APPENDIX A: **Stream Temperature Modeling in Nontidal Coldwater Streams in Maryland**

INTRODUCTION

Stream temperature is an important measure of water quality and a key parameter for protecting aquatic life (MDE 2013) that reflects the amount of heat energy in the water (WSDE 2011). Temperature is a physical property of water that affects most biological and chemical processes that occur in water. Temperature exerts a major influence on biological activity and growth. Temperature governs the kinds of organisms that can live in rivers and lakes, as aquatic species all have a preferred temperature range. Temperature is also important because of its influence on water chemistry, especially dissolved oxygen. Warm water holds less dissolved oxygen than cool water, and may not contain enough dissolved oxygen for the survival of different species of aquatic life.

Stream temperature is spatially and temporally dynamic and controlled by a complex and interacting set of factors, such as local air mass characteristics, solar radiation, riparian shade, channel characteristics, hydrologic residence time, stream flow volume, as well as shallow and deep groundwater recharge (George et al. 2011). Anthropogenic stressors, including increased watershed imperviousness, destruction of riparian vegetation, and changes in climate, can influence the thermal regime of streams, which drives the distribution and abundance of aquatic species, thereby causing changes in the biological community (MDE 2013; Nelson and Palmer 2007). Management practices that affect these factors can have the potential to secondarily impact stream temperature dynamics.

Imperviousness was among the anthropogenic factors examined in two important studies in the State of Maryland. In the Piedmont physiographic region, Stewart et al. (2005) conducted a study in the urbanized Gwynns Falls Watershed, where the effectiveness of riparian forest buffers was evaluated. In this research, the relationships between temperature exceedance, riparian buffer area, the percentage of imperviousness, and the baseflow discharge was explored. The analysis indicated that baseflow discharge is the most important predictor of temperature exceedance. In addition, Stranko et al. (2008) found that increases in temperature are associated with increasing percentages of urbanization and imperviousness. Brook trout were not found in catchments where impervious land cover exceeded 4 percent within a 100-meter buffer (50-meters on each stream bank). Generally, stream quality and watershed health decline when impervious cover exceeds 10 to 15 percent (MDE 2009; Brabec et al. 2002).

Management practices that are noted to positively impact stream temperature dynamics include riparian buffers and infiltration practices. Shading of the stream channels by riparian woody vegetation typically exerts a positive influence on the thermal regime of a stream and can improve the state of aquatic ecology (George et al. 2011; Broadmeadow et al. 2010). However, the validity of this assertion is conditional and dependent on site conditions, water management, and the site's potential to support woody plant communities (George et al. 2011). Riparian corridors can, in addition to blocking direct sunlight, produce microclimates that maintain cooler local stream and air temperatures. In Maryland, it has been observed that a 15-year-old stream buffer can already provide ecosystem services through shading, minimizing warming, and creating a more stable microclimate (DNR 2018). Stormwater retrofit projects that capture, infiltrate, and cool down stormwater runoff before it is delivered to streams are considered a viable treatment option for mitigating thermal impacts and preserving cold-water habitat. In addition, these practices can reduce incidents of non-coastal riverine and urban flooding, while capturing other pollutants that help the State meet its Bay TMDL goals. However, retrofitting alone may not be sufficient to maintain critical stream temperatures in sensitive waters and it should be implemented in conjunction with riparian corridors. In addition, design and site characteristics appear to play an important role in the effectiveness of these structures (MDE 2009; Jones 2008; Schueler et al. 2007).

Most stream temperature TMDLs that were reviewed for this project have been developed to assess streams on the west coast of the US and they were focused mainly on the promotion of riparian shade as a control measure to mitigate thermal impairments in forested basins. In these studies, the heat load, or the heating of a water body by solar radiation, is the preferred allocation metric, and is calculated using water quality models and surrogate measures, the most common of which is riparian shade. According to the WSDE (2011), air temperature, watershed hydrology, channel morphology, riparian vegetation, heat transfer and the mixing of water are the key environmental variables that a stream temperature model must include. Water quality models that simulate stream temperature were either deterministic or stochastic.

For example, deterministic and dynamic watershed models such as the Soil Water Assessment Tool (SWAT) and the Hydrologic Simulation Program – FORTRAN (HSPF) that are also physically based and spatially semi-distributed include stream temperature modules. Ficklin et al. (2012) developed a stream temperature component for the SWAT model that represents the combined effects of air temperature and hydrology on stream temperature. Brennan (2015) determined the new SWAT model component is an appropriate tool to simulate stream temperatures at a watershed scale due to its user-friendly interface and its finer spatial resolution. A more sophisticated and data-intense model was developed that uses GIS-derived riparian shade characteristics, sun position and stream location and orientation. The HSPF SHADE module calculates the amount of stream surface shade contributed by riparian vegetation and consequently adjusts the incoming solar radiation that is absorbed by the stream water. HSPF was used to simulate hourly stream temperatures in the Upper Grande Ronde Basin in northeast Oregon (Chen et al. 1998). Simulation results showed that to benefit the survival and reproduction of salmon, that riparian vegetation is the only critical factor that can be managed to make significant changes in stream temperature (Chen et al. 1999).

Stochastic models provide an alternative approach to deterministic models. Nelson and Palmer (2007) conducted a study in the Piedmont region of Maryland in five small highly urbanized catchments located north of Washington, DC, using a stochastic modeling approach. They found that stream temperature may be more pervasively impacted by urbanization than by climate change. However, the authors suggest that quantitative tools are needed to better assess the magnitude and direction of altered thermal regimes. Spatial Stream Network (SSN) models have been developed for the Western US and New England states to describe and predict the thermal regime of streams (Detenbeck et al. 2016; Isaak et al. 2017). SSN models require the development of databases to identify a suite of metrics that can predict stream temperature. Even though stochastic models can be easily implemented at the regional scale, they require extensive monitoring databases (usually non-existent in cold water streams) for their development and verification, and they are generally time invariant.

In Maryland, climate change is expected to negatively influence water quality parameters and water use, and to more frequently disrupt Maryland's infrastructure through extreme weather events and sea level rise (MCCC 2017). Precipitation and near-surface air temperature are projected to increase over the 21st century (Runkle et al. 2017). These changes are expected to result in more pollution from runoff and to exacerbate the risk of flooding.

In this study, the SWAT model was selected not only because it is able to represent key environmental variables that affect stream temperature, but also because it is dynamic and less data intensive. Furthermore, the SWAT model was used to simulate the combined effects of urbanization, riparian deforestation, and future climate on hydrology and stream temperature in coldwater streams. SWAT is a physically based and continuous model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in watersheds (Neitsch et al. 2011). The objectives of this research are: 1) to develop a stream temperature TMDL methodology that can be applied to temperature-impaired Use Class III – Nontidal Coldwaters in the State of Maryland and 2) to facilitate implementation by expressing the TMDL both as heat loads and restoration activities, providing modeling results and guidance to watershed managers and other stakeholders.

STUDY AREA

The study sites were selected based on impairment listing, data availability, and landuse type. Two of the watersheds, Hoyes Run and Baisman Run, are forest-dominated watersheds, whereas Gwynns Falls is a urban-dominated watershed (Table A1). The Gwynns Falls watershed is located in the Patapsco River sub-basin of the Chesapeake Bay watershed within Baltimore County and Baltimore City, Maryland. The watershed begins in the suburbs of Reisterstown and Owings Mills, crossing through Baltimore City neighborhoods, and finally flowing through Carroll Camden Industrial Area before discharging into the Middle Branch of the Patapsco River. The coldwater streams of the watershed, Red Run and Upper Gwynns Falls, lie in the northernmost portion of the Gwynns Falls watershed, in Baltimore County (Figure 1). The proposed stream temperature TMDL methodology was tested in the Use Class III – Nontidal Coldwater streams of the Gwynns Falls watershed that were first listed for temperature impairment on Maryland's 2014 Integrated Report of Surface Water Quality (MDE 2015).

Table A1. Watershed Characteristics

Watershed	Hoyes Run	Baisman Run	Gywnns Falls	Upper Gwynns Falls	Red Run
Area (mi^2)	4.4	1.5	32.6	9.1	7.4
Latitude (°)	39.543	39.481	39.406	39.448	39.416
Longitude (°)	-79.385	-76.696	-76.784	-76.795	-76.814
Forest (%)	79	81	44	43	51
Agriculture/ Mix open (%)	11	8	13	11	17
Developed (%)	9	11	42	46	30

METHODOLOGY

The Maryland Department of the Environment (MDE) assigns a Use Class to each of the State's waterbodies following the Code of Maryland Regulations (COMAR), which defines designated uses that should be supported including the protection and propagation of fish, shellfish, and wildlife, and for recreation in and on the water. Use Class III – Nontidal Coldwater streams are suitable for the growth and propagation of trout and other cold-water obligate species, and capable of supporting self-sustaining trout populations and their associated food organisms (COMAR 2018). Maryland has adopted numeric temperature criteria (68°F/20°C) associated with Use Class III. The assessment methodology uses observations taken between June and August, to determine whether water quality standards are being met in Use Class III streams. The 90th percentile temperature of a Use Class III stream must be equal to or less than 68°F/20°C, outside of any mixing zone established by the Department, to be considered not impaired (MDE 2019). The stream temperature TMDL methodology involves simulating the conditions and management framework in which an appropriate temperature regime could be restored in the Use Class III – Nontidal Coldwater streams of the Gwynns Falls watershed. In addition, the TMDL is expressed in heat loads and it is estimated using surrogate measures, such as riparian canopy percent and stormwater retrofit area.

Model Description

The ArcSWAT ArcGIS graphical interface developed by Winchell et al. (2013) was used in setting up the model and calculating the system parameters that describe the physical state of the system modeled such as watershed size, slope, channel characteristics, texture of the soils, etc. The model setup consists of delineating the watershed, dividing it into subbasins and hydrologic response units, handling weather inputs, and specifying the simulation period. This interface also allows the user to conduct landuse change analyses by updating hydrologic response unit (HRU) fractions and to simulate future climate conditions by changing monthly precipitation and air temperature, and updating carbon dioxide (CO2) concentrations. Sub-basin delineation for the Gwynns Falls SWAT model was performed utilizing Baltimore County's 1:2400 scale hydrography network information and a 30-meter digital elevation model (DEM). The smallest stream drainage area threshold in the ArcSWAT interface was chosen in order to capture headwater and low order streams, resulting in a sub-basin delineation containing 105 sub-basins. Three landscape characteristics are used in delineating the HRUs: 2013 Chesapeake Conservancy high-resolution (1-meter) land-cover dataset, STATSGO soil data, and slopes derived from the DEM. Wastewater and drinking water is handled via inter-basin transfer, meaning that there are no major wastewater discharges to the watershed, nor are there any water supply withdrawals. Sewage is sent out of the watershed, and drinking water is brought into the watershed.

Maryland's climate is characterized by moderately cold and occasionally snowy winters and warm, humid summers. Average annual precipitation varies from around 50 inches in the extreme west to around 40 inches just east of the Appalachian Mountains (Runkle et al. 2017). Evapotranspiration is an important quantity that often represents the largest sink for precipitation arriving to the land surface. In the State of Maryland, evapotranspiration represents approximately 40 to 70% of the total annual precipitation (Hanson 1991; Hayhoe et al. 2006; Sandford and Selnick 2013). Daily weather input files were created using the North American Land Data Assimilation System (NLDAS) data product. The dataset, which includes state variables such as rainfall, air temperature, relative humidity, solar radiation, and wind speed, is available for the last four decades.

The SWAT stream temperature model, developed by Ficklin et al. (2012), calculates stream temperature in three steps: (1) temperature and amount of local hydrological contributions (snowmelt, stormflow, and groundwater) within the subbasin; (2) temperature and inflow volume from upstream subbasin(s); and (3) heat transfer at the air-water interface during the streamflow travel time in the subbasin.

$$T_{local} = \frac{T_{snow} \times snowmelt + T_{gw} \times baseflow + \gamma \times T_{air,lag} \times stormflow}{water\ yield} \tag{1}$$

$$T_{initial} = \frac{T_{upstream}(Q_{outlet} - water\ yield) + T_{local} \times water\ yield}{Q_{outlet}} \tag{2}$$

$$T_{water} = T_{initial} + (T_{air} - T_{initial})K(TT) \tag{3}$$

Here, T_{snow} is the temperature of snow (0.1°C), T_{gw} is the temperature of groundwater (°C), $T_{air,lag}$ is the average daily air temperature with a lag (°C), *snowmelt* is the snowmelt contribution in subbasin (m^3/d), *baseflow* is the groundwater contribution in subbasin (m^3/d), *stormflow* is the stormwater contribution in subbasin (m^3/d), *water yield* is the water yield contribution (all hydrologic components) in subbasin (m^3/d), γ is the calibration coefficient relating the relationship between $T_{air,lag}$ and stormflow, $T_{upstream}$ is the water temperature of stream entering subbasin (°C), Q_{outlet} is the streamflow discharge at the outlet of subbasin (m^3/d), *TT* is the travel time (hr) and *K* is the coefficient of heat transfer (1/hr). Because of the stream temperature simulation dependency on hydrological contributions, a well calibrated model for hydrology is needed to accurately represent stream water temperature.

Conceptually, the heat transfer coefficient (*K)* is the only element that allows representing the effects of riparian shade on stream temperature. If stream temperature is approximately the same as air temperature, then *K* is 1. If there is a short travel time and extensive tree shading, then *K* is less than 1 (Eq. 3). Although the SWAT model representation of best management practices reduces pollutant loads, it does not influence hydrologic calculations and balances, and it does not represent physical processes associated with these practices (Arnold et al. 2011; Bosch et al. 2010; Ullrich and Volk 2009). Because currently SWAT does not have a mechanism that explicitly represents retrofit practices and its hydrologic benefits, the Maryland stormwater design manual was used to guide the simulation of retrofit practices (MDE 2009). The primary goal of Maryland's Stormwater Management Program is to achieve predevelopment runoff conditions. In this study stormwater retrofit practices are simulated following Environmental Site Design (ESD) sizing criteria guidelines and by using curve numbers that mimic good forested conditions. According to Baltimore County, infiltration practices installed in Red Run and Upper Gwynns Falls treat 6.9 percent and 1.5 percent of the urban land, respectively. This information is included in the calibration.

Model Calibration and Evaluation

The first step in the calibration of a model is the identification of the parameters to which the model is the most sensitive. Recommendations regarding model sensitivity and calibration techniques developed for the SWAT model by Feyereisen et al. (2007), Schmalz and Fohrer (2009), Arnold et al. (2011), Arnold et al. (2012), and Abbaspour (2015) were considered in this study. SWAT allows for either deterministic or/and stochastic calibration approaches. For this study, both approaches were used to obtain the best possible calibration for the study watersheds. SWAT calibration parameters-values were manually changed until the desired water balance was achieved (deterministic approach). After manual calibration, the SWAT calibration and uncertainty prediction software (SWAT-CUP) was used to optimize the final calibration parameters (automated or stochastic approach). SWAT-CUP is a calibration/uncertainty and sensitivity program that utilizes an optimization algorithm to perform several iterations or model runs where parameter ranges get smaller, zooming in on a region where better calibration results are produced. The SUFI-2 algorithm in the SWAT-CUP software package maps uncertainties on the model parameters and attempts to capture most of the measured data within the model's 95% prediction uncertainty (95PPU). It is important to indicate that SWAT-CUP does not provide a single calibration, but rather an envelope of good solutions (95PPU), generated by a certain parameter range.

The model's accuracy was evaluated following guidelines developed by Moriasi et al. (2007) and it is estimated by calculating quantitative indicators of model skill, such as percent bias (PBIAS) and Nash-Sutcliffe efficiency (NSE). NSE is a normalized statistic that indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE optimal value is 1 and values between 0 and 1 are viewed as acceptable levels of performance. PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0 (Moriasi et al. 2007). SWAT-CUP also provides additional accuracy measurements such as a *P-factor* and an *R-factor* as the means to quantify the strength of a calibration/uncertainty analysis. The *P-factor* is the fraction of measured data bracketed by the 95PPU. The quantity (1-*P-factor*) could be referred to as the model error. The *R-factor*, which ranges from zero to infinity, is the average thickness of the 95PPU band divided by the standard deviation of the measured data.

RESULTS

RESULTS

Hydrologic models were calibrated using both an automated calibration approach and a manual calibration procedure to simulate hydrologic budget components from 1983 to 2017. Observed streamflow information used in this study was obtained from the US Geological Survey (USGS). Figure 3 shows the location of the streamflow monitoring stations. In forest-dominated watersheds, the baseflow portion of a stream discharge usually represents a higher percentage of the total annual discharge (Table A2). The observed baseflow fraction in streamflow is calculated using the SWAT baseflow filter program, Bflow. This program adopts algorithms developed by Arnold and Allen (1999) and uses observed continuous daily streamflow data. Simulated water budget components are listed in Table A2.

Table A2. Water Budgets

Hydrologic component (inches)	Hoyes Run	Baisman Run	Gwynns Falls	Upper Gwynns Falls	Red Run
Rain *	49.8	46.2	44.8	44.8	44.8
Evapotranspiration	22.1	29.9	26.2	26.4	27.4
Stormflow	7.3	2.9	9.8	9.2	8.2
Baseflow	20.4	12.4	8.7	8.6	8.9
Evapotranspiration (%) **	44	65	59	59	61
Baseflow (%) ***	74	81	47	47	51

***Observed. **Percent of rainfall. ***Percent of streamflow.**

The curve number (CN2) and evaporation compensation parameter (ESCO) were used to calibrate runoff and evapotranspiration, respectively. The saturated hydraulic conductivity (SOL_K) parameter was adjusted to improve lateral flow and stormflow simulation. Baseflow was adjusted by changing the baseflow alpha factor (ALPHA_BF), groundwater delay time (GW_DELAY), and groundwater threshold (GWQMN). The shape of the recession limb of the hydrograph peak was strongly influenced by the adjustment of the ALPHA_BF and GW_DELAY parameters. GWQMN parameter allows simulating continuous low flow during dry seasons, resulting in an overall better representation of baseflow, in terms of both trends and magnitude. The parameter values resulting from the hydrology calibration and sensitivity analysis are listed in Table A3.

Table A3. Hydrology Model Parameters

Model Component	Model Parameter	Description	Units	Max Value	Min Value	Hoyes Run	Baisman Run	Gwynns Falls
Surface response*	ESCO	Soil evaporation compensation factor	-	0	1	0%	-15%	3%
	CN2	SCS runoff curve number	-			0%	-20%	-15%
	SOL_K	Saturated hydraulic conductivity	mm/hr			-40%	-32%	-
	SOL_AWC	Soil layer available water capacity	Mm H_2O/mm soil			-	38%	-2%
Subsurface response	GW DELAY	Groundwater delay	days	1	300	1	128	182
	ALPHA BF	Baseflow alpha factor	1/days	0	1	0.06	0.275	0.865
	GWQMN	Depth of water for return flow to occur	mm	0	5000	500	925	367.5
Water routing	CH_N2	Manning's "n" value for the main channel	-	0.01	0.3	-	0.136	0.243
	ALPHA_BNK	Baseflow alpha factor for bank storage	days	0	1	-	0.985	0.125

* The default parameter values are multiplied by value in the table. Other parameters are to be replaced by the given value.

Time series plots provide a visual comparison of observed and simulated constituent data and a first overview of model performance. Figures A1, A2 and A3 show observed and simulated streamflow, stormflow, and baseflow time series, respectively. The average magnitude of simulated streamflow was within the very good range (PBIAS < ±10%), and the ability of the model to depict streamflow trends was within the good and satisfactory range (0.5<NSE≤0.75). Overall calibration statistics indicate SWAT was able to produce a good hydrology calibration (Table A4). Figure A4 shows summer streamflow for all river segments, as represented in SWAT.

Table A4. Monthly Streamflow Calibration Statistics

Model Component		**Hoyes Run**	**Baisman Run**	**Upper Gwynns Falls**	**Gwynns Falls**	**Gwynns Falls**
	Statistics	HRB	01583580	01589197	01589290	01589300
	Years*	1980-2017	2000-2017	1999 - 2017	2006-2017	1983 - 1988, 1996 - 2017
Streamflow	Observed mean (cfs)	5.3	1.7	5.5	4.2	45.1
	Simulated mean (cfs)	5.4	1.7	5.3	4.6	43.8
	Monthly PBIAS	1.8	0.3	-2.6	8	-3
	Monthly NSE	0.7	0.62	0.7	0.76	0.71
	P-factor	-	0.82	0.7	0.72	0.77
	R-factor	-	1.55	0.75	0.58	0.72
Stormflow	Observed mean (cfs)	1.48	0.31	2.8	2.8	22.8
	Simulated mean (cfs)	1.49	0.32	2.8	2.7	23.3
	Monthly PBIAS	0.9	5.4	1.9	-5.4	2.3
	Monthly NSE	0.58	0.5	0.75	0.8	0.73
Baseflow	Observed mean (cfs)	3.83	1.4	2.7	1.4	22.4
	Simulated mean (cfs)	3.71	1.3	2.4	1.8	19.5
	Monthly PBIAS	-3.2	0.9	-11.8	28.1	-13
	Monthly NSE	0.66	0.6	0.45	0.39	0.44
	Observed baselow ratio	0.72	0.82	0.43	0.37	0.42
	Simulated baseflow ratio	0.69	0.78	0.45	0.39	0.44

* Years of continuous daily monitoring.

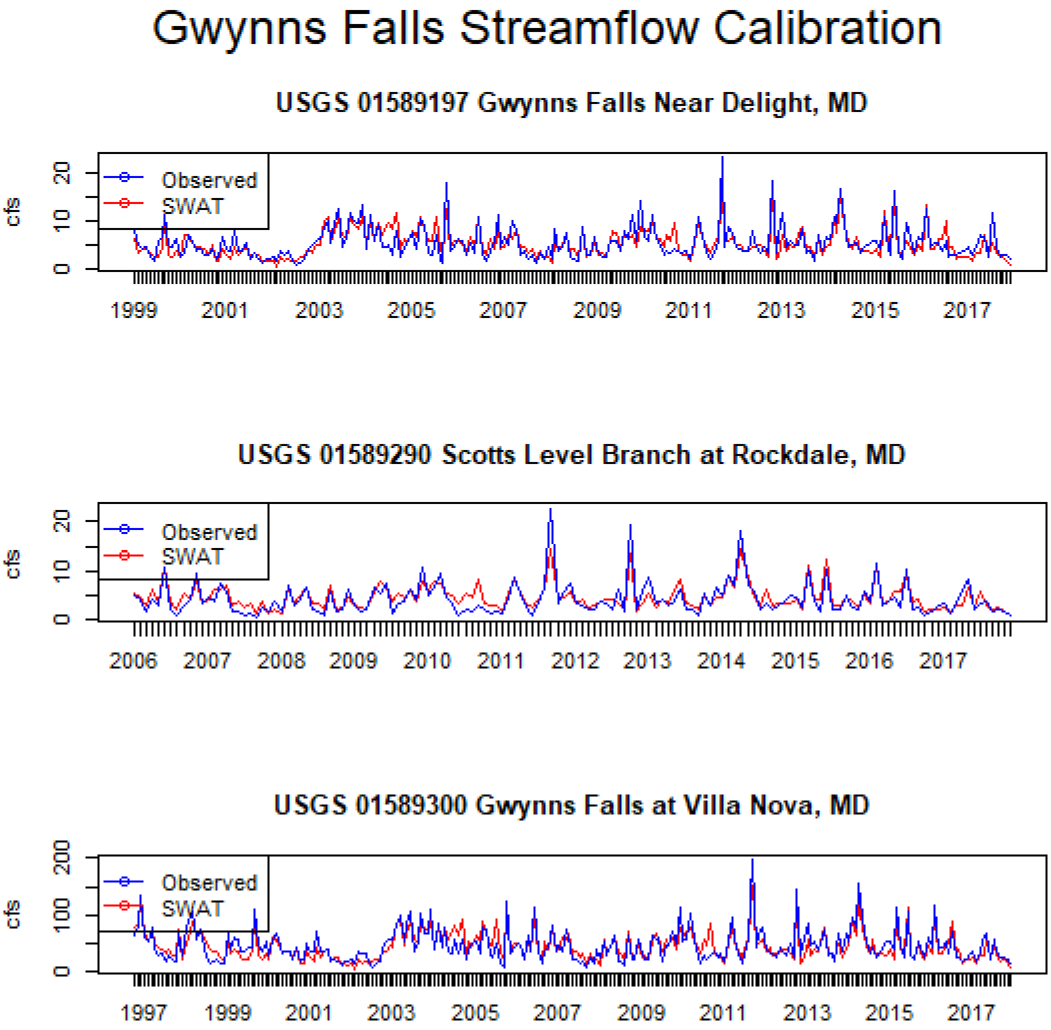

Figure A1. Observed and Predicted Monthly Streamflow for the Gwynns Falls Watershed

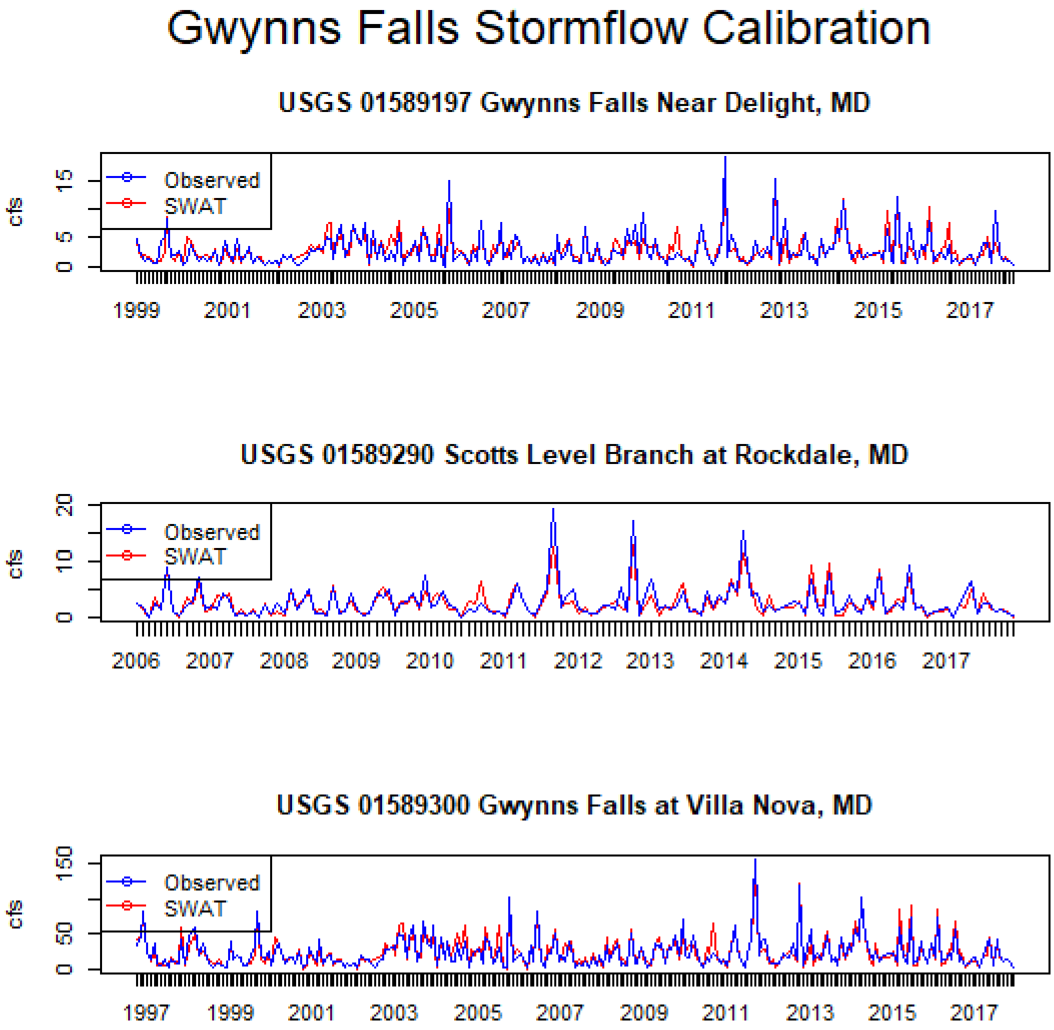

Figure A2. Observed and Predicted Monthly Stormflow for the Gwynns Falls Watershed

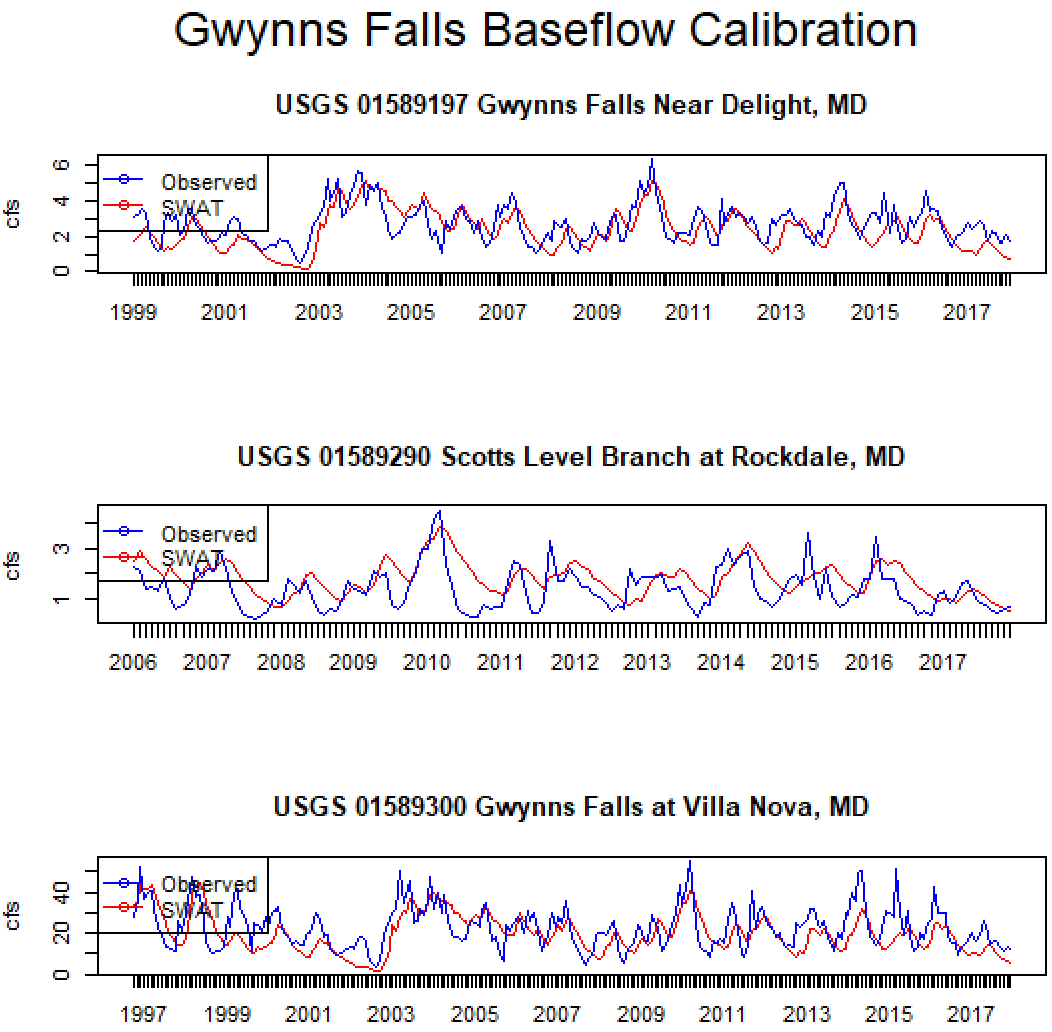

Figure A3. Observed and Predicted Monthly Baseflow for the Gwynns Falls Watershed

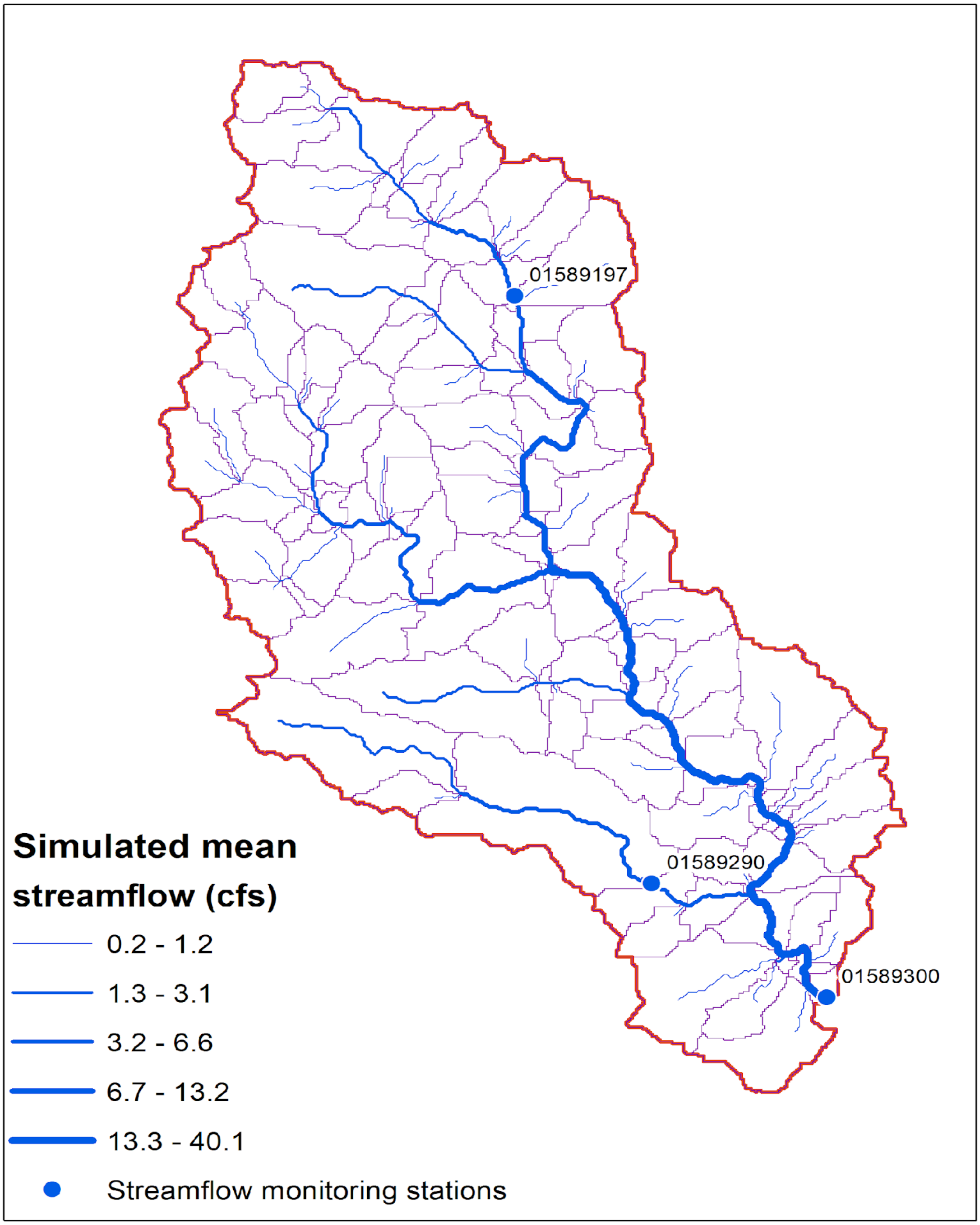

Figure A4. Map showing summer streamflow for all river segments, as represented in SWAT

MDE deployed loggers to measure stream and air temperature for the years of 2016 and 2017 in the study area. Measurements were taken every 15 minutes and the daily average was calculated to use in the calibration[1]. Additional information from previous studies provided by the Baltimore Ecosystem Study (BES), Department of Natural Resources (DNR), and Baltimore County was also included in the stream temperature observations dataset. Figure 3 shows the location of the temperature calibration stations. Generally, groundwater temperatures average about 1-2 °C higher than the mean annual air temperature (Otton et al. 1964; Ficklin et al. 2012). In Gwynns Falls watershed model groundwater temperature is 14 °C.

The coefficient of heat transfer (*K*) is the parameter to which the stream temperature model is the most sensitive (Eq. 3). The calibration coefficient relating the relationship between air temperature and stormflow (γ) and the lag in air temperature (*lag*) parameter were also included in the calibration. The model was manually calibrated by altering the coefficients by subbasin (Table A5). Overall, altering the *K* parameter was sufficient to improve the magnitude and efficiency of the model. Even though smaller *lag* values helped better represent daily fluctuations and flashiness of the watershed, improvements in model efficiencies resulted in the overestimation of the 90th percentile. The default value of 7 was used. The γ parameter was only altered when the model was too sensitive to stormflow. Riparian canopy percentage, within a stream buffer of 100-meters (50 meters on each streambank), was measured using the Chesapeake Conservancy high-resolution (1-meter) land-cover dataset, which is derived from 2013 imagery. On average 69% and 79% of the riparian area is covered by tree canopy in Upper Gwynns and Red Run, respectively. Canopy percentages above each calibration station are available in Table A6.

Table A5. Stream Temperature Model Parameters.

Watershed	Station	γ	*K*	lag
Red Run	T4	0.9	0.08	7
	T25	1	0.09	7
	T23	1	0.18	7
	T3	1	0.11	7
	T67	1	0.1	7
	T19	1	0.1	7
	T15	1	0.08	7
Upper Gwynns	T9	1	0.09	7
	T11	1	0.08	7
	T13	1	0.09	7

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[1] Daily temperature data was calculated instead of directly using the 15 minute data due to the limitations of the SWAT model. There are several models available that use hourly data, but they are more data intensive and require information for calibration that was not available. Statistical analysis of the 15 minute data and the daily datasets showed that the maximum and minimum values would be different between the two datasets, but the mean and 90th percentile in both datasets are almost the same.

Cumulative distribution and 1:1 plots provided an overview of the temperature model performance (Figures A5, A6 and A7). The average magnitude of simulated summer values was within the very good range (Percent Bias < ±10%) and the ability of the model to depict summer trends was acceptable (NSE>0). Overall calibration statistics indicate SWAT summer stream temperature output was within the good range (Table A6). The model was able not only to successfully simulate in-stream temperatures in urban-dominated watersheds but also to portray relatively undisturbed systems such as Hoyes Run and Baisman Run (Figure A7). Figure A8 shows summer stream temperature for all river segments, as represented in SWAT.

Table A6. Daily In-Stream Temperature Calibration Statistics

	Upper Gwynns			Red Run							Baisman Run	Hoyes Run
Statistics	T9	T11	T13	T4	T25	T3	T23	T67	T19	T15	01583580	HRB
Years of continuous daily monitoring	2016-2017	2005; 2007-2008; 2016-2017	2016-2017	2009-2010	2007; 2016-2017	2009-2010	2004; 2016-2017	2016-2017	2016-2017	2016-2017	2005-2007	2016-2017
Observed riparian canopy (%)	45	73	69	67	91	76	91	78	79	79	98	94
Observed summer mean	21.0	20.5	21.9	18.2	19.5	20.5	19.3	21.2	21.7	22.4	19.1	15.2
Observed summer 90th percentile	22.9	22.5	24.1	20.3	21.8	22.7	21.4	23.4	23.9	24.6	21.4	17.5
Observed exceedance	74%	62%	84%	16%	42%	60%	35%	74%	81%	87%	34%	0%
Summer mean	20.5	20.4	21.7	18.6	19.7	20.4	19.1	21.0	21.5	22.1	19.3	15.2
Simulated summer 90th percentile	23.0	22.9	24.2	21.6	21.7	22.8	21.0	23.2	23.8	24.7	21.2	17.8
Simulated exceedance	63%	61%	82%	16%	39%	49%	29%	70%	79%	85%	32%	0%
BIAS	-2.30	-0.30	-1.30	1.70	0.60	-1.10	-1.10	-1.20	-1.20	-1.40	1.10	-0.10
NSE	0.07	0.25	0.30	0.19	0.28	0.15	-0.06	0.37	0.36	0.35	0.54	0.50
K-test	0.21	0.07	0.10	0.19	0.07	0.19	0.13	0.13	0.12	0.11	0.10	0.10

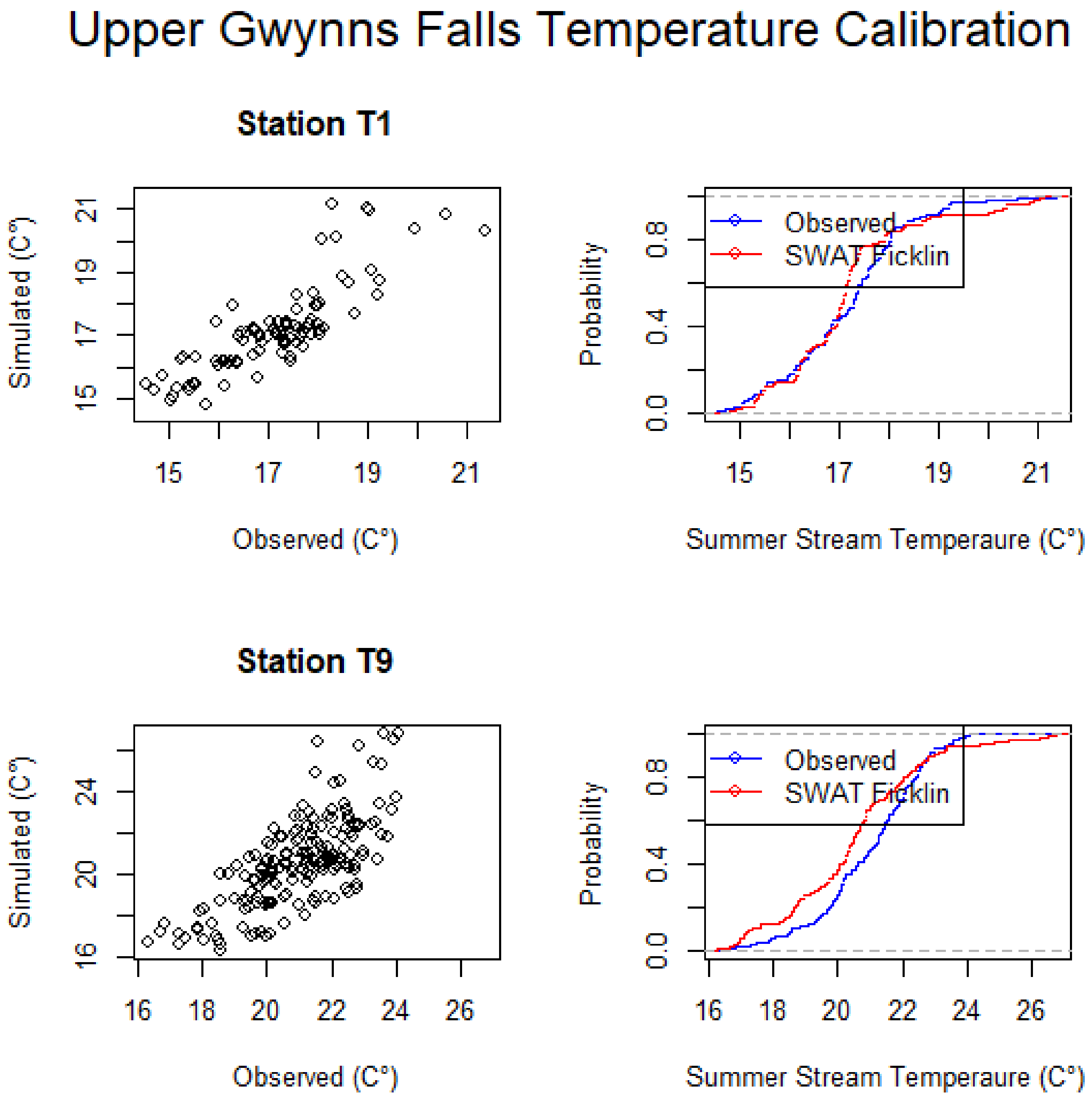

Figure A5. Observed and Simulated Daily In-Stream Summer Temperature in Upper Gwynns Falls Cold Water Streams

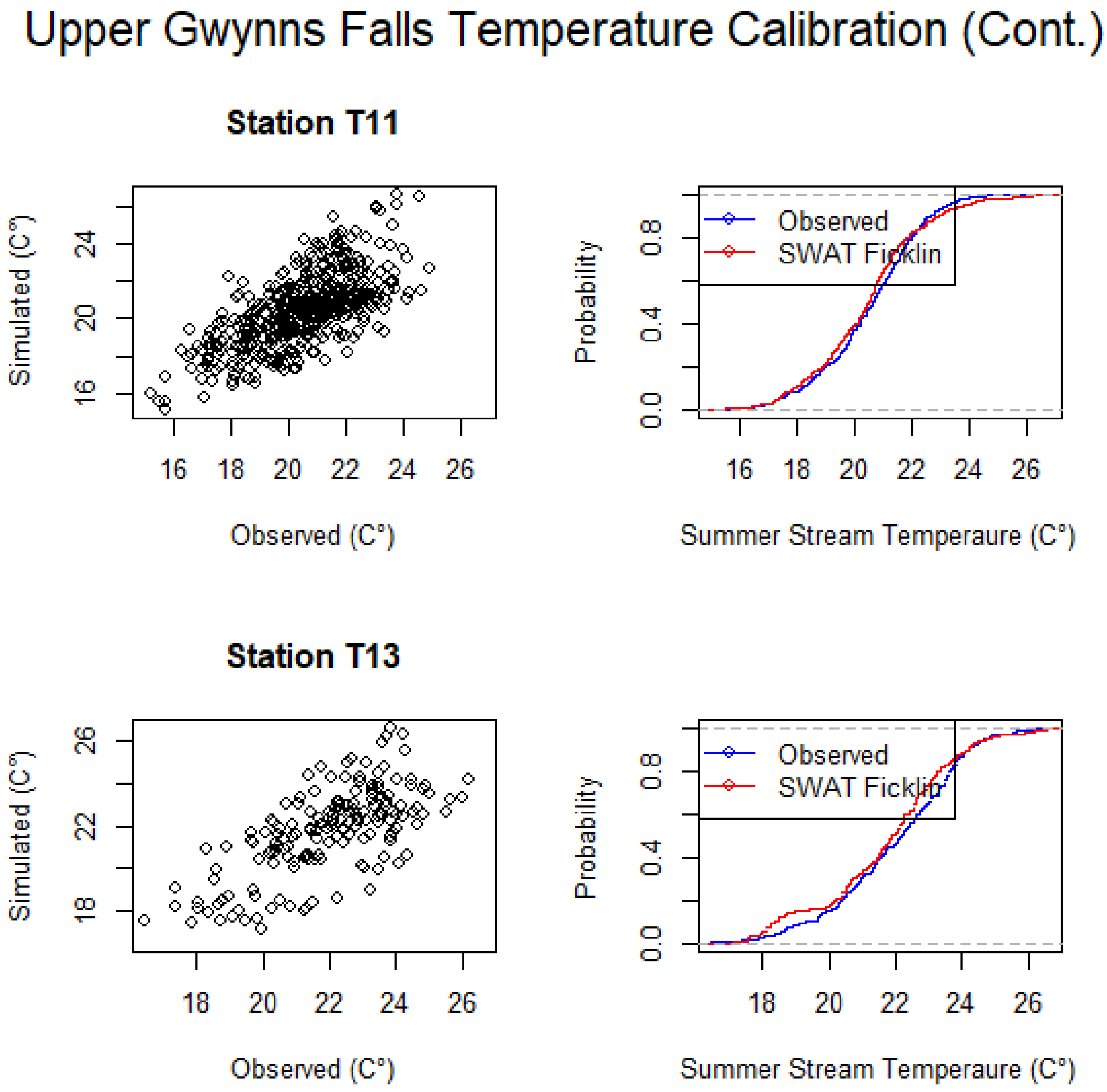

Figure A5 (cont). Observed and Simulated Daily In-Stream Summer Temperature in Upper Gwynns Falls Cold Water Streams

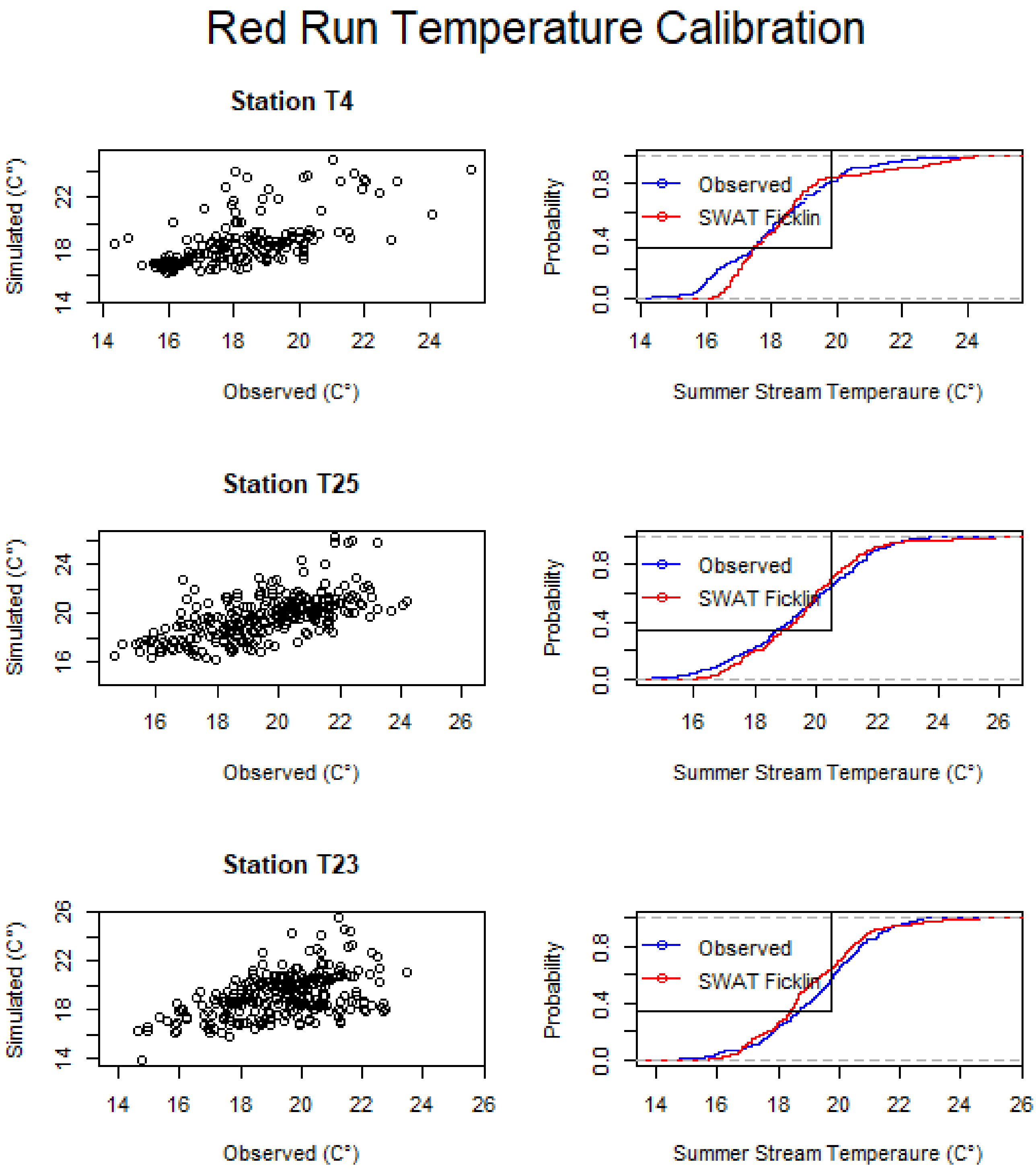

Figure A6. Observed and Simulated Daily In-Stream Summer Temperature in Red Run Cold Water Streams

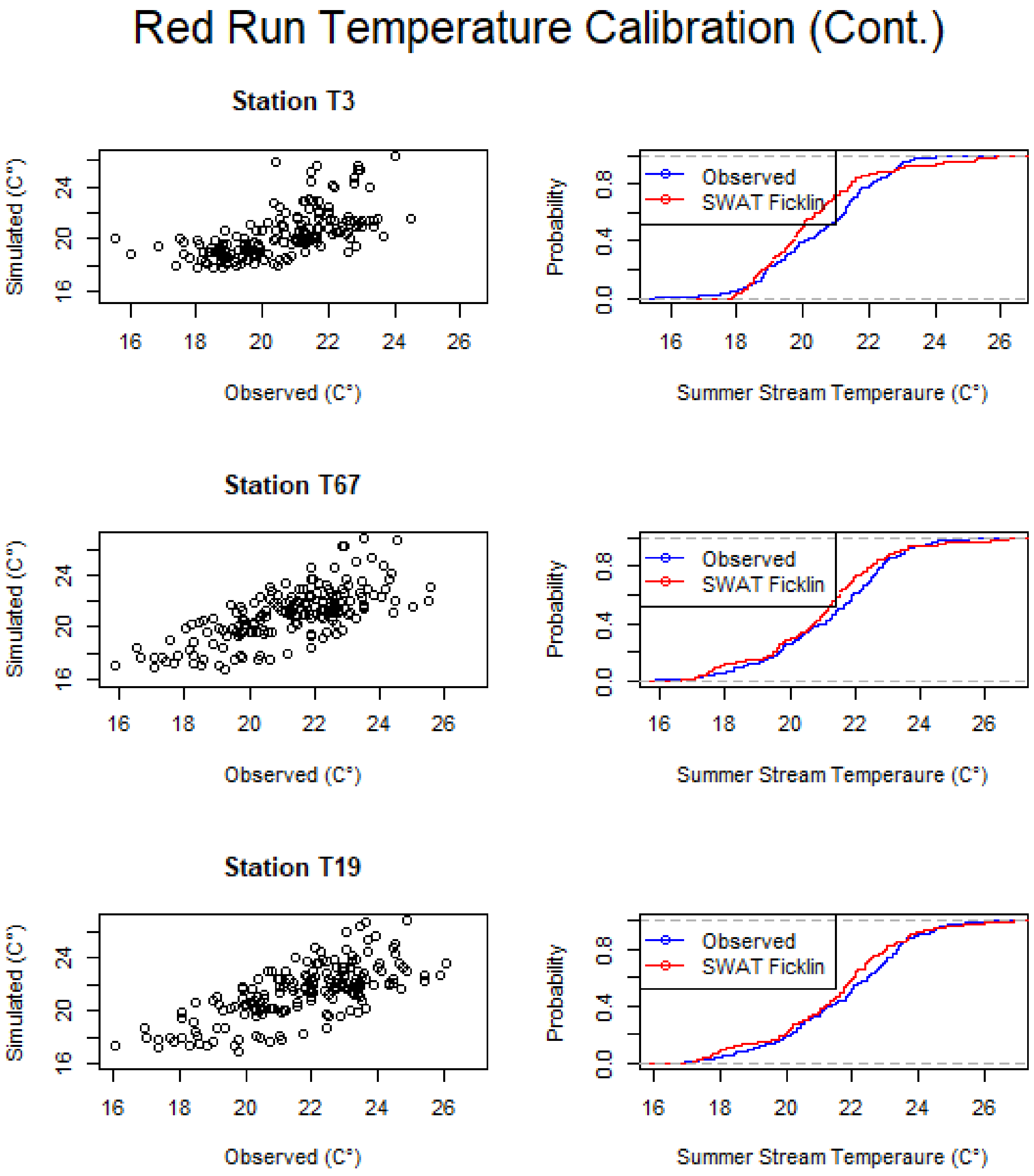

Figure A6 (cont). Observed and Simulated Daily In-Stream Summer Temperature in Red Run Cold Water Streams

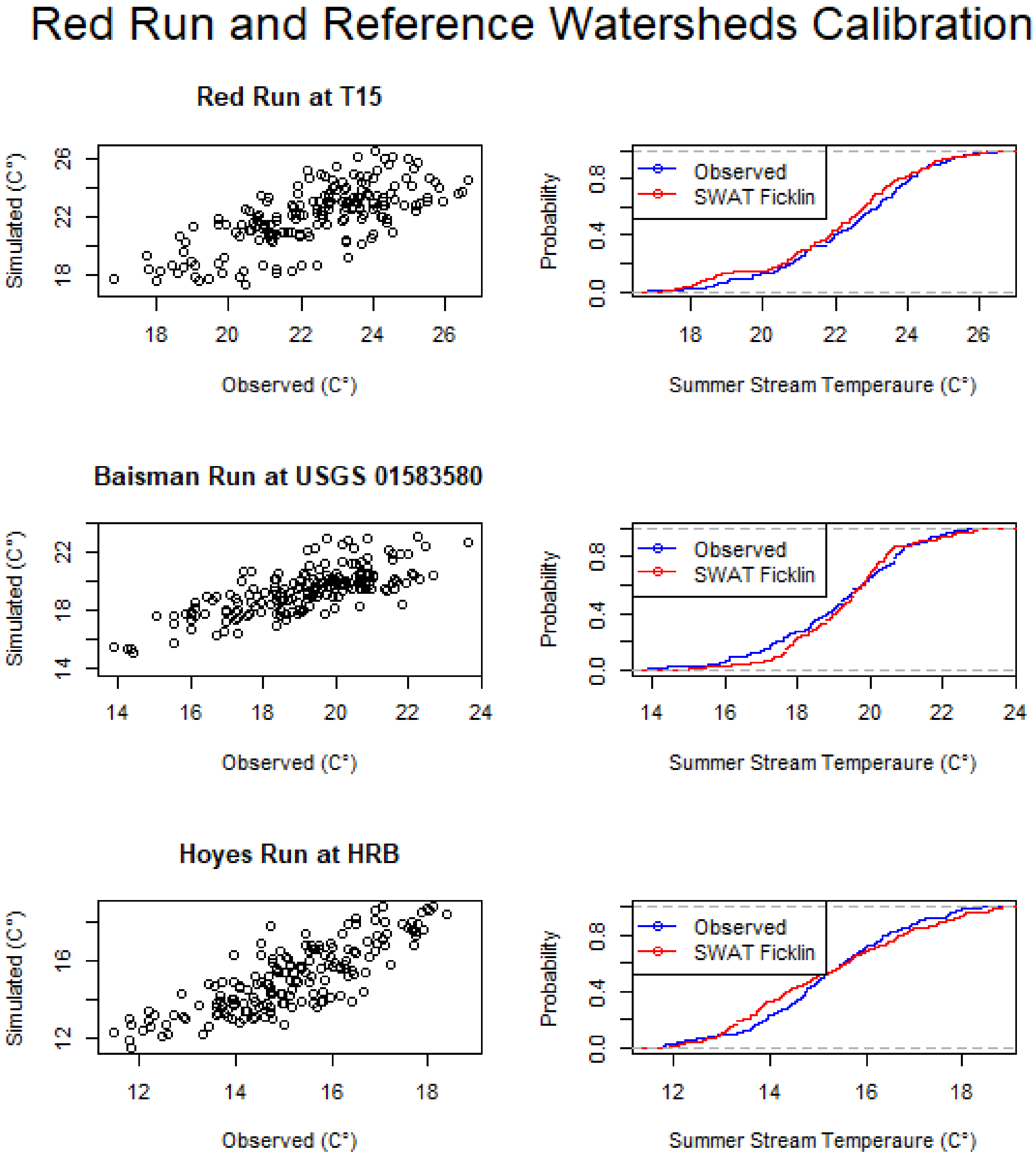

Figure A7. Observed and Simulated Daily In-Stream Summer Temperature in Red Run Outlet and Reference Watersheds

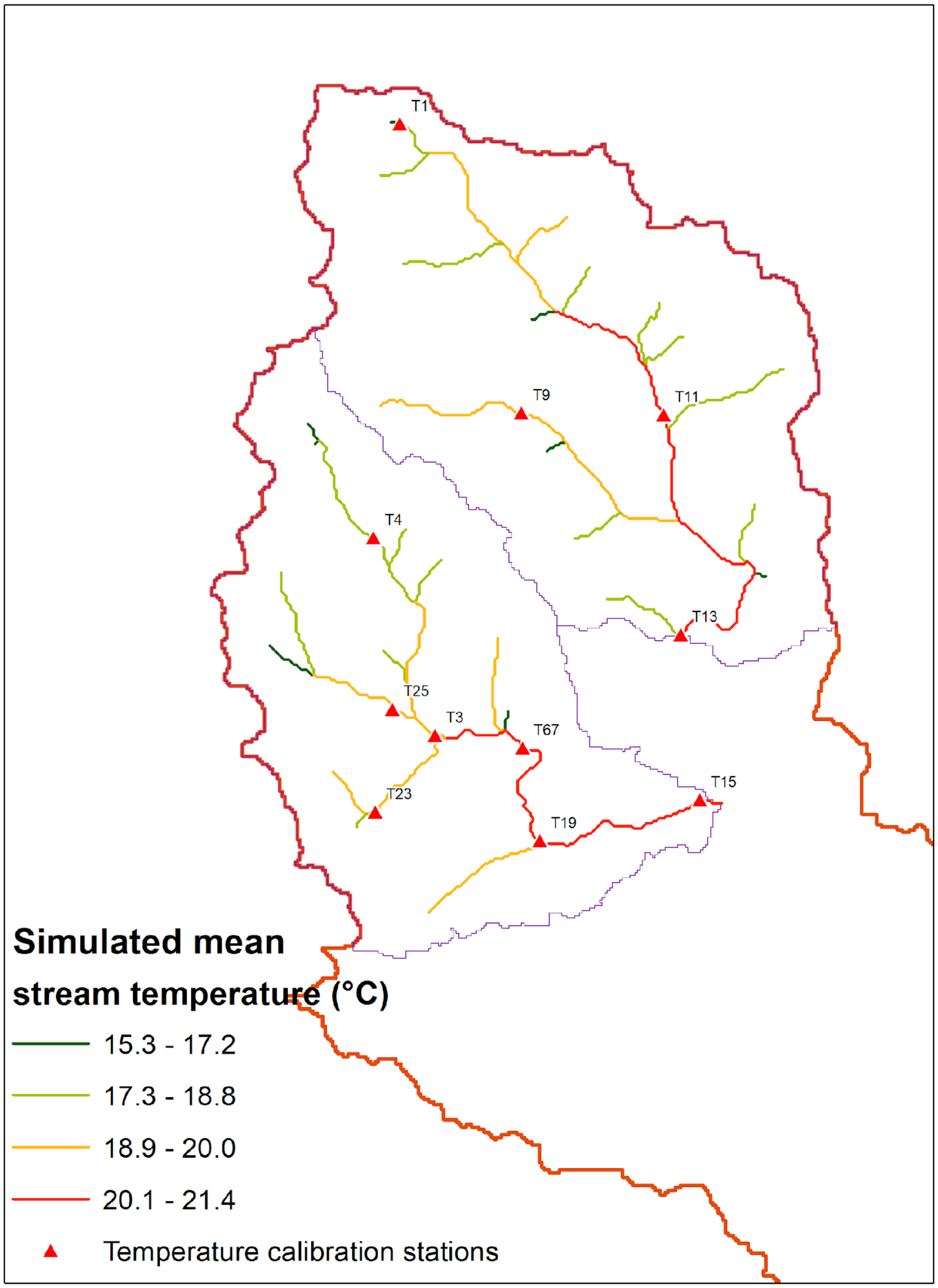

Figure A8. Map showing summer stream temperature for all river segments, as represented in SWAT

Allocation metrics and scenario results

In this study, and for the purposes of TMDL development, the model output and allocations are expressed as heat transfer rates, or heat loads, in gigajoules per day (GJ/d). The mean stream temperature and the 90th-percentile temperature were estimated by looking at the daily temperature at every model segment within the cold water region. A rate of 1 GJ/d is equal to 11, 574 Joules per second (J/s). Water has to absorb 4,182 Joules of heat for the temperature of one kg of water to increase by one degree Celsius. Heat loads are calculated using Equation 4 below:

$$Heat\ load\ (J\ s^{-1}) = wtmp\ \times flow \times \frac{4182\ J}{kg\ °C} \times \frac{998.2kg}{1m^3} \tag{4}$$

For this equation, *wtmp* is the simulated mean stream temperature ($°C$) across the assessment period and *flow* is the simulated mean streamflow (m^3/s) for that same period. The assessment period covers the summer months (June 1 to August 31) for the entire simulation period (1983 to 2017).

The heat load for each subbasin under the calibration conditions was designated as the baseline load. An initial management scenario was created by defining all land in the subbasin as forest, with a heat transfer coefficient of 0.037 in Gwynns Falls and 0.035 in Red Run to simulate full riparian shading. Called the All Forest scenario, this model run had the lowest heat load of any scenario in this study. Under this scenario, water quality standards are met at the outlet of the cold-water portion. 90th-percentile temperatures, shown in the tables below, were significantly lower than 20°C, the TMDL endpoint, for both the Red Run and Upper Gwynns Falls subbasins.

These results were consistent with those observed in the relatively undisturbed Hoyes Run and Baisman Run watersheds, where actual conditions are close to those simulated in the all forest scenarios. The Hoyes Run results, shown in Table A6 and Figure A7, showed an observed average summer temperature of 15.2°C and a 90th-percentile temperature of 17.5°C.

To establish TMDLs meeting the temperature endpoint, the baseline scenario was modified by adjusting two model inputs—the land use and the coefficient of heat transfer. The land use was modified to simulate the implementation of stormwater infiltration practices to treat runoff from existing urban land. This was done by changing the Runoff Curve Number (RCN) for a portion of all urban land. RCN values for urban land range from 63 to 97. These values were changed to an RCN of 60, which is consistent with the Hydrologic Soil Group B target RCN for pre development runoff in Chapter 5 of the Maryland Stormwater Design Manual. The fraction of the urban land treated through infiltration retrofits is referred to as percent retrofit. The coefficient of heat transfer was adjusted to represent increases in riparian shading.

For each subbasin, implementation actions were simulated in the model by creating scenarios with incrementally higher levels of stormwater infiltration practices and riparian shading. For each scenario, a 90th-percentile temperature across the assessment period was calculated and compared to the TMDL endpoint of 20°C. Management actions were gradually increased in subsequent scenarios until the TMDL endpoint was reached.

For Red Run, it was determined that the TMDL endpoint would be met when 35 percent of the urban land had been retrofitted using infiltration practices, and an additional 21 percent of riparian canopy had been established. This resulted in the heat load decreasing from 399 GJ/d to 348 GJ/d, a change of 13 percent. These results are provided in Table A7.

Table A7. Baseline, TMDL and all-forest scenario results for Red Run.

Parameter	All forest	TMDL	Baseline
Retrofit (%)	100	35	-[1]
Riparian canopy (%)	100	90	79
Simulated summer stream temperature mean (ºC)	16.2	17.2	18.9
Simulated summer 90th percentile (ºC)	17.8	20.0	22.2
Summer streamflow (cfs)	1.7	2	2.1
Heat (Gigajoules per day)	285.5	348.5	399.4

[1] The baseline retrofit inherently includes infiltration practices on urban lands of 6.9%.

For Upper Gwynns Falls, the implementation required to meet the TMDL endpoint is 55 percent retrofit and an additional 30 percent of riparian shading. The reduction in heat load between the baseline and the implementation scenarios, from 493 to 396 GJ/d, or 20 percent, is shown in Table A8.

Table A8. Baseline, TMDL, and all-forest scenario results for Upper Gwynns Falls.

Parameter	All forest	TMDL	Baseline
Retrofit (%)	100	55	-[1]
Riparian canopy (%)	100	90	69
Simulated summer stream temperature mean (ºC)	16.3	17.2	19
Simulated summer 90 percentile (Cº)	18.1	20.0	22.3
Summer streamflow (cfs)	2.0	2.25	2.5
Heat (Gigajoules per day)	328.9	396	493

[1] The baseline retrofit inherently includes infiltration practices on urban lands of 1.5%.

CONCLUSIONS

The SWAT model and the temperature algorithm developed by Ficklin et al. (2012) were found suitable for simulating stream temperature in Maryland coldwater streams. Hydrology and stream temperature simulations were satisfactory and the model was able not only to successfully simulate in-stream temperatures in the urban-dominated Gwynns Falls Watershed at multiple sites but also to portray relatively undisturbed ecosystems such as Hoyes Run and Baisman Run. The proposed methodology was found to be appropriate to calculate stream temperature TMDL allocation metrics. The stream temperature subbasin-level calibration at multiple sites showed to better match the observed data than the basin-wide calibration especially in the headwaters. However, it is recommended an automatic, subassin-level calibration approach be implemented to further improve the accuracy of the model and to extend its applicability. It has been observed that maximum recorded stream temperatures occurred during drought periods and even though the calibrated model portrays a similar behavior, it is recommended that future monitoring programs attempt to cover drought conditions to further improve model accuracy.

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