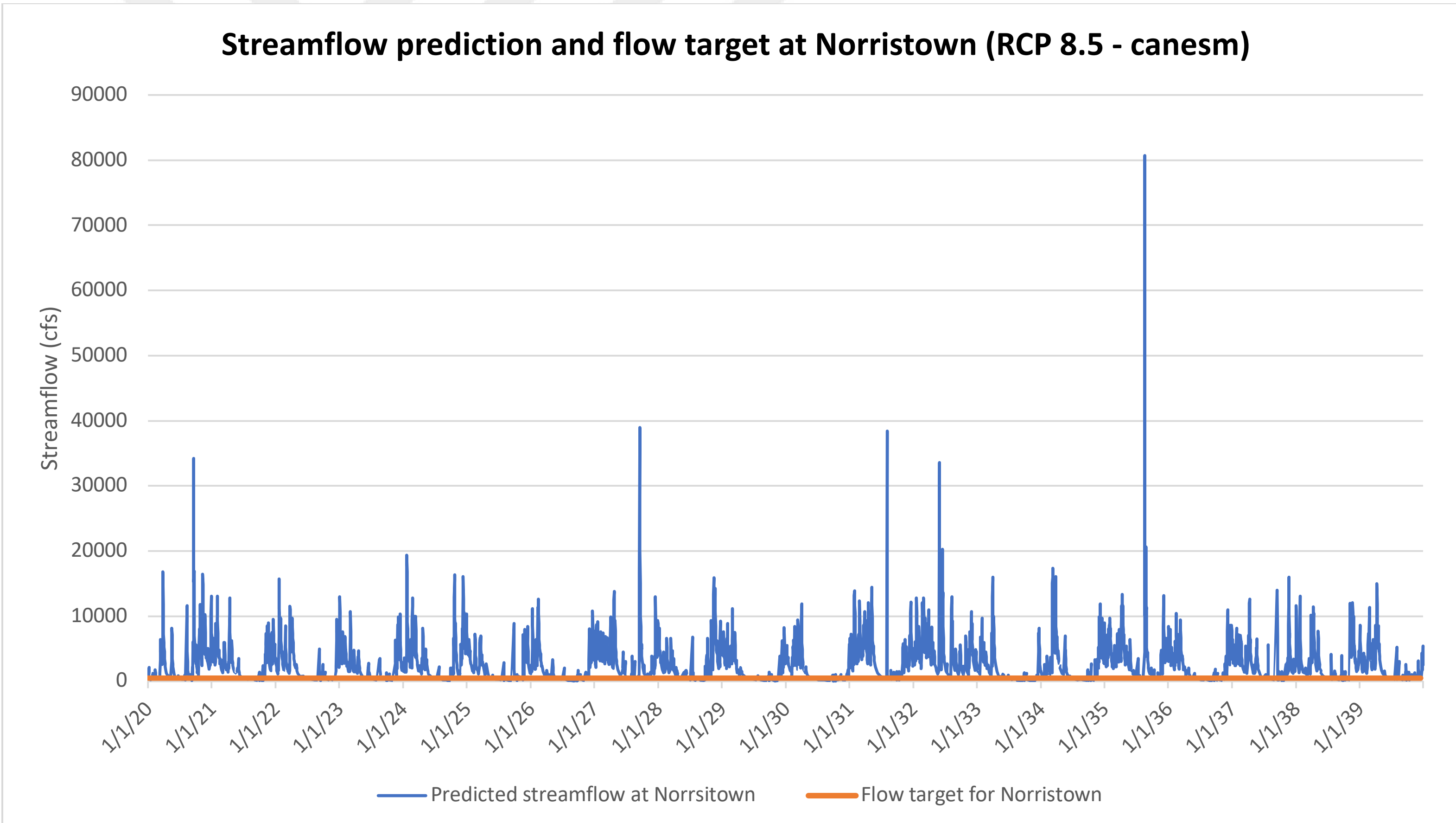


Figure 32. Predicted Future Streamflow from 2020 to 2040 and Flow Target at Norristown Under RCP 8.5 Emission Scenario and GMC Output of *canesm*

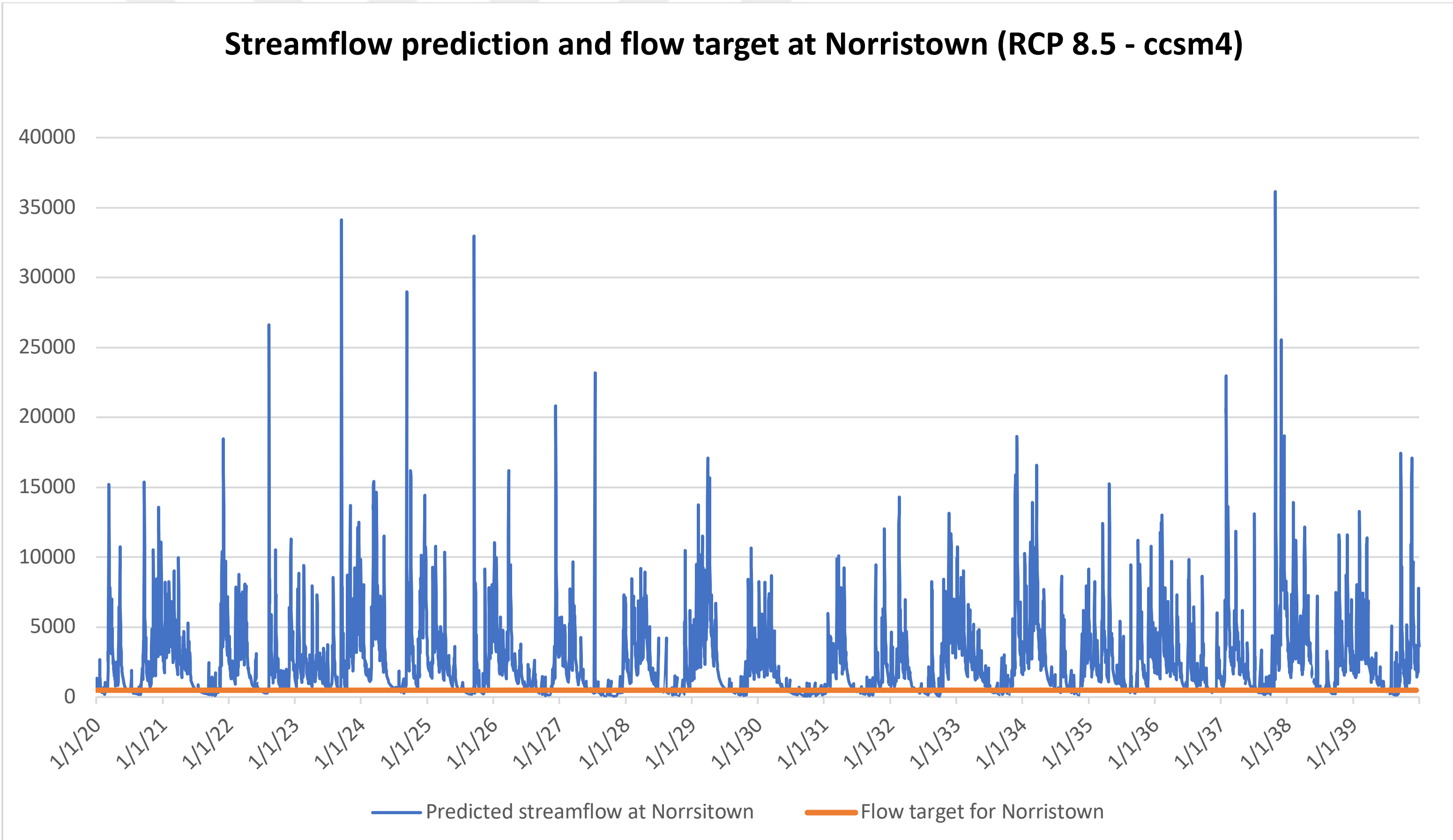


Figure 33. Predicted Future Streamflow from 2020 to 2040 and Flow Target at Norristown Under RCP 8.5 Emission Scenario and GMC Output of *ccsm4*

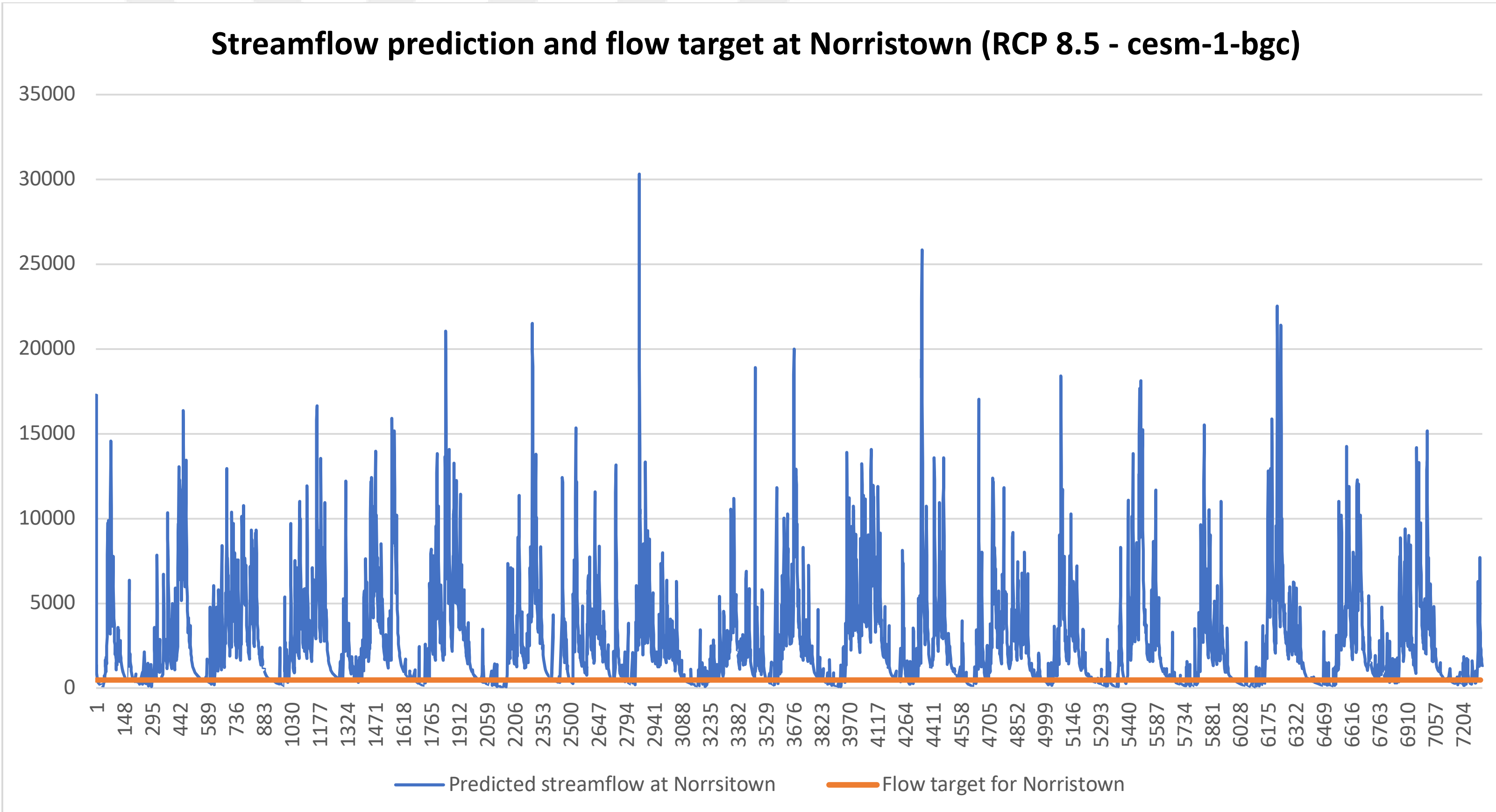


Figure 34. Predicted Future Streamflow from 2020 to 2040 and Flow Target at Norristown Under RCP 8.5 Emission Scenario and GMC Output of *cesm-1-bgc*

The number of days when the streamflow at Norristown falls below streamflow objective (491 CFS) was calculated for each scenario. Table 13 displays the water resources availability analysis result for Schuylkill River watershed for each climate change scenario as well as the availability of water resources for last twenty years of historical streamflow simulation period.

Table 13. Percentage of Number of Days When Streamflow Falls Behind Target Flow at Norristown Location for Each Climate Change Scenario

Historical Streamflow Availability	**89.79 %**	
	Emission Scenarios	
GCM Outputs	**RCP 4.5**	**RCP 8.5**
access	70.16%	75.02 %
bcc-csm-1-1	76.58%	75.44%
bcc-csm-1-1-m	76.85%	75.55 %
canesm2	67.68%	67.17 %
ccsm4	74.29%	75.14 %
cesm 1-bgc	74.31%	74.72 %

The results of these simulations showed that 89% of the days in the period of 1990-2010 met the streamflow objectives at Norristown, 67.68% -76.85% of the days in the period of 2020-2040 met the streamflow objectives under the RCP 4.5 emission scenarios and 67.17% - 75.55% of the days in the specified time period met the streamflow objectives under the RCP 8.5 emission scenarios in the Schuylkill River watershed. The impact of land use and land cover change on water resources was found to be insignificant.

6. CONCLUSION

In this research, modeling environment STELLA was used to analyze the impact of climate and land use changes on water resource in the Schuylkill River watershed. First, map-based water resource model for Schuylkill River watershed was built into the STELLA. The watershed management policies and reservoir operation rules related to the streamflow conditions were then programmed into the model to simulate the historical daily streamflow rates within the Schuylkill River watershed. The STELLA model was calibrated and validated using historical streamflow and reservoir levels from 2007 to 2010. The calibration results indicated that the STELLA model was simulated streamflow and reservoir levels fairly well.

The calibrated model was used to investigate the impact of climate and land use changes on water resources in the basin. For this purpose, climate data were projected from twelve GCMs outputs under two emission scenarios (RCP 4.5 and RCP 8.5). In addition, three land use change scenarios were developed and the demand delivery for PWD from the basin was projected based on predicted population change by 2040.

The basin characteristics, hydrologic soil type, and field capacity, were assumed to stay the same for the projected period of future analysis for the project. Additionally, the demand pattern for two intakes of LGS was assumed to remain as is due to lack of information data regarding the generation capacity of the power plant.

The availability of water resources in the future was analyzed through a streamflow objective. To analyze the availability of water resources the best-suited stream gage location would be the one located immediately upstream of Philadelphia Water Department intakes. Yet, no such stream gage exists in the Schuylkill River watershed. Norristown, the nearest upstream gage, is located ten miles upstream of Philadelphia water intakes was selected as the stream gage for the assessment. The number of days when the streamflow at Norristown falls below streamflow objective was calculated for every scenario. The result of these analyses indicated that projected streamflow is less likely to meet streamflow objective in comparison with the historical streamflow records. Therefore, meeting the all water demands within the Schuylkill River basin may be more difficult for the water resources managers over the years.

It should be noted that the result of this study should be evaluated along with the assumptions that were made within the context of the study. The reservoir operational rules, watershed characteristics, watershed management policies, or capacity of the power plant may change in the future. All of these changes might result in a decrease or increase on projected streamflow for the time period of this study in the basin.

For the future work, the STELLA model can be used to support the research on:

1. The assessing the effectiveness of alternative operation rules for Blue Marsh Reservoir as well as policies in the basin under climate change,
2. Possible drought conditions in the future due to the effect of climate and land use change,

3. To analyze the possible impact of climate and land use change on water quality in the basin.

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APPENDIX A

This appendix presents the nodes into the STELLA model along with the corresponding USGS gages, drainage areas, calculated curve numbers based on the most recent land cover data, calculated composite curve number for three land use change scenarios, calibrated baseflow rates, and initial abstraction values.

Table A 1. STELLA nodes with the corresponding USGS gages, drainage areas, and compostive curve number calculated based on the most recent land cover data set

STELLA Node	USGS Gage Number	Drainage Area (sqmi)	Curve Number (2011)
Upper Perkiomen	01472198	38	71.78837
Reading	01471510	314	74.29808
Dublin	01472620	4.05	73.53276
Skippack	01473120	53.7	77.03495
Norristown	01473500	280.3	76.24459
Schwenksville	01472810	54.65	76.10974
Philadelphia	01474500	69	85.39284
Little Schuylkill	01470500	100	69.38582
Pottstown	01472000	181.5	73.12400
Landingville	01468500	76.9	70.20668
Graterford	01473000	182.3	72.57779
Pottsville	01467500	53.4	68.38186
Blue Marsh	01470960	175	74.78754
Drehersville	01470000	79.1	68.80198
Wissahickon	01474000	64	79.15389
Tamaqua	01469500	42.9	68.74262
Manatawny	01471980	28.6	72.16517
Tulpehocken	01471000	36	75.56596
Spangsville	01471875	56.9	71.91268

Table A 2. STELLA nodes with the corresponding USGS gages, calibrated baseflow rates and calibrated initial abstraction values

STELLA Node	USGS Gage Number	Calibrated Values for Baseflow Rates	Calibrated Initial Abstraction Values
Upper Perkiomen	01472198	0.059	0.20
Reading	01471510	0.115	0.20
Dublin	01472620	0.145	0.20
Skippack	01473120	0.015	0.20
Norristown	01473500	0.157	0.20
Schwenksville	01472810	0.251	0.20
Philadelphia	01474500	0.222	0.20
Little Schuylkill	01470500	0.144	0.20
Pottstown	01472000	0.015	0.20
Landingville	01468500	0.1	0.20
Graterford	01473000	0.595	0.20
Pottsville	01467500	0.151	0.20
Blue Marsh	01470960	0.014	0.20
Drehersville	01470000	0.343	0.20
Wissahickon	01474000	0.152	0.20
Tamaqua	01469500	0.107	0.20
Manatawny	01471980	0.015	0.20
Tulpehocken	01471000	0.59	0.20
Spangsville	01471875	0.058	0.20

Table A.3. STELLA nodes with the corresponding USGS gages, drainage areas, and composite curve number calculated based on three land use change scenarios

STELLA Node	USGS Gage Number	Drainage Area (sqmi)	Curve Number for As Is Scenario	Curve Number for Smart Growth Scenario	Curve Number for Sprawl Growth Scenario
Upper Perkiomen	01472198	38	74.59815	74.52313	74.67317
Reading	01471510	314	69.53275	69.48728	69.55492
Dublin	01472620	4.05	74.9774	74.93562	75.03435
Skippack	01473120	53.7	72.37218	72.29981	72.38957
Norristown	01473500	280.3	76.02197	75.90578	76.13233
Schwenksville	01472810	54.65	72.01071	71.98621	72.03522
Philadelphia	01474500	69	71.84358	71.82978	71.85738
Little Schuylkill	01470500	100	77.23159	77.19186	77.29648
Pottstown	01472000	181.5	76.43072	76.38419	76.47726
Landingville	01468500	76.9	76.25863	76.22141	76.29586
Graterford	01473000	182.3	73.2527	73.22052	73.28487
Pottsville	01467500	53.4	72.65491	72.63558	72.67411
Blue Marsh	01470960	175	73.56826	73.55938	73.57713
Drehersville	01470000	79.1	85.58081	85.53498	85.62974
Wissahickon	01474000	64	79.25129	79.22694	79.27563
Tamaqua	01469500	42.9	70.25016	70.23929	70.26102
Manatawny	01471980	28.6	68.40781	68.40133	68.4143
Tulpehocken	01471000	36	68.81928	68.81495	68.8236
Spangsville	01471875	56.9	68.75927	68.7551	68.76343