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Simulating Thermal Stress in Rhode Island Coldwater Fish Habitat Using SWAT

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SIMULATING THERMAL STRESS IN RHODE ISLAND COLDWATER FISH HABITAT USING SWAT

BY

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OF

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ABSTRACT

Climate studies have suggested that inland stream temperatures and streamflow will increase over the next century in New England, thereby putting aquatic species sustained by coldwater habitats at risk. To effectively aid these ecosystems it has become ever more important to recognize historical water quality trends and anticipate the future impacts of climate change. This thesis uses the Soil and Water Assessment Tool (SWAT) to simulate historical and future streamflow and stream temperatures within three forested, baseflow driven watersheds in Rhode Island. The results provide a site-specific method to fisheries managers trying to protect or restore local coldwater habitats.

The first manuscript evaluated two different approaches for modeling historical streamflow and stream temperature with the Soil and Water Assessment Tool (SWAT), using i) original SWAT and ii) SWAT plus a hydroclimatological model component that considers both hydrological inputs and air temperature effects on stream temperature (Ficklin et al., 2012). Model output was used to assess stressful events at the study site, Cork Brook, RI, between 1980-2009. Stressful events for this study are defined as any day where high or low flows occur simultaneously with stream temperatures exceeding 21˚C, the threshold at which brook trout (*Salvelinus fontinalis*), a coldwater fish species, begins to exhibit physiological stress. SWAT with the hydroclimatological component performed better during calibration (Nash-Sutcliffe Efficiency (NSE) of 0.93, R^2 of 0.95) compared to original SWAT (NSE of 0.83, R^2 of 0.93). Between 1980-2009, the number of stressful events increased by 55% and average streamflow increased by 60% at the study site. This chapter supports the

application of the hydroclimatological SWAT component and provides an example method for assessing stream conditions in southern New England.

The second manuscript uses the original SWAT model to simulate both historical and future climate change scenarios for Cork Brook and two other watersheds, the Queen River and Beaver River, in Rhode Island. These three sites were selected primarily due to their pristine aquatic habitat, data availability and existing interest in natural resource conservation by local non-profit and government groups. Similar to the first manuscript, this study analyzed model output to identify stressful events for brook trout. Results indicate that the Queen River has historically had the highest percent chance (6.4 %) that a stressful event would occur on any given day and Cork Brook had the lowest percent chance (4.4%). In future climate scenarios coldwater fish species such as brook trout will be increasingly exposed to stressful events. The model predicted that between 2010-2099 stream temperatures in all watersheds will increase by 1.6 ˚C under the low emission scenario or 3.4 ˚C under the high emission scenarios. The model also predicted that high stream temperatures in the Cork Brook watershed will occur two months earlier in the year by the end of the century. Between 2010 and 2099, discharges increased by an average of 20% under the low emissions scenario and 60% under the high emissions scenario. The percent chance of a stressful event increased between historical simulations and future simulations by an average of 6.5% under low emission scenarios and by 14.2% under high emission scenarios. These results indicate that climate change will have a negative effect on coldwater fish species in these types of ecosystems, and that the resiliency of local populations will be tested as stream conditions will likely become increasingly stressful.

The purpose of this Master’s thesis was to gain a better understanding of stream conditions within Rhode Island’s coldwater fish habitat using SWAT. It was successfully shown that SWAT can be used to simulate both historical and future climate scenarios in forested, baseflow driven watersheds in Rhode Island. Moreover, a functional approach to analyzing model output is to identify thermally stressful events for coldwater species. As the demand for water quality and quantity increases for wildlife and human consumption over the next century, new evaluation techniques will help anticipate unprecedented challenges due to climate change.

ACKNOWLEDGMENTS

I would first like to thank my major advisor, Dr. Soni Pradhanang, for her guidance and support throughout the duration of this study and my committee members, Dr. Arthur Gold, Dr. Jameson Chace, and Dr. Thomas Boving for volunteering to be part of this process and offering insight to my research. All have contributed significantly to my graduate level education and made my time at the University of Rhode Island and Salve Regina University a successful and enjoyable experience. I would also like to thank my friends in the Geosciences Department and the MESM program for helping me get through the everyday challenges related to life as a graduate student.

The greatest appreciation goes to my parents Gretchen and Dave Anderson, my brother Connor Anderson, my husband Drew Chambers, and my companions Maggie, Buster and Toby. My loving family has taught me the power of hard work, dedication, the remedy in a smile and how to keep life in perspective when the road gets rough.

PREFACE

This thesis was prepared in manuscript format as specified by the University of Rhode Island Graduate School guidelines. There are two manuscripts that have each been formatted for future publication in the Multidisciplinary Digital Publishing Institute (MDPI) open-access journal *Water*, which includes research areas such as water resources management, water quality and water ecosystems. Manuscript 1 is titled "Assessing Thermally Stressful Events in Rhode Island Coldwater Fish Habitat Using SWAT Model". Manuscript 2 is titled "Climate Change Induced Thermal Stress in Coldwater Fish Habitat Using SWAT". The manuscripts were submitted to MDPI and are under review.

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ASSSESSING THERMALLY STRESSFUL EVENTS IN RI COLDWATER FISH HABITAT USING SWAT MODEL

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ABSTRACT

It has become increasingly important to recognize historical water quality trends so that the future impacts of climate change may be better understood. Climate studies have suggested that inland stream temperatures and average streamflow will increase over the next century in New England, thereby putting aquatic species sustained by coldwater habitats at risk. In this study we evaluated two different approaches for modeling historical streamflow and stream temperature in a Rhode Island, USA watershed with the Soil and Water Assessment Tool (SWAT), using i) original SWAT and ii) SWAT plus a hydroclimatological model component that considers both hydrological inputs and air temperature. Based on calibration results with four years of measured daily flow and four years of stream temperature data we examined occurrences of stressful conditions for brook trout (*Salvelinus fontinalis)* using the hydroclimatological model. SWAT with the hydroclimatological component performed better during calibration (NSE of 0.93, R^2 of 0.95) compared to original SWAT (NSE of 0.83, R^2 of 0.93). Between 1980-2009 the number of stressful events, any day where high or low flows occur simultaneously with stream temperatures >21˚C, increased by 55% and average streamflow increased by 60%. This study supports using the hydroclimatological SWAT component and provides an example method for assessing stressful conditions in southern New England's coldwater habitats.

INTRODUCTION

Stream temperatures in the New England region of the United States have been increasing steadily over the past 100 years [1]. Over the next century, freshwater ecosystems in New England are expected to experience continued increase in mean daily stream temperatures and an increase in the frequency and magnitude of extreme flow events due to warmer, wetter winters, earlier spring snowmelt, and drier summers [1-9]. As the spatial and temporal variability of stream temperatures play a primary role in distributions, interactions, behavior, and persistence of coldwater fish species such as trout [7, 10-16], it has become increasingly important to understand historical patterns of change so that a comparison can be made when projecting the future effects of climate changes on local ecosystems.

This study used the Soil and Water Assessment Tool (SWAT) [17] to generate historical streamflow and stream temperature data, followed by an assessment of the frequency of "stressful events" affecting the Rhode Island native brook trout (*Salvelinus fontinalis*). Brook trout, a coldwater salmonid, is a species indicative of high water quality and is also of interest due to recent habitat and population restoration efforts by local environmental groups and government agencies [18,19]. This fish typically spawns in the fall, and lays eggs in redds (nests) deposited in gravel substrate. The eggs develop over the winter months and hatch from late winter and early spring. However, the life-cycle of brook trout is heavily influenced by the degree and timing of temperature changes [11,20]. High stream temperatures cause physical stress including slowed metabolism and decreased growth rate, adverse effects on critical life-cycle stages such as spawning or migration triggers, and in extreme cases, mortality [7,21-24]. Distribution is also affected as coldwater fish actively avoid water temperatures that exceed their preferred temperature by 2-5 ˚C [25,26]. Studies have shown that optimal brook trout water temperatures remain below 20 ˚C. Symptoms of physiological stress develop at approximately 21 ˚C [21] and temperatures above 24 ˚C have been known to cause mortality in this species [11].

Flow regime is another central factor in maintaining the continuity of aquatic habitat throughout a stream network [22,27-32]. While temperature is often cited as the limiting factor for brook trout, the flow regime has considerable importance [33]. Alteration of the flow regime can result in changes in the geomorphology of the stream, the distribution of food producing areas as riffles and pools shift, reduced macroinvertebrate abundance and more limited access to spawning sites or thermal refugia [20,34,35]. Reductions in flow have a negative effect on the physical condition of both adult brook trout and young-of-year. Nuhfer, Zorn et al. (2017) studied summer water diversions in a groundwater fed stream and found a significant decline in spring-to-fall growth of adult and young-of-year brook trout when 75% flow reductions occurred. The consequences of lower body mass are not always immediately apparent. Adults may suffer higher mortality during the winter months following the further depletion of body mass due to the rigors of spawning. Poor fitness of spawning adults may result in lower quality or reduced abundance of eggs. [20]. Velocity of water in the stream reach may affect sediment and scouring of the stream bed and banks, reducing the availability of nest sites.

To address the importance of both stream temperature and flow regime, stressful events are defined herein as days where either high or low flow occurs simultaneously with stream temperatures above 21 ˚C. High and low flows will be considered as those values in the 25-percent and 75-percent flow exceedance percentiles (Q25, Q75) of the 30-year historical flow on record at the study site, Cork Brook in north-central Rhode Island (Figure 1).

Analytical tools can be employed to generate models showing the effects of atmospheric temperatures on stream temperatures [8,36-41]. This study uses SWAT to simulate historical streamflow and stream temperature data. Then, a hydroclimatological stream temperature SWAT component created by Ficklin et al., 2012 [36] is incorporated to demonstrate its applicability in New England watersheds. This component reflects the combined influence of meteorological conditions and hydrological inputs, such as groundwater and snowmelt, on water temperature within a stream reach. Previous studies have shown that the hydroclimatological component can be used in small watersheds [36] and in New England [42]. Lastly, the generated stream temperature and streamflow data are analyzed to understand the frequency of stressful conditions for coldwater habitat in Cork Brook.

Results provide a site-specific approach to identifying critical areas in watersheds for best management practices with the goal of maintaining or improving water quality for both human consumption and aquatic habitat. In this study, the hydroclimatological component more accurately predicted stream temperatures at the study site. Between 1980 and 2009, the percent chance of stressful conditions occurring on a given day due to low streamflow levels and higher stream temperatures have increased at Cork Brook. 98% of all stressful events simulated between 1980 and 2009 occurred during the low flow period rather than the high flow period. Knowing how water resources have historically responded to climate change and providing managers the most efficient analytical tools available will help identify habitats that have historically been less susceptible to unfavorable conditions. If climate trends continue as expected, decisions to protect a habitat based on its known resilience may have a large impact on how resources and preservation efforts will be allocated.

MATERIALS AND METHODS

The selected study site was Cork Brook in Scituate, Rhode Island. This small forested watershed is a tributary to the Scituate Reservoir, which is part of the larger Pawtuxet River basin beginning in north-central Rhode Island and eventually flowing into Narragansett Bay. The Scituate Reservoir is the largest open body of water in the State and is the main drinking water source to the City of Providence. Human disturbance within the Cork Brook watershed is minimal and most of the land cover is undeveloped forest and brushland, however a portion (14%) of the land use is classified as medium density residential. USGS station number 01115280 is located approximately four km downstream from the headwaters and been continuously recording streamflow at the site since 2008 and stream temperature since 2001[43]. The mean daily discharges at the gauge are historically lowest in September (0.025m^3/sec), highest in March (0.27 m^3/sec) and annually average approximately 0.11 m^3/sec. Average daily stream temperature is estimated at 7.8 ˚C since 2001.

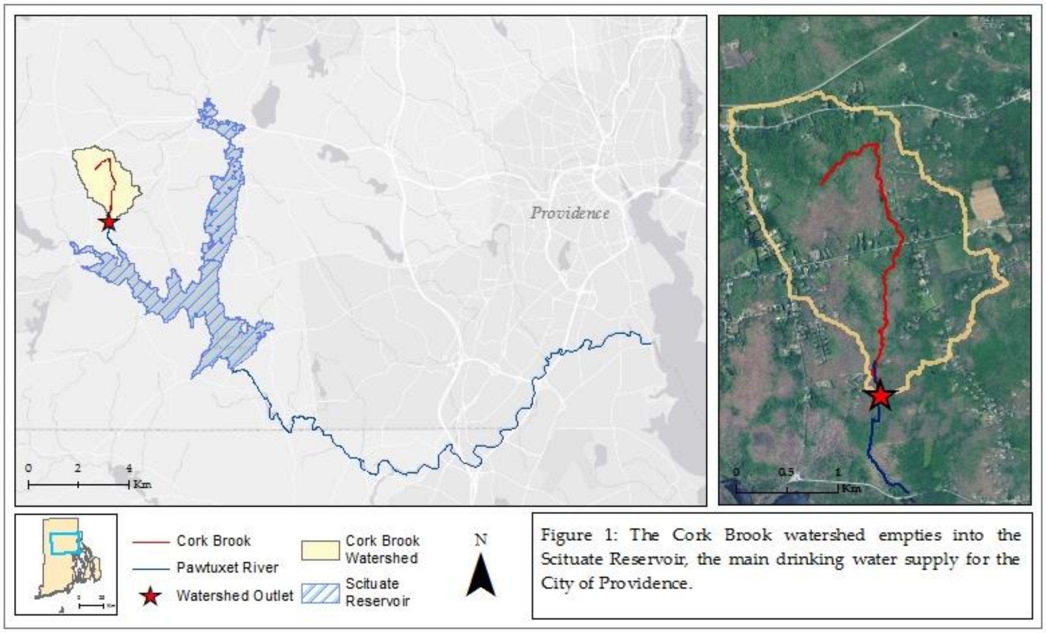


Figure 1: The Cork Brook watershed empties into the Scituate Reservoir, the main drinking water supply for the City of Providence.

This study uses hydrologic and water quality model SWAT for simulating streamflow and stream temperature. SWAT is a well-established, physically-based, semi-distributed hydrologic model created by the United States Department of Agriculture (USDA) in 1998 [17]. The model is capable of simulating on a continuous daily, monthly and long-term time-step and incorporates the effects of climate, plant and crop growth, surface runoff, evapotranspiration, groundwater flow, nutrient loading, land use and in-stream water routing to predict hydrologic response and simulate discharge, sediment and nutrient yields from mixed land use watersheds [17,44-46]. As a distributed parameter model, SWAT divides a watershed into hydrologic response units (HRUs) exhibiting homogenous land, soil and slope characteristics. Surface water runoff and infiltration volumes are estimated using the modified soil conservation service (SCS) 1984 curve number method, and potential evapotranspiration is estimated using the Penman-Monteith method [47,48].

The Rhode Island Geographic Information System (RIGIS) database is the main source for the spatial data used as model inputs [49]. RIGIS is a public database managed by both the RI government and private organizations. Typical SWAT model inputs in ArcSWAT [50] include topography, soil characteristics, land cover or land use and meteorological data. Information collected for this study includes the following: 2011 Land use/land cover data derived from statewide 10-m resolution National Land Cover Data imagery [51]; soil characteristics collected from a geo-referenced digital soil map from the Natural Resource Conservation Service (NRCS) Soil Survey Geographic database (SSURGO) [52]; and topography information extracted from USGS 7.5-minute digital elevation models (DEMs) with a 10-meter horizontal, 7-meter vertical resolution. Based on the spatial data provided, the seven km^2 Cork Brook watershed was delineated into four subbasins and 27 HRU units using land use, soil and slope thresholds of 20%, 10% and 5%. Regional meteorological data from 1979-2014 including long term precipitation and temperature records were recorded by a National Climate Data Center weather station near the study site; the data were downloaded from Texas A&M University's global weather data site [53,54].

The SWAT Calibration and Uncertainty Program (SWAT-CUP), Sequential Uncertainty Fitting Version 2 (SUFI-2) [55,56], was used to conduct sensitivity analysis, calibration and model validation on stream discharge from the output hydrograph. Performance was measured using coefficient of determination and Nash-Sutcliffe Efficiency (NSE) and percent bias (PBIAS). Coefficient of determination (R^2) identifies the degree of collinearity between simulated and measured data and NSE was used as an indicator of acceptable model performance. R^2 values range from

0 to 1 with a larger R^2 value indicating less error variance. NSE is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance [57]. NSE ranges from -∞ to 1; a value at or above 0.50 generally indicates satisfactory model performance [58]. This evaluation statistic is a commonly used objective function for reflecting the overall fit of a hydrograph. Percent bias is the relative percentage difference between the averaged modeled and measured data time series over (n) time steps with the objective being to minimize the value [59].

The most recent version of SWAT (2012) estimates stream temperature from a relationship developed by Stefan and Preud'homme [17,60] which calculates the average daily water temperature based on the average daily ambient air temperature. Ficklin et al., (2012) developed another approach using a hydroclimatological component, which calculates stream temperature based on the combined influence of air temperature and hydrological inputs, such as streamflow, throughflow, groundwater inflow and snowmelt. Once the Cork Brook model was calibrated for streamflow, the hydroclimatological component was incorporated. A separate analysis of groundwater contributions to stream discharge was conducted for Cork Brook using an automated method for estimating baseflow [61]. An estimated 60% of stream discharge at Cork Brook is contributed to baseflow as opposed to overland flow. Therefore, incorporating the hydroclimatological component into the model may provide a more accurate prediction of stream temperature. The main equations for water temperature (T_w) (˚C) in the hydroclimatological component created by Ficklin et al., (2012) are listed below:

$$T_{w.local}=\frac{(T_{snow}sub\_snow)+\left(T_{gw}sub\_gw\right)+\left(\lambda T_{air.lag}\right)(sub\_surq+sub\_latq)}{sub\_wyld} \quad (1)$$

where $T_{w.local}$ (˚C) is the temperature and amount of local water contribution within the subbasin to the stream, sub_snow is snowmelt (m^3 d^{-1}) sub_gw is groundwater (m^3 d^{-1}), sub_surq us surface water runoff (m^3 d^{-1}), sub_latq is soil water lateral flow (m^3 d^{-1}), sub_wyld is total water yield (all hydrologic components) (m^3 d^{-1}), T_{snow} is snowmelt temperature (˚C), T_{gw} is groundwater temperature (˚C), $T_{air,lag}$ is the average daily air temperature with a lag (˚C), and λ (-) is a calibration coefficient relating the relationship between sub_surq and sub_latq and $T_{air,lag}$;

$$T_{w_{initial}}=\frac{T_{w.upstream}(Q_{outlet}-sub\_wyld)+T_{w.local}sub\_wyld}{Q_{outlet}} \quad (2)$$

where $T_{w.initial}$ is the weighted average of the contributions within the subbasin and from the upstream subbasin, $T_{w.upstream}$ is the temperature of water entering the subbasin (˚C), Q_{outlet} is the streamflow discharge at the outlet of the subbasin (m^3 d^{-1});

$$T_w=T_{w_{initial}}+(T_{air}-T_{initial})K(TT) \qquad \text{if } T_{air} > 0 \quad (3)$$

$$T_w=T_{w_{initial}}+\left[(T_{air}+\varepsilon)-T_{w_{initial}}\right]K(TT) \qquad \text{if } T_{air} < 0 \quad (4)$$

where T_{air} is the average daily temperature (˚C), K(1/h) is a bulk coefficient of heat transfer ranging from 0-1, TT is the travel time of water through the subbasin (hours) and ε is an air temperature addition coefficient. The ε coefficient is an important component because it allows the water temperature to rise above 0 ˚C when the air temperature is below 0 ˚C. If air temperature is less than 0 ˚C, the model will set the stream temperature to 0.1 ˚C. These details are further discussed in the results section of the paper. The source code for the Ficklin model was downloaded from Darren Ficklin’s research webpage at Indiana State University [62] and was used to calibrated

Cork Brook SWAT model. No additional spatial data were required for the added component and no additional streamflow calibration was necessary because discharge outputs were unchanged. Stream temperature parameters associated with the hydroclimatological model component were calibrated manually with the stream temperature data recorded at USGS Gauge 01115280. The same performance metrics (NSE and R^2) were used to determine model reliability for temperature simulation.

Upon model calibration and validation, output data simulated by SWAT with the hydroclimatological component were processed to determine the occurrence of stressful conditions in Cork Brook from 1980-2009. As previously discussed, a stressful event for this study is defined as any day where both temperature and flow extremes occur. This study used the Q25 and Q75 flow exceedance percentiles as indicators because of their common use [63-65] and ecohydrological importance to brook trout. The most critical period for the species is typically the lowest flows of late summer to winter and a base flow of less than 25% is considered poor for maintaining quality trout habitat [11,66]. A Q75 represents the lowest 25% of all daily flow rates and a Q25 exceedance characterizes the highest 25% of all daily flow rates. Flow-exceedance probability, or flow-duration percentile, is a well-established method and generally computed using the following equation:

$$P = 100*[M/(n+1)], \tag{5}$$

where P is the probability that a given magnitude will be equaled or exceeded (percent of time), M is the ranked position (dimensionless) and n is the number of events for period of record [65]. For the stressful event analysis, the exceedance probability and average daily stream temperature for each date were identified. If the day fell into the

Q25 or Q75 percentile, and if the stream temperature was greater than 21 ˚C, then the day was tagged as being a thermally stressful event.

RESULTS AND DISCUSSION

Model Calibration and Validation: Stream Discharge

The initial model was run for the entire period of precipitation and rainfall data availability (1979-2014) and then calibrated in SWAT-CUP using a portion of the existing observed streamflow data from the USGS gauge. The model was calibrated for streamflow over a two-year time-span from 2009-2010 (Figures 2 and 3) due to a limited availability in observed data (2008-present). The model was validated for years 2012-2013 because the 2011 data showed evidence of discharge misreading and 2014 weather data were incomplete. The hydrological parameters producing the best overall fit of the modeled hydrograph to the observed hydrograph are summarized in Table 1, and the statistical results of calibration and validation are shown in Table 2.

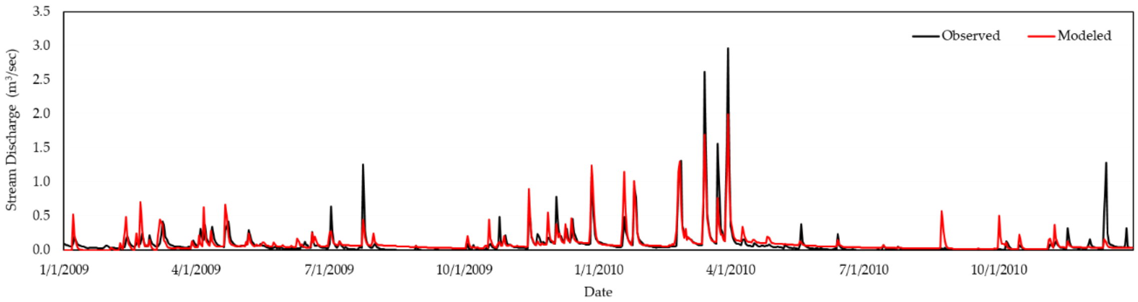


Figure 2: A simulated 2009-2010 hydrograph produced by the calibrated Cork Brook SWAT model compared to observed data from USGS Gauge 01115280.

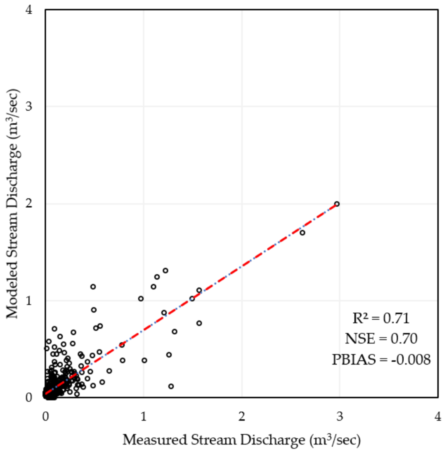


Figure 3: Streamflow scatterplot of modeled and observed streamflow from USGS gauge 0111528 during 2009-2010.

The most sensitive parameters in model calibration were primarily related to groundwater and soil characteristics. The alpha-BF (baseflow) recession value was one of the most effective parameters and had a small value of 0.049. The alpha baseflow factor is a recession coefficient derived from the properties of the aquifer contributing to baseflow; large alpha factors signify steep recession indicative of rapid drainage and minimal storage whereas low alpha values suggest a slow response to drainage [61,67]. The threshold depth of water in the shallow aquifer (GWQMN) was sensitive in model calibration and the depth of water is relatively small (0.6 meters). This is the threshold water level in the shallow aquifer for groundwater contribution to the main channel to occur. Optimal groundwater delay was short, only 1.2 days. Since groundwater accounts for the majority of stream discharge within Cork Brook, the sensitivity of soil and groundwater parameters was expected. Other factors were incorporated based on the small size of the watershed, such as surface lag time, slope length, steepness and lateral subsurface flow length, and the presence of snow at the site in the winter, such as snowmelt and snowpack temperature factors.

Table 1: Parameters used for SWAT streamflow calibration in SWAT-CUP. The parameter is listed by name and SWAT input file type, definition and the values that were selected for each model. “r” represents a relative type of change whereas “v” represents a replacement value.

Parameter	Definition	Best Value	Units
r__CN2.mgt	SCS runoff curve number	-0.094	-
v__ALPHA_BF.gw	Baseflow alpha factor	0.049	1/Days
v__GW_DELAY.gw	Groundwater delay	1.202	Days
v__SURLAG.bsn	Surface lag time	1.440	Days
v__SFTMP.bsn	Snowfall temperature	0.551	˚C
v__SMTMP.bsn	Snowmelt base temperature	0.403	˚C
v__TIMP.bsn	Snowpack temperature lag factor	0.081	-
v__ESCO.hru	Soil evaporation compensation factor	0.388	-
v__EPCO.hru	Plant uptake compensation factor	0.169	-
v__GWQMN.gw	Depth of water in shallow aquifer for return flow	678.2	mm
v__GW_REVAP.gw	Groundwater revap coefficient	0.117	-
r__SOL_AWC(1).sol	Available water capacity of the soil	0.342	mm H_2O/ mm soil
r__SOL_BD().sol	Mosit bulk density	-0.229	g/cm^3
r__SOL_K(1).sol	Saturated hydraulic conductivity	-0.249	mm/hr
r__HRU_SLP.hru	Average slope steepness	-0.156	m/m
v__OV_N.hru	Manning’s (n) value for overland flow	7.749	-
v__SLSUBBSN.hru	Average slope length	11.15	m
v__ALPHA_BNK.rte	Baseflow alpha factor for bank storage	0.627	Days
r__CH_N2.rte	Manning’s (n) value for main channel	0.022	-
v__SLSOIL.hru	Slope length for lateral subsurface flow	3.337	m

Table 2: Statistical results produced by SWAT-CUP using the parameters listed in Table 1.

Streamflow	**R^2**	**NSE**	**PBIAS**
Calibration	0.70	0.71	-0.01
Validation	0.55	0.60	0.0001

Model Calibration and Validation: Stream Temperature

Once the initial SWAT model was satisfactorily calibrated and validated for discharge the hydroclimatological component was added to the SWAT files and the model was run using both the basic SWAT approach and the revised stream temperature program. The hydroclimatological temperature model had no effect on stream discharge therefore the discharge was not re-calibrated. The simulated stream temperature was manually calibrated by changing several variables in the basin file associated with the hydroclimatological component: K, lag time and seasonal time periods in Julian days (Table 3). The K variable represents the relationship between air and stream temperature and ranges from 0 to 1. As K approaches 1, the stream temperature is approximately the same as air temperature and as K decreases the stream water is less influenced by air temperature [36]. The temperature outputs are also sensitive to the lag time, a calibration parameter corresponding to the effects of delayed surface runoff and soil water into the stream. Stream temperature was calibrated using observed data recorded by the USGS gauge from 2010-2011 and validated from 2012-2013.

Table 3. Hydroclimatological SWAT calibration parameters. Time period is in Julian days and Lag unit is days.

Time Period	Alpha	Beta	Phi	K	Lag Time
1-180	1.0	1.0	1.0	1.0	4
181-270	1.0	1.0	0.8	0.8	2
271-330	1.0	1.0	0.8	0.8	2
331-366	1.0	1.0	1.0	0.7	4

The above parameters produced satisfactory calibration statistics, as summarized in Table 4. During the winter and spring, the stream temperature is roughly the same as the air. In the summer and fall, the K value is decreased and the stream temperature is less affected by air temperature. This may be due to extensive tree shading [36], which is in agreement for Cork Brook as it is a relatively small watershed that is predominantly forested [68]. The lag time is also relatively short throughout the year although it varies with the seasons. Not surprisingly, the lag time for hydroclimatological calibration is not far from the surface and groundwater delay parameters set during stream discharge calibration. Modeled versus observed stream temperature for both the basic SWAT and hydroclimatological approach is shown in Figure 4. The Ficklin et al. (2012) approach generated comparable R^2 value but a higher NSE than the basic SWAT approach.

Table 4. Statistical results of the stream temperature calibration. The average recorded stream temperature at the USGS gauge is 7.8 ˚C.

Model Type	R^2	NSE	Mean Stream Temperature
Basic SWAT Calibration	0.93	0.83	12.5 ˚C
Basic SWAT Validation	0.94	0.83	12.9 ˚C
Ficklin Calibration	0.95	0.93	9.9 ˚C
Ficklin Validation	0.96	0.94	10.0 ˚C

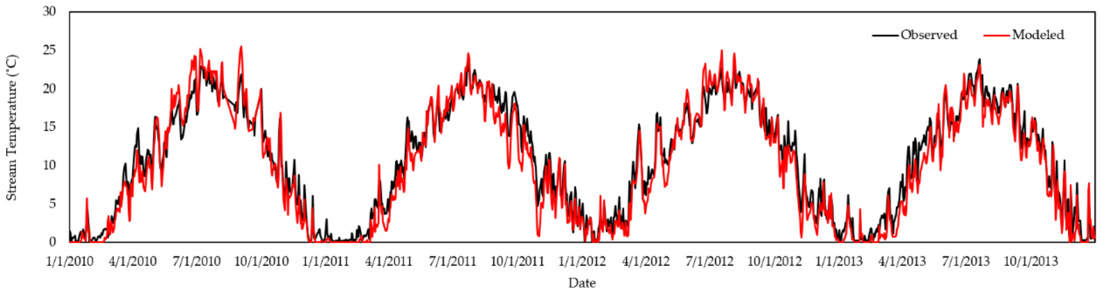


Figure 4: Cork Brook Stream Temperature 2010-2013. Comparison of observed data from USGS Gauge 01115280 and stream temperature simulated from SWAT with hydroclimatological component.

Stream Conditions and Stressful Event Analysis

The SWAT model incorporating the added hydroclimatological component was used for the stressful event analysis, as it proved to be more accurate than the basic model. The model predicted an increase in the magnitude of stream discharge increases by each decade between 1980-2009, as shown in Figure 5, although the shape of the flow duration curve stayed relatively consistent. The simulated stream discharge rates increased as well, averaging 0.06 m^3/sec in 1980-1989, 0.08 m^3/sec in 1990-1999 and 0.10 m^3/sec between 2000-2009. The maximum streamflow fluctuated, 1.74 m^3/sec in 1980-1989, 2.75 m^3/sec in 1990-1999 and 1.93 m^3/sec between 2000-2009. Several existing studies have examined how the climate has changed over the last thirty-years in New England. Since 1970, Rhode Island's annual precipitation has increased by 6-11%. Fewer days with snow cover and earlier ice-out days are also occurring [69,70]. A large scale regional study [1] collected climate and streamflow data from 27 USGS stream gauges for a historical average of 71 years throughout the New England region. The study indicated that there were increases over time in annual maximum streamflows and Q25 and Q75 streamflow percentiles. The stream discharge results produced by the Cork Brook model align well what has been observed statewide and across New England, and support claims that certain effects of climate change are already beginning to take place.

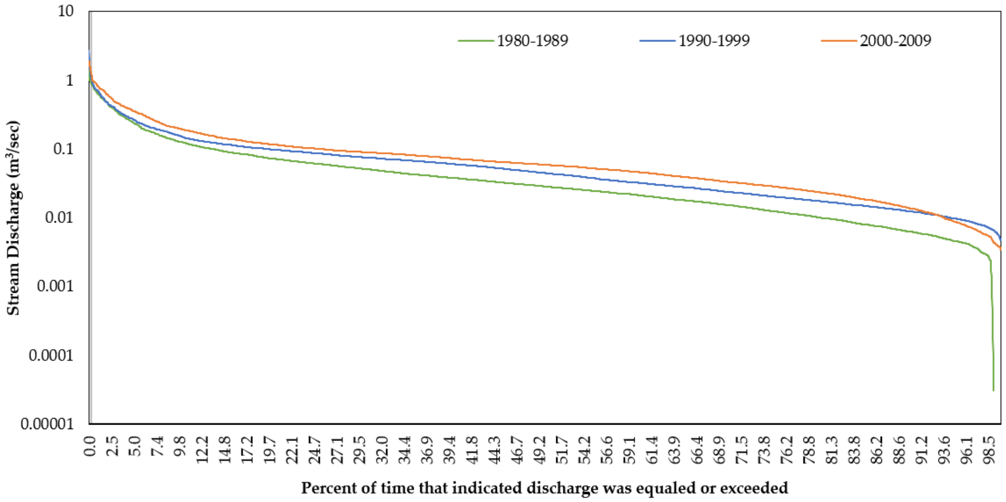


Figure 5: Simulated flow duration curves by decade generated by SWAT model with hydroclimatological component. Between January and February 1980, SWAT predicted the stream would run dry (i.e. stream discharge is equal to zero at the 100th percentile).

As water temperatures increase due to global warming, brook trout may benefit from sustained flows which will prevent stream temperatures from raising further and help ensure that downstream habitat remains connected to headwaters. On the other hand, a sustained increase in flow magnitude can change the geomorphology and may not be beneficial for aquatic species during the spawning season when flows are normally lower [30]. An increase in stream discharges during the low flow season may put redds at risk of destruction from sedimentation or sheer velocity. Changes in streamflow magnitude may also increase turbidity or redistribute riffle and pool habitat throughout the stream reach. This may decrease the availability of suitable habitat as brook trout prefer stream reaches with an approximate 1:1 pool-riffle ratio

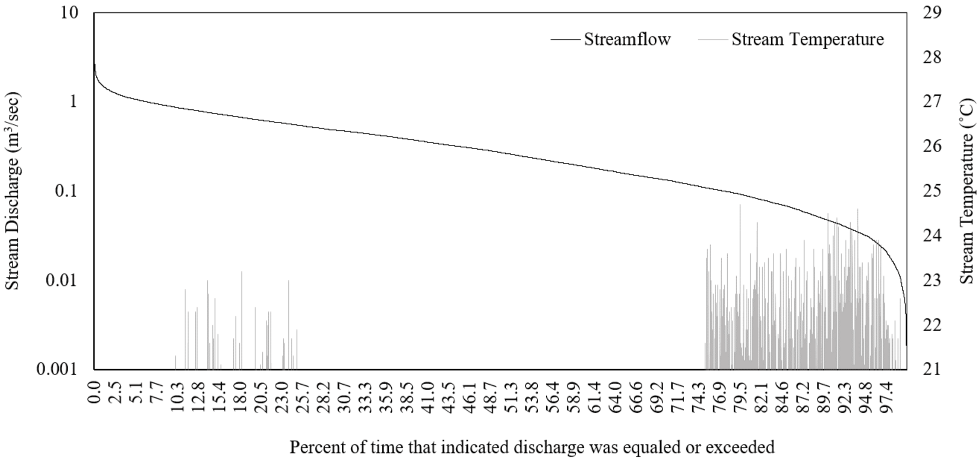
[11]. Pool and riffle redistribution can also affect the type and quantity of local macroinvertebrate populations. Since warming temperatures will have an impact on body condition as fish enter the winter months, the available food supply can become an even more critical factor as the climate changes.

To identify the number of stressful events simulated by the model, output data were analyzed by decade (1980-1989, 1990-1999 and 2000-2009) and over the entire 30 year period. The percent chance that a stressful event would occur on any given day throughout the time period was also calculated. These results are shown in Table 5 below.

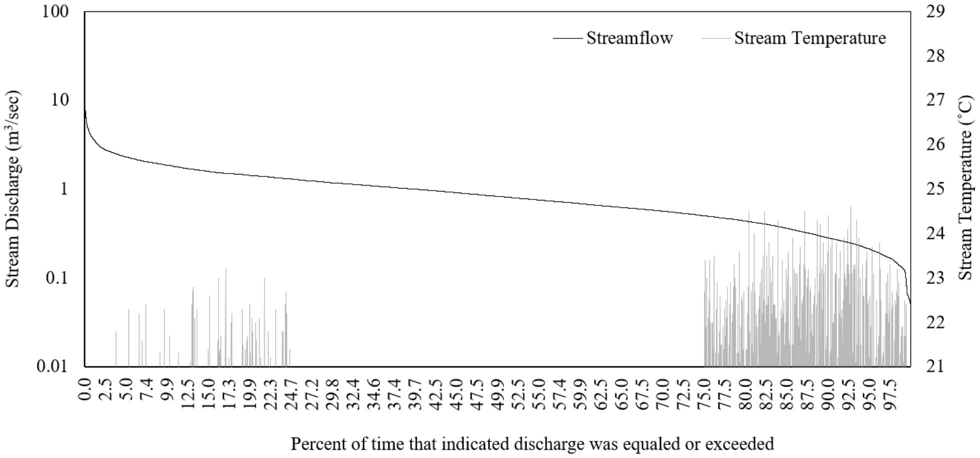
Table 5. Stressful event analysis of SWAT with hydroclimatological component. Shows the percent chance that of the 3,653 days per each decade and 10,958 days between 1980-2009, a day with any type of stress will occur, a day with flow stress will occur, a day with temperature stress will occur and the percent chance of an event.

Date	**Indicator**	**Any Type of Stress**	**Stream Temp. >21˚C**	**Q25 or Q75 Flow**	**Stressful Event**
1980-1989	Days	2066	252	1814	84
	% Chance	*56.6*	*6.9*	*49.7*	*2.3*
1990-1999	Days	2049	228	1821	122
	% Chance	*56.1*	*6.2*	*49.8*	*3.3*
2000-2009	Days	2007	196	1811	131
	% Chance	*54.9*	*5.4*	*49.6*	*3.6*
1980-2009	Days	6142	676	5466	338
	% Chance	*56.0*	*6.2*	*49.9*	*3.1*

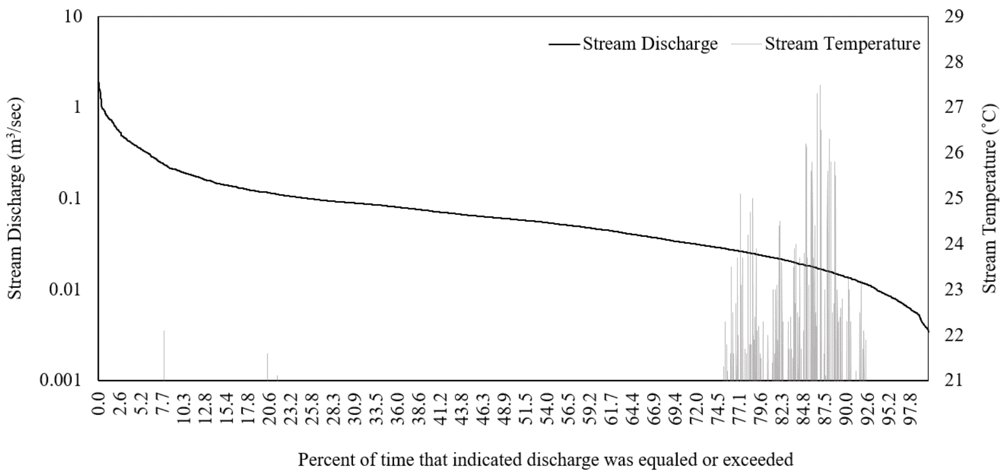
The model predicted an increase in the number of stressful events between 1980 and 2009 with the greatest change taking place between the first decade (1980-1989) and the second decade (1990-2009). It is interesting to note that although the model predicted an increase in number of stressful events between 1980 and 2009, the number of temperature stress days and the number of flow stress days generally decreased between decades (Table 5). Figures 6a-d have been created to gain a better understanding of how the co-occurrence of temperature stress and the flow stress has changed in Cork Brook.



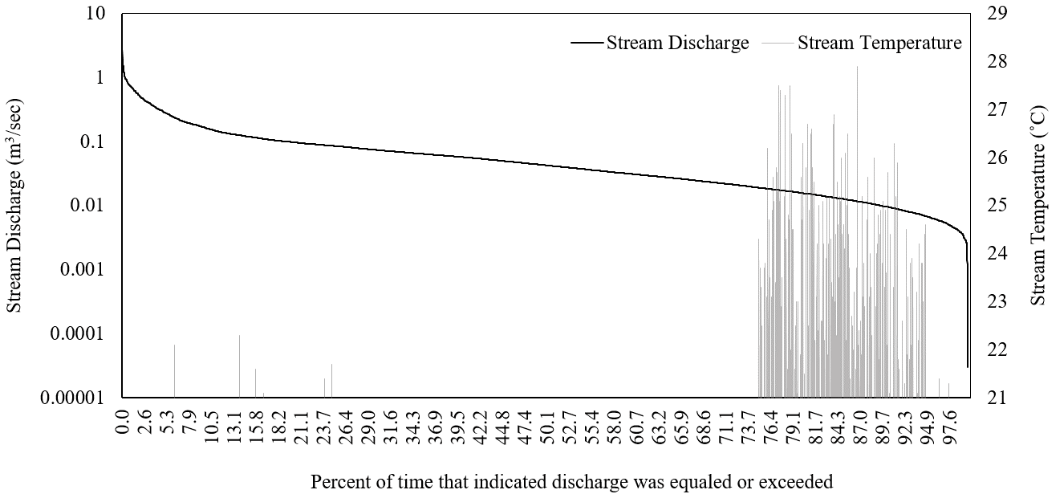
a)



b)



c)



d)

Figure 6: Cork Brook simulated flow duration curve and stream temperatures for SWAT with the hydroclimatological component over three decades. a) 1980-1989, b) 1990-1999 c) 2000-2009 and d) 1980-2009. The secondary y-axis begins at 21˚C and any temperatures that are not above the stressful threshold are not shown in the figures. The stream temperatures in the Q25-Q75 range are omitted from each figure.

The graphs show that of all 338 stressful events simulated between 1980 and 2009, only seven events occurred within the Q25 flow percentiles. The remaining events simulated by the model occurred when flows were within the Q75 – Q97 flow percentile because lower, slower flows are exposed to air longer causing them to increase or decrease in temperature more easily. The fact that there were no stressful events above the Q97 flow percentiles is most likely attributed to groundwater inputs. During the dry or low flow periods in summer and fall, baseflow will be the primary input to groundwater fed streams. Because the hydroclimatological model component takes the groundwater temperature into consideration (equation 1), the lowest discharge amounts the model simulates will likely be baseflow driven and therefore cooler than water that is continuously exposed to ambient air temperatures. This is good news for coldwater fish species which spawn in the fall or those that begin their migration into headwaters during the low flow season as the chances of exposure to high temperatures are lessened from groundwater contributions.

The greatest change in number of stressful events occurred between the first and second decades where the count of stressful events increased from 84 in 1980-1989 to 122 in 1990-1999. Comparing Figures 6a and 6b, the stressful events stretch from Q75 to Q87 in 1980-1989, whereas in 1990-1999 the events extend into the Q96 percentile. This shows that a combination of flow and temperature should be taken into consideration when making management decisions or evaluating the quality of aquatic habitat. For instance, managers can be reassured that withdrawing water during Q25 flows will not be as harmful to fish as withdrawing during Q75 flows. During drought years, it may become tempting to withdraw additional groundwater resources. However, knowing that groundwater can help reduce the frequency of stressful events to fish during the Q5-Q10 percentiles may influence a manager’s choice. Being that Cork Brook is upstream from the Scituate Reservoir, water resource management decisions are especially applicable to this watershed.

Such details can have important implications for aquatic species. Brook trout have been observed to tolerate higher stream temperatures provided their physical habitat remains stable [34]. If the co-occurrence of temperature and flow stresses increases, then physiological stresses to individual trout may become more apparent. The data simulated from 1980-2009 provides a helpful baseline for comparing future projections and will help determine if the resilience of local brook trout populations may become strained under future climate conditions.

CONCLUSIONS AND FUTURE WORK

Since the hydroclimatological model was shown to be more accurate, future research projects should consider using the new component in similar watersheds throughout the region for both historical and climate change assessments. This study found that the long-term historical stream temperature data recorded by the USGS gauge at Cork Brook was necessary for model calibration. Therefore, scientists should have a reliable set of observed stream temperature data to calibrate and validate the stream temperature output, especially if studying ecosystems that are particularly sensitive to temperature related parameters. Other related future work may include applying the methodology to other types of temperature sensitive aquatic organisms such as certain macroinvertebrate species. Macroinvertebrates form part of the base of the food chain and fluctuations in their population or distributions throughout a stream reach can impact higher trophic level species that prey on these organisms.

Another consideration for future work is to limit the stressful event analysis to the spring and summer months when brook trout are more sensitive to warmer stream temperatures. Also, a study could be conducted to see if stressful events occur sequentially. This study took a wider approach by examining how stream temperatures and streamflow vary throughout the entire year. This timeframe was chosen for several reasons. First, since this is the only study of its kind within these watersheds we did not have enough information to say with certainty that no changes to stream temperature or streamflow would occur during the fall and winter. In fact, some scientists predict that by the end of the century Rhode Island will have a climate similar to that of Georgia [70] in which case stream temperatures would almost certainly increase during the winter months. Second, while stream temperatures and streamflow during the winter months are not as critical for brook trout compared to the summer, winter conditions do effect embryo development. For instance, the length of embryo incubation during the winter ranges from 28-45 days depending on the temperature of the stream water [11]. Lastly, while this study focused on brook trout, our hope is that the methodology can be applied to other types of aquatic species that may be sensitive to stream conditions during other seasons.

The purpose of this study was to gain a better understanding of the historical conditions in coldwater habitat using SWAT. We successfully showed that SWAT with the hydroclimatological component is more accurate than the original SWAT model at this forested, baseflow driven watershed in Rhode Island. Moreover, thermally stressful event identification is a functional approach to analyzing model output. The data simulated from 1980-2009 provide a helpful baseline for comparing future projections by combining two important indicators for survival.

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MANUSCRIPT 2

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CLIMATE CHANGE INDUCED THERMAL STRESS IN COLDWATER FISH HABITAT USING SWAT

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ABSTRACT

Climate studies have suggested that inland stream temperatures and average streamflows will increase over the next century in New England, thereby putting aquatic species sustained by coldwater habitats at risk. This study uses the Soil and Water Assessment Tool (SWAT) to simulate historical streamflow and stream temperatures within three forested, baseflow driven watersheds in Rhode Island, USA followed by simulations of future climate scenarios for comparison. The output data are analyzed to identify daily occurrences where brook trout (*Salvelinus fontinalis*) are exposed to stressful events, defined for this study as any day where Q25 or Q75 flows occur simultaneously with stream temperatures exceeding 21 ˚C. Model simulations indicate that coldwater fish species such as brook trout will become increasingly exposed to stressful events under both high and low future greenhouse gas emission scenarios. Percent chance of stressful event occurrence increased by an average of 6.5% under low emission scenarios and by 14.2% under high emission scenarios relative to the historical simulations.

INTRODUCTION

Concerns have arisen regarding the consequential impacts of warming stream temperatures on brook trout (*Salvelinus fontinalis*) habitat due to climate change. Over the next century, freshwater ecosystems in the New England region of the United States are expected to experience continued increase in mean daily stream temperatures and an increase in the frequency and magnitude of extreme high flow events due to warmer, wetter winters, earlier spring snowmelt, and drier summers [1-

9]. As the spatial and temporal variability of stream temperatures play a primary role in distributions, interactions, behavior, and persistence of coldwater fish species [7,10-16], it has become increasingly important to understand what challenges freshwater fisheries managers will face due to climate change. Analytical models such as the Soil and Water Assessment Tool (SWAT) [17] can be used to estimate the effects of climate change on stream temperatures [5,18-24]. Several studies have used global climatic model output or temperature and precipitation variations to drive hydrologic and stream temperature models for the United States [25] and worldwide [8]. This study uses both SWAT and global climate data downscaled for New England [3,26-28], to simulate the effects of increasing air temperatures and changes to regional rainfall patterns on coldwater fish habitat in Rhode Island watersheds.

SWAT model was used to generate historical and future stream temperature and streamflow data, followed by an assessment of the frequency of “stressful events” affecting the Rhode Island native brook trout. Brook trout, a coldwater salmonid, is a species indicative of high water quality and is also of interest due to recent habitat and population restoration efforts by local environmental groups and government agencies [29, 30]. This fish typically spawns in the fall, and lays eggs in redds (nests) deposited in gravel substrate. Eggs develop over the winter months and hatch from late winter to early spring [11,12,31]. However, the life-cycle of brook trout is heavily influenced by the degree and timing of temperature changes. High stream temperatures cause physical stress including slowed metabolism and decreased growth rate, adverse effects on critical life-cycle stages such as spawning or migration triggers, and in extreme cases, mortality [7,10,32-35]. Distribution is also affected as coldwater fish actively avoid water temperatures that exceed their preferred temperature by 2-5 ˚C [36,37]. Studies have shown that optimal brook trout water temperatures are below 20 ˚C, symptoms of physiological stress develop at approximately 21 ˚C [33] and temperatures above 24 ˚C have been known to cause mortality in this species [12].

Flow regime is another central factor in maintaining the continuity of aquatic habitat throughout a stream network [35,38-43]. While temperature is often cited as the limiting factor for brook trout, the flow regime has considerable equal importance [44]. Alteration of the flow regime can result in changes in the geomorphology of the stream, the distribution of food producing areas as riffles and pools shift, reduced macroinvertebrate abundance and more limited access to spawning sites or thermal refugia [12,31,45,46]. Reductions in flow have a negative effect on the physical condition of both adult brook trout and young-of-year. Nuhfer, Zorn et al. (2017) found a significant decline in spring-to-fall growth of brook trout when 75% flow reductions occurred. The consequences of lower body mass are not always immediately apparent. Adults may suffer higher mortality during the winter months following the further depletion of body mass due to the rigors of spawning. Poor fitness of spawning adults may result in lower quality or reduced abundance of eggs. [31]. Velocity of water in the stream reach can affect sediment and scouring of the stream bed and banks, minimizing the availability of nest sites or, in the event of low flows, cause water temperatures to rise.

To address the importance of both stream temperature and flow regime, stressful events are defined herein as days where either high or low flow occurs simultaneously with stream temperatures exceeding 21 ˚C. For the purpose of this study high and low flows will be considered as those values in the 25-percent and 75-percent flow exceedance percentiles (Q25, Q75). Two Wood-Pawcatuck River headwater subbasins, the Queen River and Beaver River, were selected as study sites due primarily to their pristine aquatic habitat (Figure 1). A third pristine watershed, Cork Brook, was chosen for the study because of its association with the Scituate Reservoir which supplies drinking water to the City of Providence. Existing scientific studies have been conducted on water quality in the Wood-Pawcatuck watersheds [47-49] and its subbasins [50-53]. Potential brook trout habitat restoration areas in Rhode Island [29] have also been researched. These studies have provided information regarding regional water resources. SWAT, however, has never been utilized to study climate change effects on flow and temperature conditions at a basin-wide scale in these Rhode Island watersheds.

Results provide a site-specific approach for watershed managers trying to determine the types and distribution of future habitat risks to coldwater species. As the demands for water quality and quantity increase for wildlife and human consumption over the next century, new evaluation techniques will help anticipate and solve unprecedented challenges. In the Wood-Pawcatuck and Cork Brook watersheds, the anticipated challenges may include an increase in stressful conditions. Results indicate that under both high and low emission greenhouse gas scenarios, coldwater fish species such as brook trout will be increasingly exposed to stressful events. Percent chance of a stressful event occurrences between historical simulations and future simulations increased by an average of 6.5% under low emission scenarios and by 14.2% under high emission scenarios. Additionally, in the Cork Brook watershed stream temperatures were predicted to reach stressful levels earlier in the year under both high and low emissions by the end of the century.

MATERIALS AND METHODS

Three gauged watersheds were studied to achieve the objective: Queen River, Beaver River and Cork Brook. The Queen and Beaver watersheds lie adjacent to each other within the larger Wood-Pawcatuck watershed in southern Rhode Island. In its entirety, this watershed is comprised of seven drainage basins and two major rivers. The upper reaches of the Wood-Pawcatuck watershed trend towards undisturbed rural environments. The watershed becomes increasingly urban and impaired towards the downstream reaches before emptying into Little Narragansett Bay. The effects of climate change on Rhode Island stream water quality parameters is a serious concern in the Wood-Pawcatuck watershed, which supports high quality habitat and a species diversity that is unique for a watershed of this scale in southern New England [30,50,54,55]. Rhode Island native brook trout are known to occur within the Wood-Pawcatuck watershed [47,55,56] and many non-profit organizations, recreational fishing groups and government agencies have taken interest in ensuring the long-term survival of local populations.

The Beaver River and the Queen River watersheds cover areas of approximately 23 km^2 and 52 km^2, respectively. Many similarities exist between the two subbasins. Both are HUC 12 river headwaters to the larger Pawcatuck river and each watershed hosts nature preserves owned and managed by The Nature Conservancy [54,57]. Land use in each subbasin is primarily forest although wetlands and agriculture make up a small portion of each watershed. Continuous and permanent United States Geological Survey (USGS) gauges have been recording flow data for several decades within each river [58]. The Beaver River USGS gauge number 01117468 is located near Usquepaug, RI where it intersects State Highway 138, or approximately 5.8 km upstream from its confluence with the Pawcatuck River. The gauge has been in continual operation since 1974. Mean daily discharges at the Beaver River gauge are typically lowest in September (0.02 m^3/sec) and highest in April (1.04 m^3/sec), with annual mean daily discharge of 0.59 m^3/sec. USGS gauge station gauge number 01117370 is located on the Queen River at its intersection with Liberty Road, near Liberty, RI, and has been recording data since 1998. Discharges at the Queen River gauge are higher, historically lowest in August (0.039 m^3/sec) and highest in March (2.08 m^3/sec) with mean daily discharges of approximately 1.06 m^3/second. A separate analysis of groundwater contributions to stream discharge was conducted using an automated method for estimating baseflow (Arnold and Allen, 1999). A noteworthy difference between the two watersheds is the baseflow contributions to each river, 93% within the Beaver River and 78% for the Queen River.

The third study site is Cork Brook in Scituate, Rhode Island. This small forested watershed is a tributary to the Scituate Reservoir, which is part of the larger Pawtuxet River basin beginning in north-central Rhode Island and eventually flowing into Narragansett Bay. The Scituate Reservoir is the largest open body of water in the state and is the main drinking water source to the city of Providence. Cork Brook is approximately four km long and covers an area of approximately seven km^2. Human disturbance within the watershed is minimal and most of the land use within the watershed is undeveloped forest and brushland, although a portion (14%) of the land area is classified as medium density residential. USGS station number 01115280 is located on Rockland Road near Clayville, RI and has been continuously recording streamflow at the site since 2008 [58]. A primary difference between the Cork Brook and Wood-Pawcatuck watersheds is size and stream discharge amounts. The mean daily discharges at the gauge are historically lowest in September (0.025 m^3/sec), highest in March (0.27 m^3/sec) and annually average approximately 0.11 m^3/sec. Average daily stream temperature is estimated at 7.8 ˚C since 2001. An important similarity to the Beaver and Queen watersheds is groundwater contribution; baseflow contributes the majority (60%) of stream discharges.

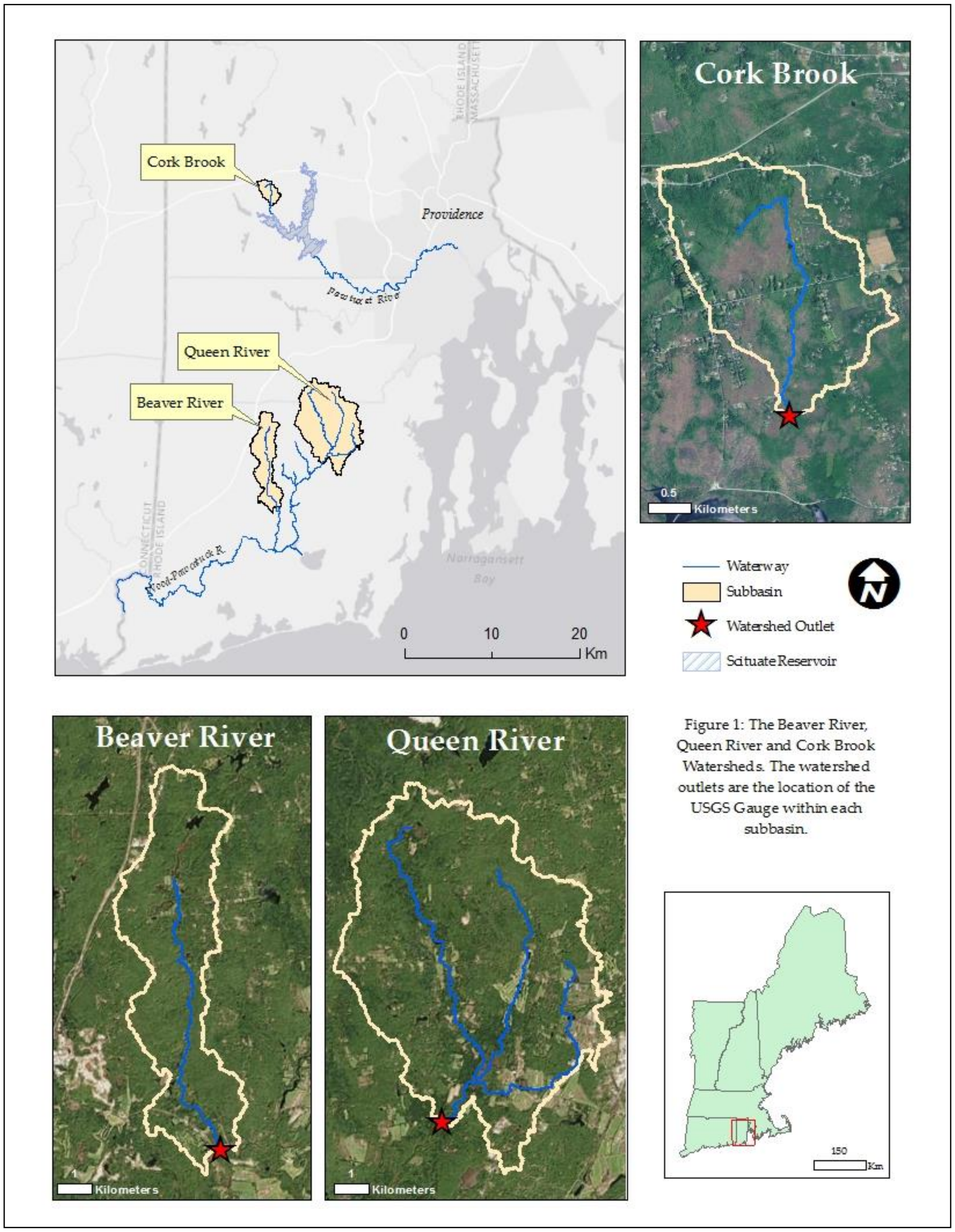


Figure 1: The Beaver River, Queen River and Cork Brook Watersheds. The watershed outlets are the location of the USGS Gauge within each subbasin.

This study uses the hydrologic and water quality model SWAT for simulating streamflow and stream temperature. SWAT is a well-established, physically-based, semi-distributed hydrologic model created by the United States Department of Agriculture (USDA) in 1998 [17]. The model is capable of simulating on a continuous daily and sub-daily time-step and incorporates the effects of climate, plant and crop growth, surface runoff, evapotranspiration, groundwater flow, nutrient loading, land use and in-stream water routing to predict hydrologic response and simulate discharge, sediment and nutrient yields from mixed land use watersheds [17,59-61]. As a distributed parameter model, SWAT divides a watershed into hydrologic response units (HRUs) exhibiting homogenous land, soil and slope characteristics. Surface water runoff and infiltration volumes are estimated using the modified soil conservation service (SCS) 1984 curve number method, and potential evapotranspiration is estimated using the Penman-Monteith method [62,63]. Stream temperature is estimated from air temperature based on a linear regression method developed by Stefan and Prued'homme (1993) [17,64]:

$$T_W(t) = 5.0 + 0.75T_{air}(t - \delta) \tag{1}$$

Where (T_W) represents average daily water temperature (˚C), (T_{air}) represents average daily air temperatures (˚C). Time (t) and lag (δ) are in days. Water temperatures follow air temperatures closely, the time lag for a shallow stream is expected to be on the order of a few hours due to the thermal inertia of the water [64]. The average relationship indicates that when the daily air temperature is close to 0 ˚C that the water will be approximately 5 ˚C warmer. When the daily air temperature is below 20 ˚C the water temperature is likely to be greater than the air temperature [64].

The Rhode Island Geographic Information System (RIGIS) database is the main source for the spatial data used as model inputs [65]. RIGIS is a public database managed by both the RI government and private organizations. Typical SWAT model inputs in ArcSWAT [66] include topography, soil characteristics, land cover or land use and meteorological data. Information collected for this study includes the following: 2011 Land use/land cover data derived from statewide 10-m resolution National Land Cover Data imagery [67]; soil characteristics collected from a geo-referenced digital soil map from the Natural Resource Conservation Service (NRCS) Soil Survey Geographic database (SSURGO) [68]; and topography information extracted from USGS 7.5-minute digital elevation models (DEMs) with a 10-meter horizontal, 7-meter vertical resolution. Regional meteorological data from 1979-2014 including long term precipitation and temperature statistics were recorded by National Climate Data Center weather stations near Cork Brook and the Wood-Pawcatuck watersheds; the data were downloaded from Texas A&M University's global weather data site [69,70]. Based on the spatial data provided, SWAT delineated the watersheds into HRU units which are represented as a percentage of the subwatershed area. The user sets a soil, land and slope threshold and when a parcel of land meets or exceed all thresholds a HRU is created. SWAT delineated the Beaver River into five subbasins and 12 HRUs using land, soil and slope thresholds of 20%. The Queen River was delineated into eight subbasins and 17 HRUs using land, soil and slope thresholds of 25%, 20% and 20%. Cork Brook was delineated in SWAT to create four subbasins and 27 HRUs using land, soil and slope thresholds of 20%, 10% and 5%.

The SWAT Calibration and Uncertainty Program (SWAT-CUP), Sequential Uncertainty Fitting Version 2 (SUFI-2) [71,72], was used to conduct sensitivity analysis, calibration and model validation on stream discharge from the output hydrograph. Performance was measured using coefficient of determination and Nash-Sutcliffe Efficiency (NSE) and percent bias (PBIAS). Coefficient of determination

(R^2) identifies the degree of collinearity between simulated and measured data and NSE was used as an indicator of acceptable model performance. R^2 values range from 0 to 1 with a larger R^2 value indicating less error variance. NSE is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance [73]. NSE ranges from $-\infty$ to 1; a value at or above 0.50 generally indicates satisfactory model performance [74]. This evaluation statistic is a commonly used objective function for reflecting the overall fit of a hydrograph. Percent bias is the relative percentage difference between the averaged modeled and measured data time series over (n) time steps with the objective being to minimize the value [75].

Climate variables in the calibrated SWAT subbasin input files were edited to simulate future climate scenarios. Carbon dioxide (CO_2) concentrations, relative rainfall adjustment and temperature increases (˚C) used in this study are based on values published by Wake et al. (2014) at the University of New Hampshire [4,26-28], which were generated from four global climatic models downscaled to the New England region. The anticipated change in average air temperature and precipitation over short term (2010-2039), medium term (2040-2069) and long term (2070-2099) time-spans for low and high greenhouse gas (GHG) scenarios were incorporated and compared to the unchanged historical period (1980-2009). Low greenhouse gas emission scenarios are based on the 2007 International Panel on Climate Change Special Report on Emissions Scenarios (SRES) B1 scenario and the high emissions are based on the SRES A1fi scenario. The B1 scenario is a situation where economic growth incorporates clean, ecologically friendly technology and GHG emissions levels return to pre-industrial concentrations, estimated at CO_2 levels of 300 parts per million (ppm). The high emissions scenario (A1fi) is a scenario based on fossil fuel intensive technologies for worldwide economic growth resulting in CO_2 levels reaching 940 ppm. Two of the published climate grids for Rhode Island were adopted and modified for this study and four different CO_2 levels were used. SWAT output for all low-emission scenarios is based on 330 ppm (the lower limit in the SWAT program code) and the RI climate grid change factors. In the high emissions alternative, the short, medium and long-term SWAT climate change simulations were run with CO_2 levels at 540 ppm, 740 ppm and 940 ppm, respectively, in addition to the RI climate grid change factors. Table 1 below details the climate change variables substituted in this study.

Table 1: Climate change variables adopted and modified from Wake et al., 2014 for a) and b) Kingston, RI (Beaver River and Queen River) and c) and d) North Foster, RI (Cork Brook). High emissions (a and c) based on SRES A1fi scenario and low emissions (b and c) based on SRES B1 scenario. Temperatures (Temp.) listed as degree (˚C) increase, averaged from the published minimum and maximum temperatures. Precipitation (Precip.) values listed as a relative change computed based on the published values.

a) Low Emissions – Kingston, RI

Indicator	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Short-term Temp.	0.97	0.97	1.42	1.42	1.42	0.83	0.83	0.83	0.36	0.36	0.36	0.97
Med-term Temp.	1.50	1.50	2.47	2.47	2.47	1.58	1.58	1.58	0.56	0.56	0.56	1.50
Long-term Temp.	2.17	2.17	3.25	3.25	3.25	1.97	1.97	1.97	0.83	0.83	0.83	2.17
Short-term Precip.	8.76	8.76	9.80	9.80	9.80	17.9	17.9	17.9	5.59	5.59	5.59	8.76
Med-term Precip.	14.3	14.3	10.3	10.3	10.3	17.9	17.9	17.9	6.90	6.90	6.90	14.3
Long-term Precip.	14.9	14.9	16.3	16.3	16.3	18.6	18.6	18.6	10.6	10.6	10.6	14.9

b) High Emissions – North Foster, RI

Indicator	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Short-term Temp.	0.97	0.97	0.83	0.83	0.83	1.11	1.11	1.11	1.00	1.00	1.00	0.97
Med-term Temp.	2.22	2.22	2.36	2.36	2.36	3.06	3.06	3.06	3.00	3.00	3.00	2.22
Long-term Temp.	3.83	3.83	4.28	4.28	4.28	5.22	5.22	5.22	4.92	4.92	4.92	3.83
Short-term Precip.	8.09	8.09	14.2	14.2	14.2	12.5	12.5	12.5	4.93	4.93	4.93	8.09
Med-term Precip.	10.0	10.0	15.8	15.8	15.8	12.5	12.5	12.5	6.2	6.2	6.2	10.0
Long-term Precip.	22.3	22.3	22.0	22.0	22.0	10.2	10.2	10.2	8.16	8.16	8.16	22.3

c) Low Emissions – North Foster, RI

Indicator	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Short-term Temp.	1.00	1.00	1.42	1.42	1.42	0.97	0.97	0.97	0.39	0.39	0.39	1.00
Med-term Temp.	1.58	1.58	2.53	2.53	2.53	1.81	1.81	1.81	0.58	0.58	0.58	2.22
Long-term Temp.	2.22	2.22	3.33	3.33	3.33	2.25	2.25	2.25	0.81	0.81	0.81	2.22
Short-term Precip.	10.6	10.6	11.3	11.3	11.3	16.9	16.9	16.9	6.62	6.62	6.62	10.6
Med-term Precip.	12.9	12.9	11.9	11.9	11.9	17.4	17.4	17.4	10.1	10.1	10.1	12.9
Long-term Precip.	16.2	16.2	15.6	15.6	15.6	17.4	17.4	17.4	11.8	11.8	11.8	16.2

d) High Emissions – North Foster, RI

Indicator	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Short-term Temp.	0.97	0.97	0.89	0.89	0.89	1.22	1.22	1.22	0.89	0.89	0.89	0.97
Med-term Temp.	2.22	2.22	2.50	2.50	2.50	3.28	3.28	3.28	2.78	2.78	2.78	2.22
Long-term Temp.	3.86	3.86	4.47	4.47	4.47	5.50	5.50	5.50	4.64	4.64	4.64	3.86
Short-term Precip.	6.29	6.29	10.8	10.8	10.8	15.7	15.7	15.7	2.08	2.08	2.08	6.29
Med-term Precip.	8.84	8.84	11.3	11.3	11.3	18.0	18.0	18.0	2.76	2.76	2.76	8.84
Long-term Precip.	17.7	17.7	20.0	20.0	20.0	17.4	17.4	17.4	5.37	5.37	5.37	17.7

Upon model calibration, validation, and incorporation of climate change variables, output data for both model versions were processed to predict the occurrence of stressful conditions in all three watersheds from 1980-2099. As previously discussed, a stressful event for this study is defined as any day where both temperature and flow extremes occur. This study used the Q25 and Q75 flow exceedance percentiles as indicators because of their common use [76-78] and ecohydrological importance to brook trout. The most critical period for the species is typically the lowest flows of late summer to winter and a base flow of less than 25% is considered poor for maintaining quality trout habitat [12,44]. A Q25 exceedance characterizes the highest 25% of all daily flow rates and Q75 represents the lowest 25% of all daily flow rates. Flow-exceedance probability, or flow-duration percentile, is a well-established method and generally computed using Equation 2:

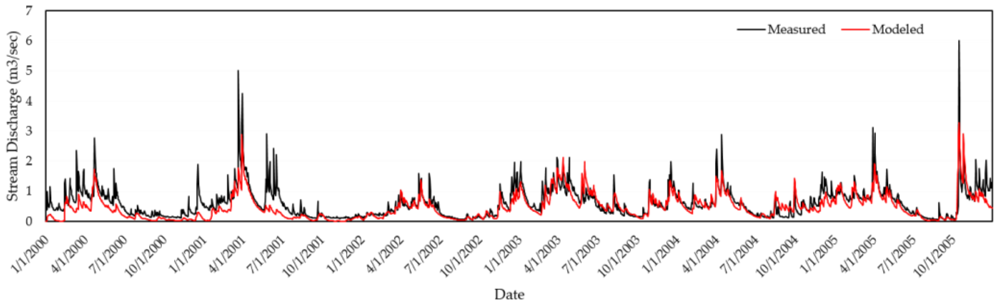
$$P = 100 \times [M/(n+1)] \tag{2}$$

where P is the probability that a given magnitude will be equaled or exceeded (percent of time), M is the ranked position (dimensionless) and n is the number of events for period of record [78]. For the stressful event analysis, the exceedance probability and average daily stream temperature for each date were identified. If the day fell into the Q25 or Q75 percentile, and if the stream temperature was greater than 21˚C, then the day was tagged as being a thermally stressful event.

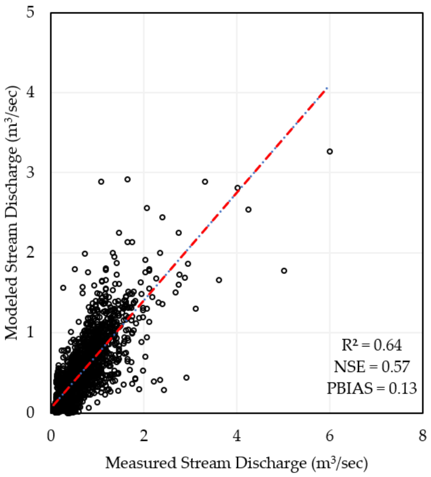
RESULTS AND DISCUSSION

Model Calibration and Validation

Each model was run for the entire period of precipitation and rainfall data availability (1979-2014) and then calibrated for streamflow in SWAT-CUP via SUFI-2 using a portion of the existing observed data at each associated USGS gauge. For consistency, both watersheds were calibrated over the same five-year time span from 2000-2005, which were also chosen in part to avoid streamflow anomalies in 2010 and 2006. Validation occurred from 2007-2008 in both the Beaver and Queen River watersheds. Meanwhile, the Cork Brook model was calibrated for streamflow over a shorter two-year time-span from 2009-2010 due to a limited availability in observed discharge data (2008-present). The Cork Brook model was validated for years 2012-2013. The same streamflow calibration parameters were used for each watershed, further showing similarities and differences between the three subbasins. The calibration parameters producing the best overall fit of the modeled hydrographs to the observed hydrographs (Figures 2, 3 and 4) are summarized in Table 2, and the statistical results of calibration and validation are shown in Table 3 and Table 4.



a)



b)

Figure 2: (a) Hydrograph and (b) scatterplot of observed versus SWAT modeled streamflow at Beaver River USGS gauge 01117468 during calibration years 2000-2005

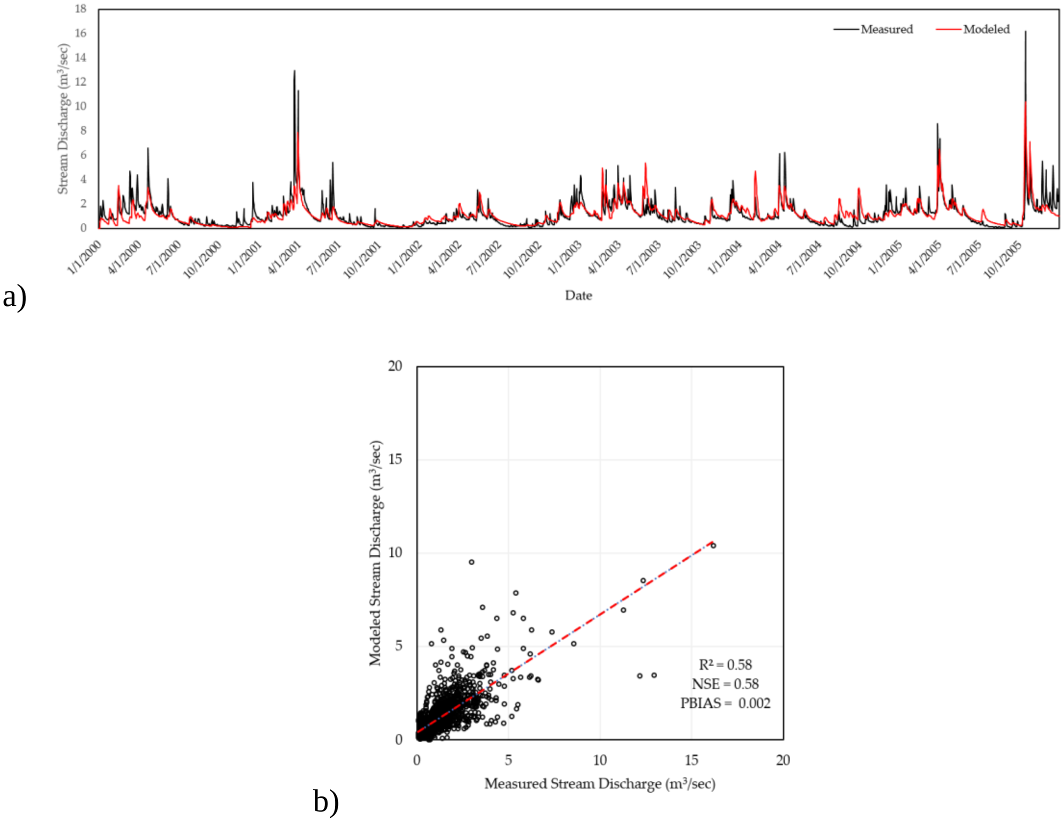


Figure 3: (a) Hydrograph and (b) scatterplot of observed versus SWAT modeled streamflow at Queen River USGS gauge 01117370 during calibration years 2000-2005.

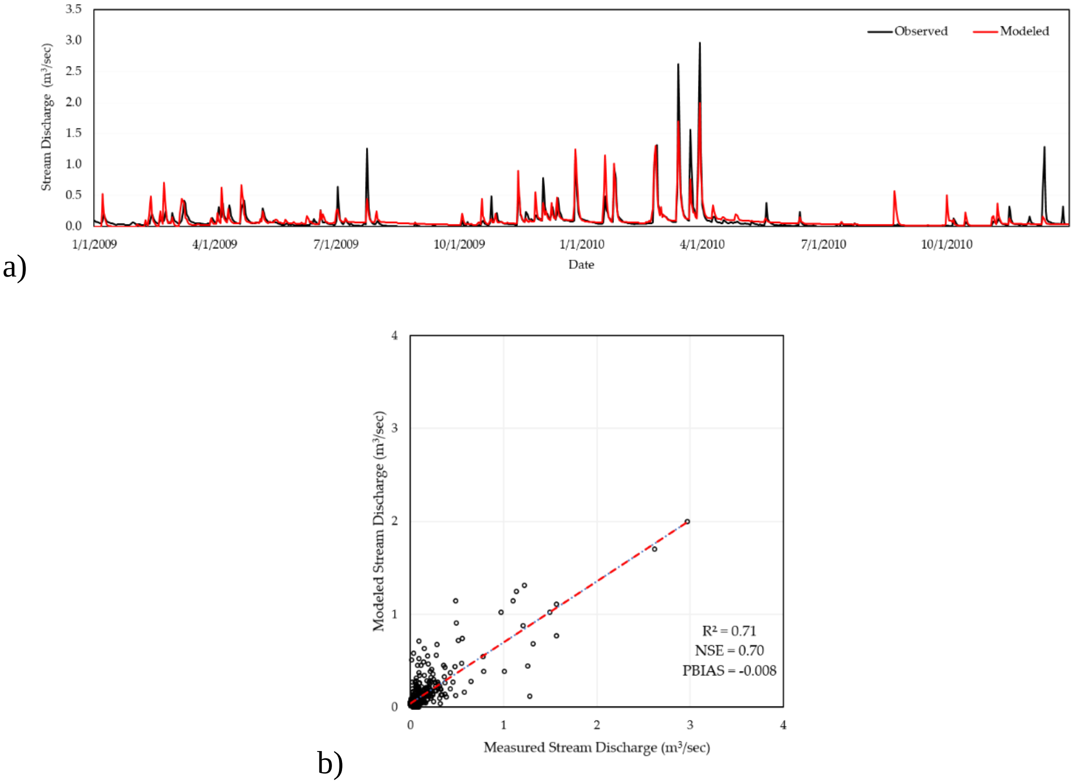


Figure 4: (a) Hydrograph and (b) scatterplot of observed versus SWAT modeled streamflow at Cork Brook USGS gauge 01115280 during calibration years 2009-2010.

The more sensitive parameters in model calibration were primarily related to groundwater and soil characteristics. The alpha-BF (baseflow) recession value was one of the most effective parameters for all three models and the values were all very small. The alpha baseflow factor is a recession coefficient derived from the properties of the aquifer contributing to baseflow; large alpha factors signify steep recession indicative of rapid drainage and minimal storage whereas low alpha values suggest a slow response to drainage [79,80]. Alpha-bnk (bankflow) was another sensitive parameter which is simulated with a recession curve like that used for groundwater. For this parameter, a high value at all three sites indicates a flat recession curve, which is similar to the alpha-bf value that specifies a slow response to drainage. The threshold depth of groundwater in the shallow aquifer (GWQMN) is small and very similar between all three models, less than a meter within each. This is the threshold water level in the shallow aquifer for groundwater contribution to the main channel to occur. There were minor differences in soil parameters. Available water content was relatively increased at the Cork Brook and Queen River sites and the hydraulic conductivity at Cork Brook is relatively decreased. Since groundwater accounts for the majority of stream discharge at all sites, the sensitivity of soil and groundwater parameters was expected. Other factors reflect the size differences between the watersheds. Cork Brook is smaller than the other two and has a lower surface lag time, groundwater delay and lower slope length.

Table 2: Parameters used for SWAT streamflow calibration in SWAT-CUP. The parameter is listed by name and SWAT input file type, definition and the values that were selected for each model. “r” represents a relative type of change whereas “v” represents a replacement value.

Parameter	**Definition**	**Beaver River**	**Queen River**	**Cork Brook**	**Unit**
r__CN2.mgt	SCS runoff curve number	-0.390	0.093	-0.094	-
v__ALPHA_BF.gw	Baseflow alpha factor	0.037	0.078	0.049	1/Days
v__GW_DELAY.gw	Groundwater Delay	7.02	7.68	1.20	Days
v__SURLAG.bsn	Surface Lag Time	2.30	2.60	1.44	Days
v__SFTMP.bsn	Snowfall temperature	-0.52	0.75	0.55	˚C
v__SMTMP.bsn	Snowmelt base temperature	1.67	2.155	0.403	˚C
v__TIMP.bsn	Snowpack temperature lag factor	0.61	0.088	0.081	-
v__ESCO.hru	Soil evaporation compensation factor	0.55	0.62	0.34	-
v__EPCO.hru	Plant uptake compensation factor	0.64	0.46	0.17	-
v__GWQMN.gw	Depth of water in shallow aquifer for return flow	694.0	767.3	678.2	mm

v__GW_REVAP.gw	Groundwater revap coefficient	0.0959	0.067	0.117	-
r__SOL_AWC(1).sol	Available water capacity of the soil	-0.0147	0.451	0.342	mm H_2O/ mm soil
r__SOL_BD().sol	Mosit bulk density	0.0618	-0.144	-0.229	g/cm^3
r__SOL_K(1).sol	Saturated hydraulic conductivity	0.143	0.199	-0.249	mm/hr
r__HRU_SLP.hru	Average slope steepness	0.0224	-0.104	-0.156	m/m
v__OV_N.hru	Manning's (n) value for overland flow	27.2	14.9	7.75	-
v__SLSUBBSN.hru	Average slope length	32.7	15.1	11.2	m
v__ALPHA_BNK.rte	Baseflow alpha factor for bank storage	0.867	0.732	0.627	Days
r__CH_N2.rte	Manning's (n) value for main channel	-0.457	-0.035	0.022	-
v__SLSOIL.hru	Slope length for lateral subsurface flow	23.8	1.54	3.34	m

Table 3. Statistical results of streamflow calibration produced by SWAT-CUP using the parameters listed in Table 1.

Watershed	**R^2**	**NSE**	**PBIAS**
Beaver River	0.64	0.57	0.13
Queen River	0.58	0.58	0.002
Cork Brook	0.70	0.71	-0.01

Table 4. Statistical results of streamflow validation produced by SWAT-CUP using the parameters listed in Table 1.

Streamflow	**R^2**	**NSE**	**PBIAS**
Beaver River	0.66	0.60	0.13
Queen River	0.60	0.59	0.003
Cork Brook	0.55	0.60	0.0001

Stressful Event Analysis: Historical

The modeled average daily stream temperature was nearly the same at all three sites. The average daily discharge, however, was different at all three sites and corresponded to watershed area, with the highest discharge within the Queen River (largest watershed) and the lowest discharge within Cork Brook (smallest watershed) (Table 5). This is in agreement with the observed data in that the Queen River had the highest discharge for the years on record at the USGS Gauge followed by the Beaver River and Cork Brook. The calibrated model for each watershed was first run over the entire thirty-year period (1980-2009) (Table 5) to understand the percent chance that a stressful event will occur on a given day. Of the three study sites, the Queen River had the highest percent chance that a stressful event would occur on any given day and the Beaver River had the lowest percent chance (Table 6).

Table 5: The average stream temperature simulated by SWAT 1980-2009.

Watershed	**Average Daily Stream Temp. (˚C)**	**Average Daily Discharge (m^3/sec)**
Beaver River	13.0	0.38
Queen River	13.0	1.0
Cork Brook	12.5	0.081

Table 6: Stressful event analysis of SWAT simulation for the three study sites. Shows the percent chance that of the 10,958 days between 1980-2009, a day with any type of stress will occur, a day with flow stress will occur, a day with temperature stress will occur and the percent chance of an event.

Date	**Watershed**	**Indicator**	**Any Type of Stress**	**Stream Temp. >21˚C**	**Q25 or Q75 Flow**	**Stressful Event**
1980-2009	Beaver River	Days	6416	959	5457	511
		% Chance	*58.6%*	*8.8%*	*49.8%*	*4.7%*
	Queen River	Days	6506	959	5547	700
		% Chance	*59.4%*	*8.8%*	*50.6%*	*5.5%*
	Cork Brook	Days	6875	1409	5466	551
		% Chance	*62.7%*	*12.9%*	*49.9%*	*4.4%*

The frequency of stress events in the three watersheds are similar (Table 6). Cork Brook and the Beaver River have nearly the same chance of days with Q25 or Q75 flow. The chance of a Q25 or Q75 occurring in the Queen River is only 0.8%

higher than that in the other two. Likewise, the chances of any type of stress occurring within the maximum and minimum watersheds vary by just 1.1%. One difference between Cork Brook and the Pawcatuck watersheds is the number of days with stream temperatures greater than 21 ˚C. The Beaver River and the Queen River have the same number of days with temperature stress because the air temperature for each model was collected from the same weather station. The number of days with stream temperature greater than 21 ˚C at Cork Brook is 46% higher than the Pawcatuck watersheds. This may be attributed to the low discharge levels at Cork Brook (0.081 m^3/sec) because lower, slower flows are exposed to air longer causing them to increase or decrease in temperature more (i.e. a shorter lag time (Equation 1)). This interpretation is illustrated in Figures 5, 6 and 7, which show the distribution of high stream temperatures within the Q25 and Q75 percentiles for each watershed. For all watersheds, a greater number of stressful events occurred during periods of low flow rather than periods of high flow.

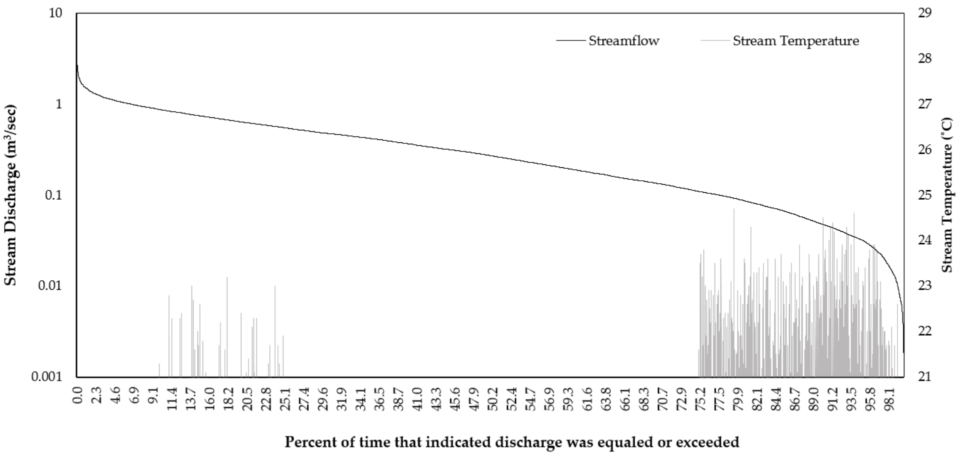


Figure 5: Beaver River simulated historical flow duration curve and stream temperatures. The secondary y-axis begins at 21 ˚C and any temperatures that are not above the stressful threshold are not shown in the figure. The stream temperatures in the Q25-Q75 range are omitted from the figure.

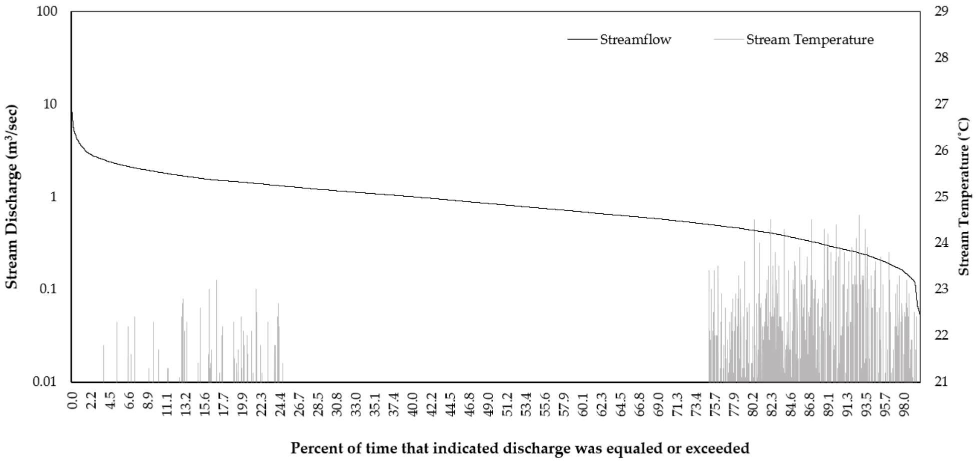


Figure 6: Queen River simulated historical flow duration curve and stream temperatures. The secondary y-axis begins at 21 ˚C and any temperatures that are not above the stressful threshold are not shown in the figure. The stream temperatures in the Q25-Q75 range are omitted from the figure.

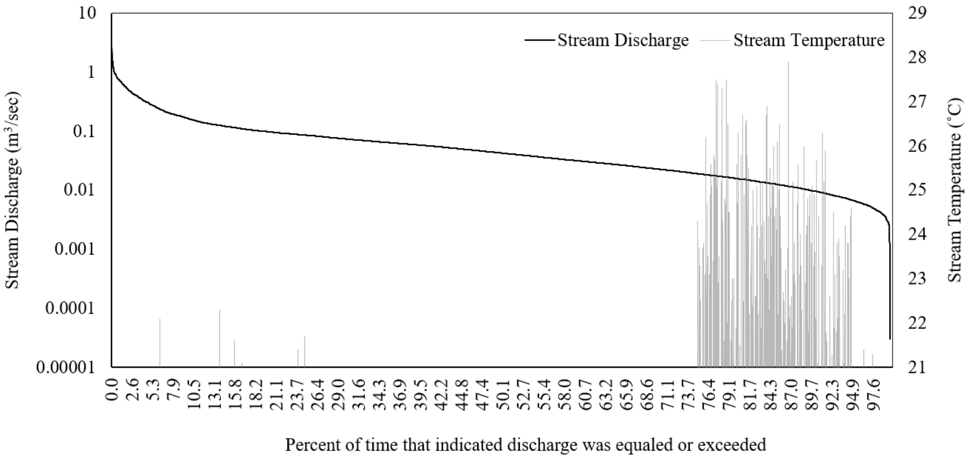


Figure 7: Cork Brook simulated historical flow duration curve and stream temperatures. The secondary y-axis begins at 21 ˚C and any temperatures that are not above the stressful threshold are not shown in the figure. The stream temperatures in the Q25-Q75 range are omitted from the figure.

Last, it is interesting to note the occurrences of stressful events within each watershed. Even though the Queen River has the same number of temperature stress days as the Beaver River, a difference of only 90 flow stress days increased the percent chance of stressful event occurrences from 4.7% in the Beaver River to 5.5%

chance in the Queen River. This shows that a combination of flow and temperature should be taken into consideration when making management decisions or evaluating the quality of aquatic habitat. Such details can have important implications for aquatic species. Brook trout have been observed to tolerate higher stream temperatures provided their physical habitat remains stable [45]. If the co-occurrence of temperature and flow stresses increases, then physiological stresses to individual trout may become more apparent. The data simulated from 1980-2009 provide a helpful baseline for comparing future projections and will help determine if the resilience of local brook trout populations may become strained under future climate change conditions by combining two important indicators for survival.

Future Projections: Stream Discharge and Stream Temperature

The modeled average daily stream temperature and average daily stream discharge increased at all sites for both low and high CO_2 emission scenarios due to warmer ambient air temperature and change in the timing and magnitude of precipitation (Table 7, 8 and 9). New England is predicted to experience a warmer and wetter climate due to global warming [3]. Since 1970 in Rhode Island the average maximum and minimum air temperatures have increased by 1.2 ˚C annually, and by 2020-2099 it is expected that there will be hotter summers with 12-44 more days above 50 ˚C in Rhode Island [26]. Annual precipitation has also increased 6-11%. By 2020-2099, annual precipitation averages are predicted to rise by 18-20% and a two-fold increase in extreme precipitation events is expected to occur. A decrease in snow cover is also projected and Rhode Island may have 20-32 fewer snow covered days [26].

Within the Beaver and Queen Rivers the simulated stream temperature change was much greater for high CO_2 emission scenarios 2010-2099 than for low CO_2 emission scenarios, a change of 3.4 ˚C as opposed to 1.6 ˚C, respectively. Discharges between the two Wood-Pawcatuck subbasins were different and a greater change was observed in the Beaver River subbasin. In the Beaver River, under the low emission scenario 2010-2099 the discharges increased by 23% related to historical discharges and under the high emission scenario increased by 71%. In the Queen River, under the low emission scenario 2010-2099 the discharges increased by 19% of historical discharge levels and under the high emission scenario increased by 49%. This is interesting because groundwater inputs are greater in the Beaver River (93%) than in the Queen River (78%). In the New England region, baseflow contributions have shown an upward trend likely linked to increasing precipitation [81] and climate change may be impacting storage by increasing the volume of water held in groundwater or as soil moisture within the basin. When storage is exceeded, the upper streamflow quantiles may be affected [82]. Brook trout can benefit from increased baseflow. Groundwater inflow can cool stream water [83], especially when flows are lower in the summer months [84]. Brook trout rely on groundwater seeps as refugia from increased stream temperatures and to keep developing embryos submerged in cool water [12].

An increase in stream temperature and streamflow was also seen in Cork Brook. Stream temperature increased by 1.6 ˚C between 2010 and 2099 under the low emission scenario and 3.5 ˚C under the high emission scenario, very similar to the degree changes in the Pawcatuck watersheds. Between 2010 and 2099, discharges increased by 20% under the low emissions scenario and 60% under the high emissions scenario. While not exact, the changes in discharge at Cork Brook for the low emission scenario are more similar to the changes within the Queen River based on percent increase although under the high emissions scenario Cork Brook is the median between the Beaver River and Queen River. Overall, the SWAT streamflow projections in the three watersheds align well with climate change predictions for New England under the low emission simulations and exceed predictions under the high emission simulations [26].

Table 7: Average Beaver River stream temperature and streamflow simulated with climate change variables. High and low CO_2 emission scenarios projected for short (2010-2039), medium (2040-2069) and long-term (2070-2099). Unchanged historical results included for reference.

Scenario	Date	Average Daily Stream Temp. (˚C)	Average Daily Discharge (m^3/sec)
Historical	1980-2009	13.0	0.38
Low Emissions	2010-2039	13.6	0.44
	2040-2069	14.2	0.45
	2070-2099	14.6	0.47
High Emissions	2010-2039	13.7	0.49
	2040-2069	15.0	0.53
	2070-2099	16.4	0.65

Table 8: Average Queen River stream temperature and streamflow simulated with climate change variables. High and low emission CO_2 scenarios projected for short (2010-2039), medium (2040-2069) and long-term (2070-2099). Unchanged historical results included for reference.

Scenario	**Date**	**Average Daily Stream Temp. (˚C)**	**Average Daily Discharge (m^3/sec)**
Historical	1980-2009	13.0	1.0
Low Emissions	2010-2039	13.6	1.1
	2040-2069	14.2	1.2
	2070-2099	14.6	1.2
High Emissions	2010-2039	13.7	1.2
	2040-2069	15.0	1.3
	2070-2099	16.4	1.5

Table 9: Average Cork Brook stream temperature and streamflow simulated with climate change variables. High and low CO_2 emission scenarios projected for short (2010-2039), medium (2040-2069) and long-term (2070-2099). Unchanged historical results included for reference.

c) Scenario	**Date**	**Average Daily Stream Temp. (˚C)**	**Average Daily Discharge (m^3/sec)**
Historical	1980-2009	12.5	0.08
Low Emissions	2010-2039	13.2	0.09
	2040-2069	13.3	0.10
	2070-2099	14.1	0.10
High Emissions	2010-2039	13.3	0.10
	2040-2069	14.5	0.10
	2070-2099	15.9	0.13

The flow duration curves for each watershed were compared to historical streamflow (1980-2009) and future long term (2070-0299) scenarios to assess the flow conditions at the end of the century (Figures 8, 9 and 10). The curve for each watershed under the low emission scenarios changed very little in shape even though the stream discharges were increased in magnitude. Under the high emissions scenario the magnitude of discharges also increases but in the Beaver River and Cork Brook, the shape of the rating curve became flatter in the Q50-Q75 percentiles. A flat curve generally indicates that flows are sustained throughout the year and can be caused by factors such as groundwater contributions to the stream reach.

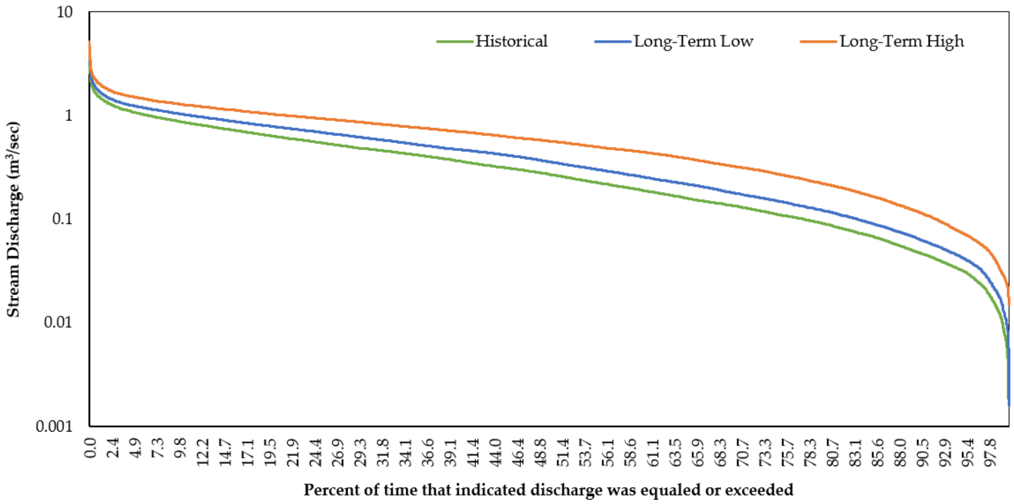


Figure 8: Beaver River flow duration curves simulated for high and low CO_2 emission scenarios by the end of the long-term (2070-2099). Unchanged historical results included for reference.

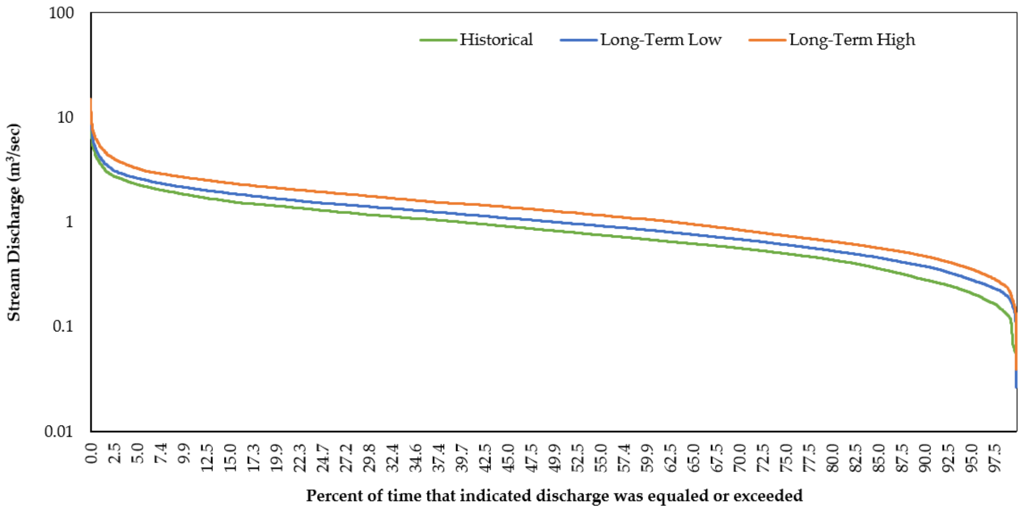


Figure 9: Queen River flow duration curves simulated for high and low CO_2 emission scenarios by the end of the long-term (2070-2099). Unchanged historical results included for reference.

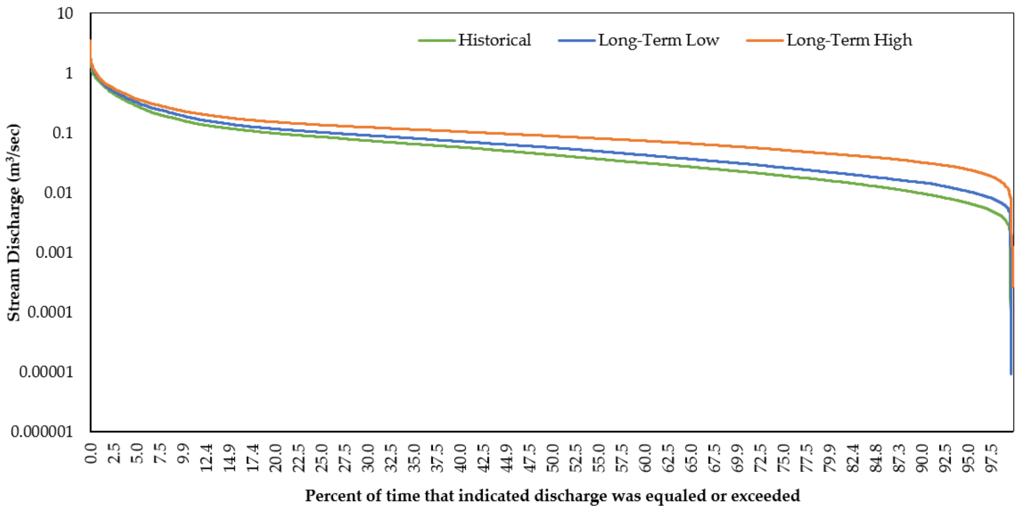
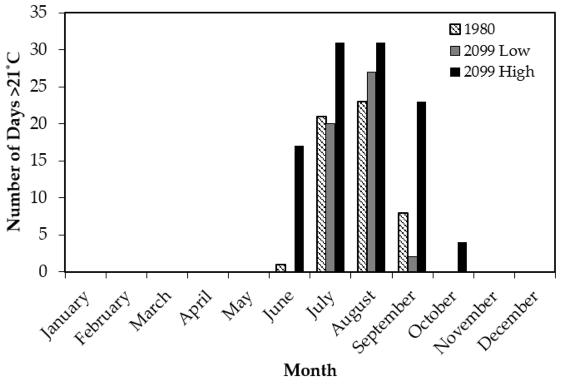


Figure 10: Cork Brook flow duration curves simulated for high and low CO_2 emission scenarios by the end of the long-term (2070-2099). Unchanged historical results included for reference.

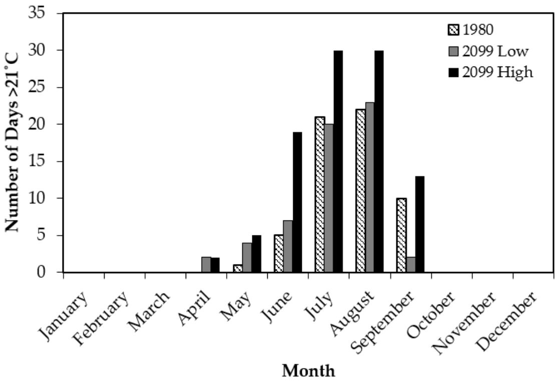
As water temperatures increase due to global warming, brook trout may benefit from sustained flows which will prevent stream temperatures from rising further and help ensure that downstream habitat remains connected to headwaters. From this perspective, the Beaver River and Cork Brook may provide better future trout habitat in comparison to the Queen River, which saw little change to the shape of the rating curve. On the other hand, a sustained increase in flow magnitude can change the geomorphology and may not be beneficial for aquatic species during the spawning season when flows are historically lower [41]. An increase in stream discharges during the low flow season may put nests at risk of destruction from sedimentation or sheer velocity. Changes in streamflow magnitude may also increase turbidity or redistribute riffle and pool habitat throughout the stream reach. This may decrease the availability of suitable habitat as brook trout prefer stream reaches with an approximate 1:1 pool-riffle [12]. Pool and riffle redistribution can also affect the type and quantity of local macroinvertebrate populations. Since warming temperatures will have an impact on body condition as fish enter the winter months, the available food supply can become an even more critical factor as the climate changes.

Future Projections: Timing of Stream Temperatures

The model predicted that between 1980-2099 stream temperatures in all watersheds will increase by 1.6 ˚C under the low emission scenario or 3.4 ˚C under the high emission scenarios (Tables 7, 8 and 9). Further analysis was conducted to assess if the temporal distribution of stream temperatures has changed throughout the year. In the Beaver and Queen River watersheds no change to the timing of high stream temperatures was observed and high temperatures continued to occur primarily in July-September (Figure 11a). In the Cork Brook watershed, however, the model predicted that the occurrence of high stream temperatures will increase and will occur as early as April by the end of the century under both high and low emission scenarios (Figure 11b). In all watersheds, the number of days with stressful temperatures during the low emission scenario increased only slightly compared to historical observations. The number of occurrences per month increased under the high emission scenario for all watersheds compared to historical simulations.



a)



b)

Figure 11: The number of days per month that stream temperatures exceeded the stress threshold in 1980, 2099 under low CO_2 emissions and 2099 under high CO_2 emissions in a) the Beaver and Queen Rivers which had the same weather station and b) Cork Brook.

Stream temperatures reaching the stressful threshold sooner in the year will have implications for those coldwater species in Cork Brook. A shift in the timing of high stream temperatures can influence the development of both young-of-year and adult individuals. Embryos develop over winter and the length of incubation is temperature dependent; 45 days for development at 10 ˚C compared to 165 days at 2.8 ˚C [12]. Higher temperatures earlier in the spring will mean that fish experience physiological stress sooner and may not be able to survive until the spawning period in late fall when stress will be relieved by cooler temperatures. Additionally, because brook trout avoid warmer water and are rarely found in streams with 60 days mean temperatures above 20 ˚C [7,33], changes to the temporal distribution of stream temperatures will likely have an effect on the spatial distribution of trout [7, 10-16].

Future Projections: Stressful Events

The results of the stressful event analysis are summarized in Table 10 over 30-year increments. There are few notable differences between the three watersheds when the data were assessed over these 30-year increments. An analysis in 10-year increments, however, yielded different results. Of the three sites between 1980-2099, the Queen River watershed had the greatest (i.e. maximum) number of stressful days and percent chance of an event occurring under both low CO_2 emissions (7 of 12 decades) and high CO_2 emissions (8 of 12 decades). Under low emission scenarios, the Beaver River had the maximum count just once and under the high emission scenario the Cork Brook watershed had the maximum count once. Under the low emission scenario, the percent chance of a stressful event occurring from 1980-1989 compared to 2090-2099 increased by 4.6 percentage points in the Beaver River, 6.7 in the Queen River and 8.4 in Cork Brook. Under the high emission scenario, the difference in chance of a stressful event occurring from 1980-1989 compared to 2090-2099 is 13.4 percent points in the Beaver River, 14.8 in the Queen River and 14.3 in Cork Brook.

The Beaver River has a lower change in stressful event chance than the other watersheds for both low emission and high emission climate change scenarios. This may be because it has the greatest percent of groundwater contributions and streams that are groundwater fed receive inputs that are less exposed to ambient air temperatures. The benefits of groundwater inputs are greater under the low emission scenario and less effective under the high emission scenarios. For instance, the watershed with the least amount of baseflow (Cork Brook) has a change in percent chance that is almost double that of the watershed with the highest baseflow (Beaver River). Under the high emission scenario, however, the change in percent chance is less distributed and the Beaver River and Cork Brook differ by just 0.9%. Groundwater temperatures are expected to follow projected increases in mean annual air temperature from climate warming ([84]). Under the high emission scenario, this effect may be more prominent allowing for less buffering of in-stream temperatures by baseflow inputs.

Table 10: Percent chance of a stressful event occurring under future climate scenarios. Results for each watershed by 30-year increments. High and low CO_2 emission scenarios projected for short (2010-2039), medium (2040-2069) and long-term (2070-2099). Unchanged historical results included for reference.

Date	Emission Scenario	Beaver (% Chance)	Queen (% Chance)	Cork Brook (% Chance)
1980-2009	Historical	4.7	5.5	4.4
2010-2039	Low	6.2	6.9	6.5
	High	7.2	7.9	7.2
2040-2069	Low	7.9	8.5	7.1
	High	12.4	13.1	11.3
2079-2099	Low	9.0	9.8	8.6
	High	16.1	16.8	15.2

The number of stressful events under the high emission scenario is greater than the number of events under the low emission scenario for every decade since 2010, in every watershed (Figures 12, 13 and 14). The graphs also show that for future high emission simulations the number of events in any given decade is higher than the previous decade except for 2060-2069 in the Queen River and 2070-2079 in the Beaver River and Cork Brook. Additionally, it should be noted that there is a minor disconnect between the historical trend and the short-term future simulations; In the Queen River and in Cork Brook Cork there is a higher occurrence between 2000-2009 than there is 2010-2019. The timing of the decrease is likely a result of the shifting the model from the regular SWAT code to SWAT with added climate variables, rather than the simulation itself.

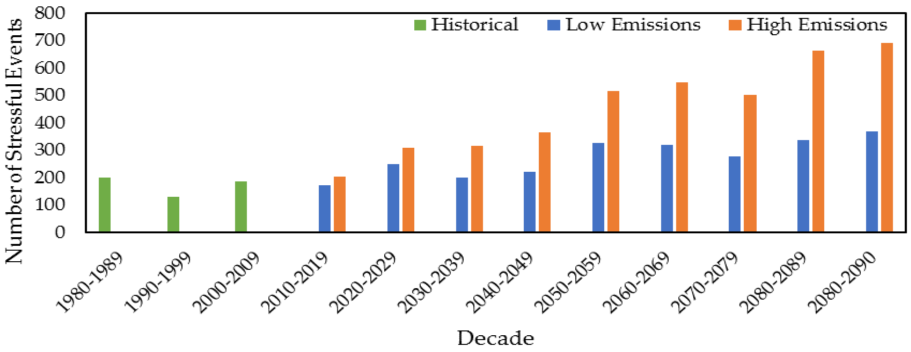


Figure 12: Number of stressful events predicted in the Beaver River watershed between 1980-2099 under historical conditions, low CO_2 emissions and high CO_2 emission scenarios.

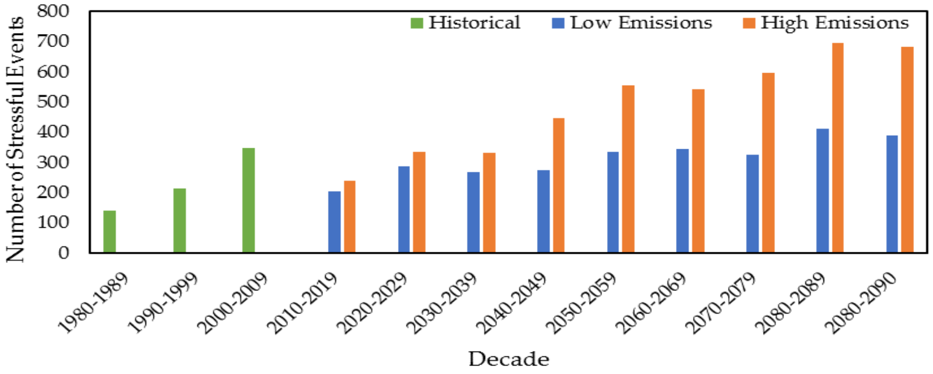


Figure 13: Number of stressful events predicted in the Queen River watershed between 1980-2099 under historical conditions, low CO_2 emissions and high CO_2 emission scenarios

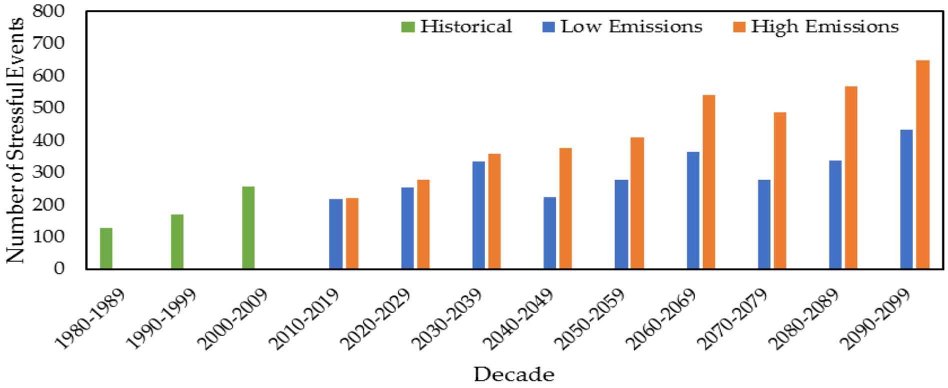


Figure 14: Number of stressful events predicted in the Cork Brook watershed between 1980-2099 under historical conditions, low CO_2 emissions and high CO_2 emission scenarios

Of the three watersheds, the Beaver River and Cork Brook are most likely to provide resilient habitat for brook trout as the local water conditions change due to global warming. Under low emission scenarios, the Beaver River more frequently displayed the lower percent chance of a stressful event occurring and under the high emission scenario Cork Brook more frequently had the lowest percent chance by the end of the century. Under both the low and high emission scenarios, the chance of stressful events occurring was consistently predicted to be greater in the Queen River. Possible causes of this difference are the larger size of the Queen River watershed and the two tributaries located upstream of the watershed outlet. Fisherville Brook and Queen's Fort Brook are two waterways that discharge into the Queen River (Figure 1). The Queen's Fort Brook flows along the eastern side of the watershed through the agricultural area and Fisherville Brook is located along the western side of the watershed where the slope is steeper. Additionally, the main stem of the Queen River itself flows through a large golf course in the middle of the watershed. The tributaries and the main stem come into closer contact with the heterogeneous areas of the basin and may be able to capture additional effects of climate change not seen in the other watersheds. This is not to say that coldwater habitat restoration is not worthwhile in the Queen River, rather that more effort will be needed to restore or maintain brook trout populations in this watershed.

Stream temperatures in all three watersheds were simulated to increase under both low CO_2 and high CO_2 emission scenarios. It is challenging to discern from this study if stream temperatures in the Beaver River or the Queen River differ significantly because the UGSG gauges at the basin outlet do not record stream temperature and the weather station data used in SWAT simulations was the same for both watersheds. Simulated results do show, however, that stream temperatures will increase through the end of the century by either 1.6 ˚C under low emissions or 3.4 ˚C under high emissions in these two watersheds. One way resource managers can buffer this effect is by preserving existing canopy cover along the riparian corridor. Forest harvesting can increase solar radiation in the riparian zone as well as wind speed and exposure to air advected from clearings, typically causing increases in stream water temperature regimes [85,86]. Additionally, managers may also advocate for preserving groundwater resources that discharge to the streams because baseflow will help regulate stream temperatures, especially if the global low CO_2 emission scenario is achieved.

CONCLUSIONS AND FUTURE WORK

To help managers identify which areas within a watershed are in the greatest need of protection, a subbasin analysis could be conducted. For instance, both Wood-Pawcatuck basins are home to small preserves managed by the Nature Conservancy. Setting up the model so that a subbasin outlet (as opposed to the watershed outlet) is located within each preserve will allow for assessing site specific conditions when it is not practical to create a model on a small scale. If model output shows that historically these preserves have changed very little, and that future simulations predict minimal change, then managers can put efforts and financial resources towards other preserves that are in greater need.

Another consideration for future work is to limit the stressful event analysis to the spring and summer months when brook trout are more sensitive to warmer stream temperatures. Also, a study could be conducted to see if stressful events occur sequentially. This study took a wider approach by examining how stream temperatures and streamflow vary throughout the entire year. This timeframe was chosen for several reasons. First, since this is the only study of its kind within these watersheds we did not have enough information to say with certainty that no changes to stream temperature or streamflow would occur during the fall and winter. In fact, some scientists predict that by the end of the century Rhode Island will have a climate similar to that of Georgia [26] in which case stream temperatures would almost certainly increase during the winter months. Second, while stream temperatures and streamflow during the winter months are not as critical for brook trout compared to the summer, winter conditions do effect embryo development. For instance, the length of embryo incubation during the winter ranges from 28-165 days depending on the temperature of the stream water [12]. Lastly, while this study focused on brook trout, our hope is that the methodology can be applied to other types of aquatic species that may be sensitive to stream conditions during other seasons.

Finally, since all three of these watersheds are baseflow driven, using a model approach that considers the influence of groundwater discharges on stream temperatures would be valuable. A study conducted by Ficklin et al. 2012 developed a hydroclimatological SWAT component that incorporates the effects of both air temperatures and hydrological inputs, such as groundwater, on stream temperatures. Previous studies have shown that the hydroclimatological component can be used in small watersheds [87] and in New England [88]. Since the hydroclimatological model component takes the groundwater temperature into consideration, the stream reach will receive inputs that are less exposed to ambient air and therefore cooler during the summer and slightly warmer than the air during the winter. Using a SWAT model with this component may produce more accurate stream temperature results in streams that are baseflow driven.

The purpose of this study was to gain a better understanding of the effects of climate change on coldwater habitat using SWAT. We successfully showed that SWAT can be used to simulate both historical and future climate scenarios in forested, baseflow driven watersheds in Rhode Island. Moreover, thermally stressful event identification is a functional approach to analyzing model. The results indicate that climate change will have a negative effect on coldwater fish species in these types of ecosystems, and that the resiliency of local populations will be tested as stream conditions will likely become increasingly stressful.

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APPENDIX A

Review of the Problem

The temporal and spatial variability of stream temperature and stream flow are two of the primary controls on the distribution and abundance of aquatic organisms. Likewise, they are important parameters for determining the suitability of water resources for human use. Climate change is anticipated to have effects on aquatic ecosystems in the New England region of the USA. Evidence suggests that these impacts will include warming stream temperatures and changes to the flow regimes of inland freshwater resources. The consequences are expected to result in the reduced viability of aquatic populations and loss of habitat connectivity.

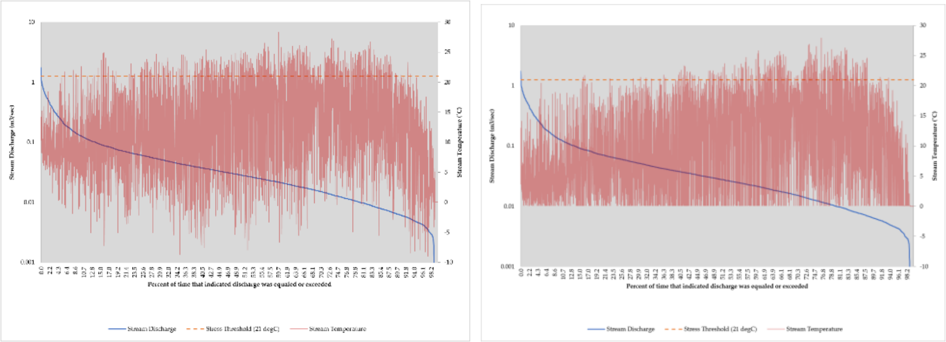
The site-specific effects of climate change on Rhode Island's inland coldwater habitats is not well studied in the Beaver River, Queen River or Cork Brook watersheds. Furthermore, hydrological models have not been used to analyze the effects of climate change on streamflow and stream temperature on Rhode Island brook trout (*Salvelinus fontinalis*) populations. This thesis approached these problems using the Soil and Water Assessment Tool (SWAT) to generate streamflow and stream temperature data within these three forested, baseflow driven watersheds in Rhode Island. The problem was also approached using a site-specific method to analyze the quality of aquatic habitat and its suitability for native coldwater fishes. The method identified "thermally stressful events" which, for the purposes of this study, are defined as any day where Q25 or Q75 flows occur simultaneously with stream temperatures >21˚C and brook trout are physiologically stressed.

The model output data were assessed to determine the number of incidences over a given time period that a day with high or low flows (Q25 or Q75) occurred, that a day with high stream temperatures (>21˚C) occurred, that any type of stress occurred, and the number of days that a stressful event occurred. The percent chance that a condition would occur was also calculated.

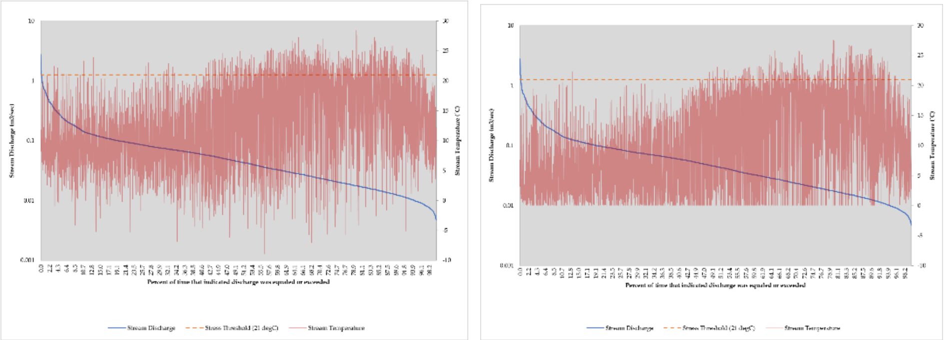
This thesis was written in two parts using similar but separate methodology. Manuscript 1, titled “Assessing Thermally Stressful Events in RI Coldwater Fish Habitat Using Swat Model” was conducted using SWAT with an added hydroclimatological component to assess the historical conditions in Cork Brook. Manuscript 2, titled “Climate Change Induced Thermal Stress in Coldwater Fish Habitat Using SWAT” was conducted using original SWAT with added climate change scenarios to assess both historical and future conditions in all three watersheds.

APPENDIX B

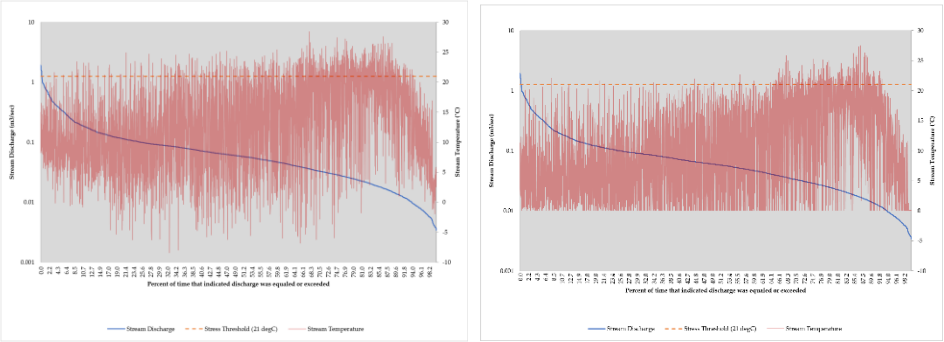
Manuscript 1 Results



a) Original SWAT 1980-1989 b) Ficklin SWAT 1980-1989



c) Original SWAT 1980-1989 d) Ficklin SWAT 1980-1989



e. Original SWAT 1980-1989 f) Ficklin SWAT 1980-1989

Figure 1: The results of the original SWAT simulations compared to the hydroclimatological (Ficklin) SWAT. The streamflow is on the y-axis in m^3/sec, stream temperature on the secondary y-axis (˚C) and the flow percentiles are shown on the x-axis. The thermal stress threshold (21 ˚C) is shown as a horizontal dashed line.

Table 1: Stressful event analysis of SWAT and SWAT with the hydroclimatological (Ficklin) component. Shows the percent chance that of days with any type of stress, a day will be stressful due to flow, percent chance that a day will be stressful due to high stream temperature, percent chance that a both stresses will occur on the same day and result in an event.

Date	**Unit**	**Any Type of Stress**		**Stream Temp. >21˚C**		**Q25 or Q75 Flow**		**Stressful Event**	
		SWAT	*Ficklin*	*SWAT*	*Ficklin*	*SWAT*	*Ficklin*	*SWAT*	*Ficklin*
1980-1989	Days	2258	2066	444	252	1814	1814	127	84
	% Chance			*19.7%*	*12.2%*	*80.3%*	*87.8%*	*5.6%*	*4.1%*
1990-1999	Days	2272	2049	451	228	1821	1821	168	122
	% Chance			*19.9%*	*11.1%*	*80.1%*	*88.9%*	*7.4%*	*6.0%*
2000-2009	Days	2341	2007	514	196	1827	1811	256	131
	% Chance			*22.0%*	*9.8%*	*78.0%*	*90.2%*	*10.9%*	*6.5%*
1980-2009	Days	6875	6142	1409	676	5466	5466	479	338
	% Chance			*20.5%*	*11.0%*	*79.5%*	*89.0%*	*8.0%*	*5.5%*

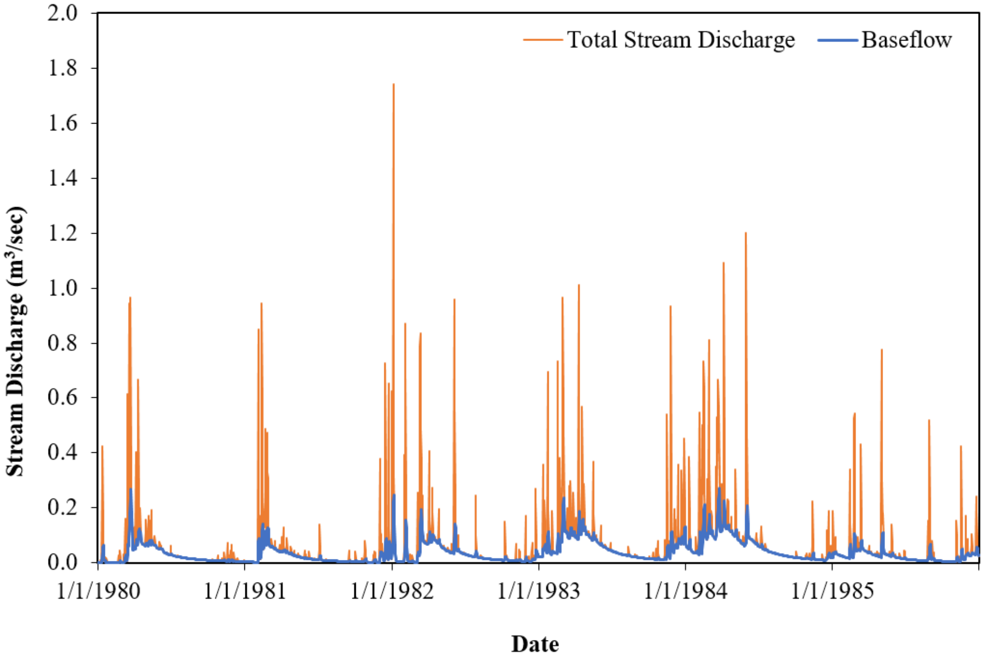


Figure 2: Example of Cork Brook SWAT simulated baseflow separated from SWAT simulated total stream discharge for the years 1980-1986. Produced using Arnold, J.G., et al., Automated Base Flow Separation and Recession Analysis Techniques. Ground Water, 1995. 33(6): p. 1010-1018.

The initial intent of this project was to incorporate the hydroclimatological component into all three watershed models. Due to limited stream temperature data, however, it was not possible to calibrate the hydroclimatological component into the Beaver River and Queen River models. The calibration attempts for the Beaver River and the Queen River are included in this appendix and shown below.

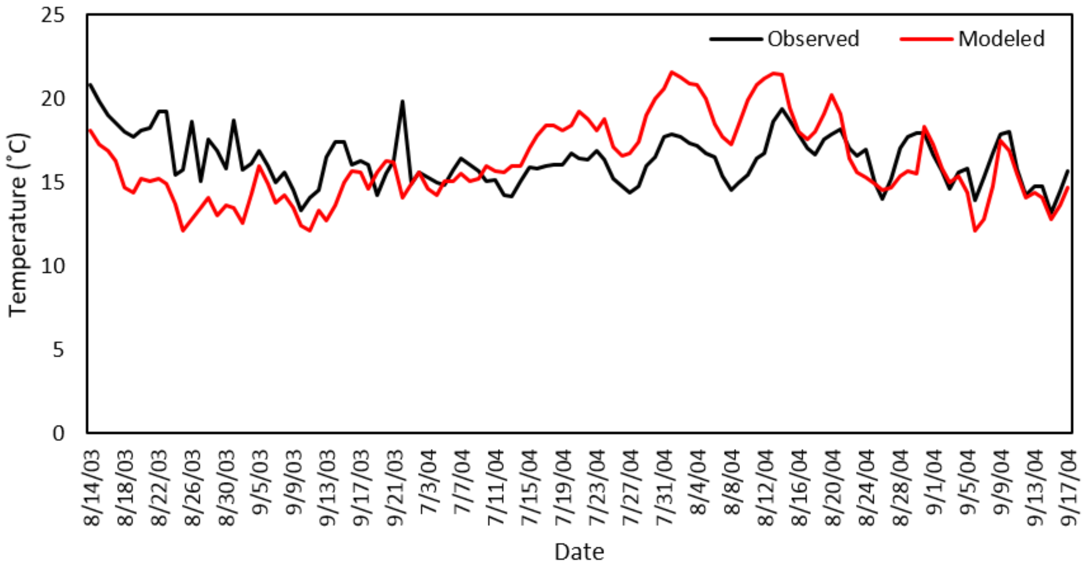


Figure 3: A hydrograph of the Beaver River stream temperature modeled versus observed 2003 and 2004. The modeled stream temperature is produced using the hydroclimatological model and the observed data was collected by the Wood-Pawcatuck Watershed Association. With minimal observed data it was not possible to produce satisfactory calibration results.

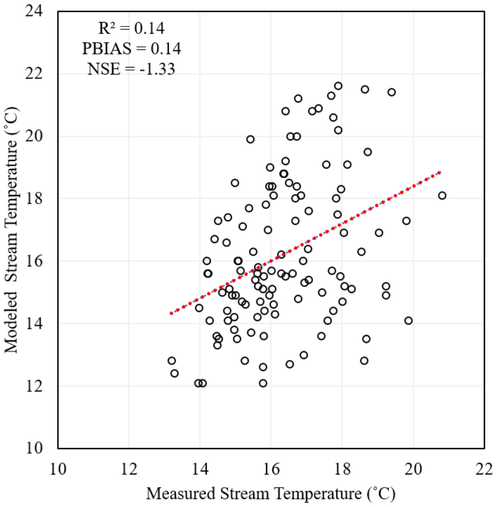


Figure 4: A scatterplot of Beaver River stream temperature modeled versus observed 2003 and 2004. The modeled stream temperature is produced using the hydroclimatological model and the observed data was collected by the Wood-Pawcatuck Watershed Association. With minimal observed data, it was not possible to produce satisfactory calibration results.

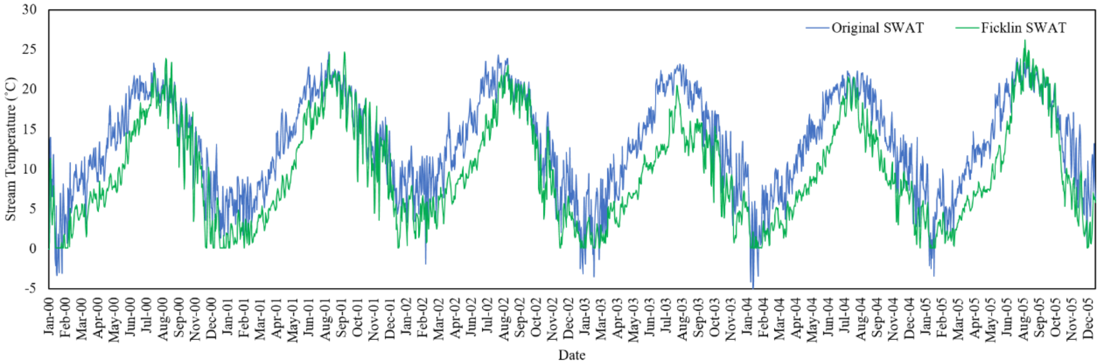


Figure 5: The Beaver River stream temperature SWAT model versus SWAT with the hydroclimatological (Ficklin) component 2000-2005.

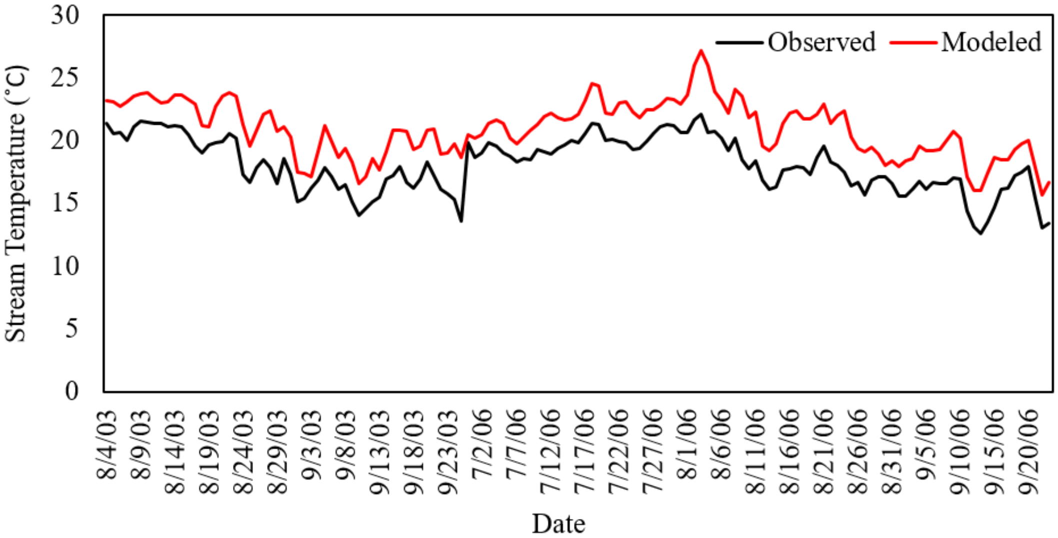


Figure 6: A hydrograph of the Queen River stream temperature modeled versus observed 2003 and 2006. The modeled stream temperature is produced using the hydroclimatological model and the observed data was collected by the Wood-Pawcatuck Watershed Association. With minimal observed data it was not possible to produce satisfactory calibration results.

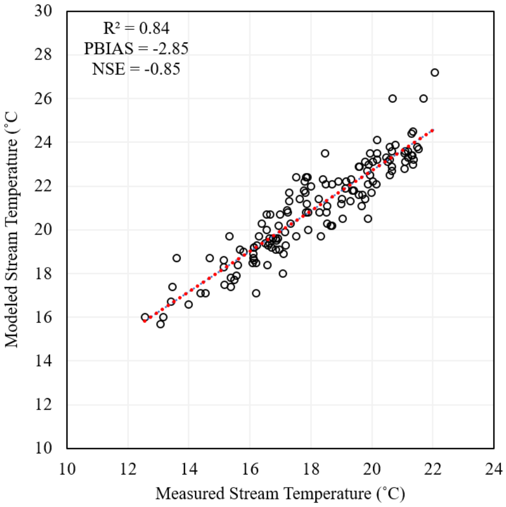


Figure 7: A scatterplot of the Queen River stream temperature modeled versus observed 2003 and 2004. The modeled stream temperature is produced using the hydroclimatological model and the observed data was collected by the Wood-Pawcatuck Watershed Association. With minimal observed data, it was not possible to produce satisfactory calibration results.

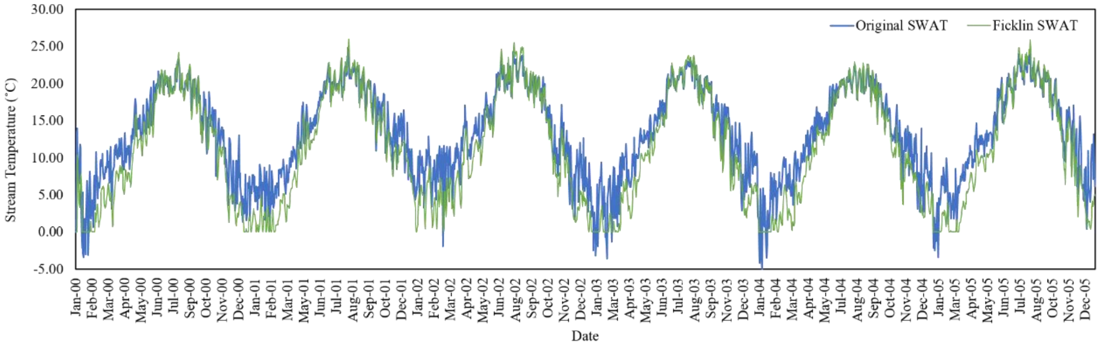


Figure 8: The Queen River stream temperature SWAT model versus SWAT with the hydroclimatological (Ficklin) component 2000-2005.

APPENDIX C

Manuscript 2 Results

Table 1: Stressful event results for each watershed by decade. High and low CO2 emission scenarios projected for short (2010-2039), medium (2040-2069) and long-term (2070-2099). Unchanged historical results included for reference.

Date	Emission Scenario	Unit	Beaver	Queen	Cork
1980-1989	Low	Days	200	141	127
		% Chance	*5.5%*	*3.9%*	*3.5%*
	High	Days	200	141	127
		% Chance	*5.5%*	*3.9%*	*3.5%*
1990-1999	Low	Days	130	213	168
		% Chance	*3.6%*	*5.8%*	*4.6%*
	High	Days	130	213	168
		% Chance	*3.6%*	*5.8%*	*4.6%*
2000-2009	Low	Days	185	346	256
		% Chance	*5.1%*	*9.5%*	*7.0%*
	High	Days	185	346	256
		% Chance	*5.1%*	*9.5%*	*7.0%*
2010-2019	Low	Days	172	141	216
		% Chance	*4.7%*	*3.9%*	*5.9%*
	High	Days	203	238	221
		% Chance	*5.6%*	*6.5%*	*6.0%*
2020-2029	Low	Days	249	213	252
		% Chance	*6.8%*	*5.8%*	*6.9%*
	High	Days	308	334	276
		% Chance	*8.4%*	*9.1%*	*7.6%*
2030-2039	Low	Days	200	346	335
		% Chance	*5.5%*	*9.5%*	*9.2%*
	High	Days	317	330	358
		% Chance	*8.7%*	*9.0%*	*9.8%*
2040-2049	Low	Days	221	273	223
		% Chance	*6.0%*	*7.5%*	*6.1%*
	High	Days	364	445	375
		% Chance	*10.0%*	*12.2%*	*10.0%*
2050-2059	Low	Days	325	334	278
		% Chance	*8.9%*	*9.1%*	*7.6%*
	High	Days	516	555	410
		% Chance	*14.1%*	*15.2%*	*11.0%*

2060-2069	Low	Days	320	343	363
		% Chance	*8.8%*	*9.4%*	*9.9%*
	High	Days	547	543	540
		% Chance	*15.0%*	*14.9%*	*14.8%*
2070-2079	Low	Days	276	326	276
		% Chance	*7.6%*	*8.9%*	*7.6%*
	High	Days	502	597	487
		% Chance	*13.7%*	*16.3%*	*13.3%*
2080-2089	Low	Days	337	412	338
		% Chance	*9.2%*	*11.3%*	*9.3%*
	High	Days	662	694	566
		% Chance	*18.1%*	*19.0%*	*15.5%*
2090-2099	Low	Days	370	389	433
		% Chance	*10.1%*	*10.6%*	*11.9%*
	High	Days	692	682	649
		% Chance	*18.9%*	*18.7%*	*17.8%*

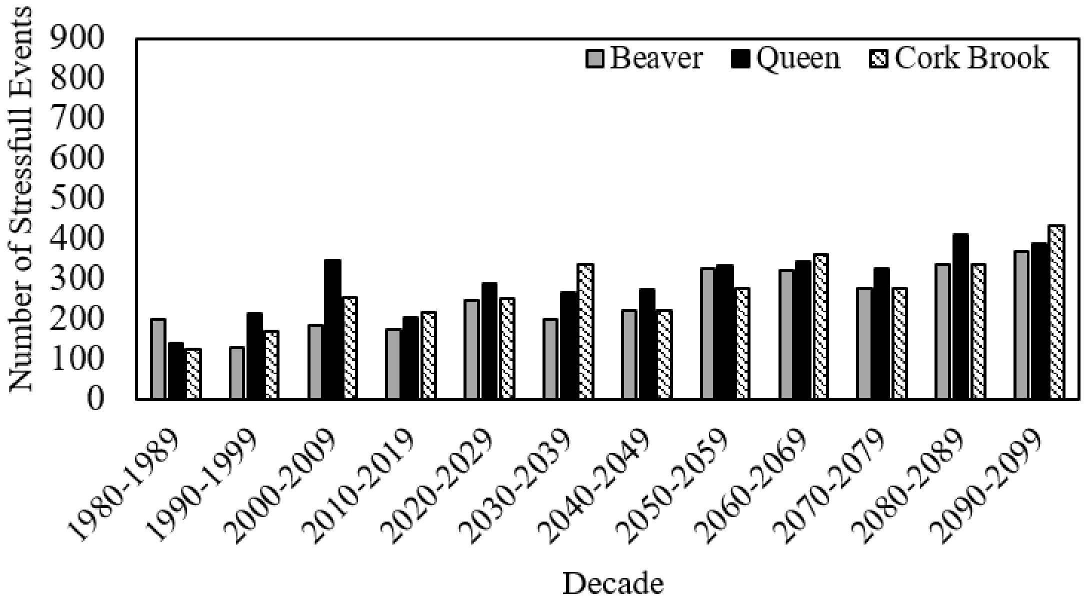


Figure 1: Number of simulated stressful events 1980-2099. Years 2010-2099 simulated low emissions climate change variables.

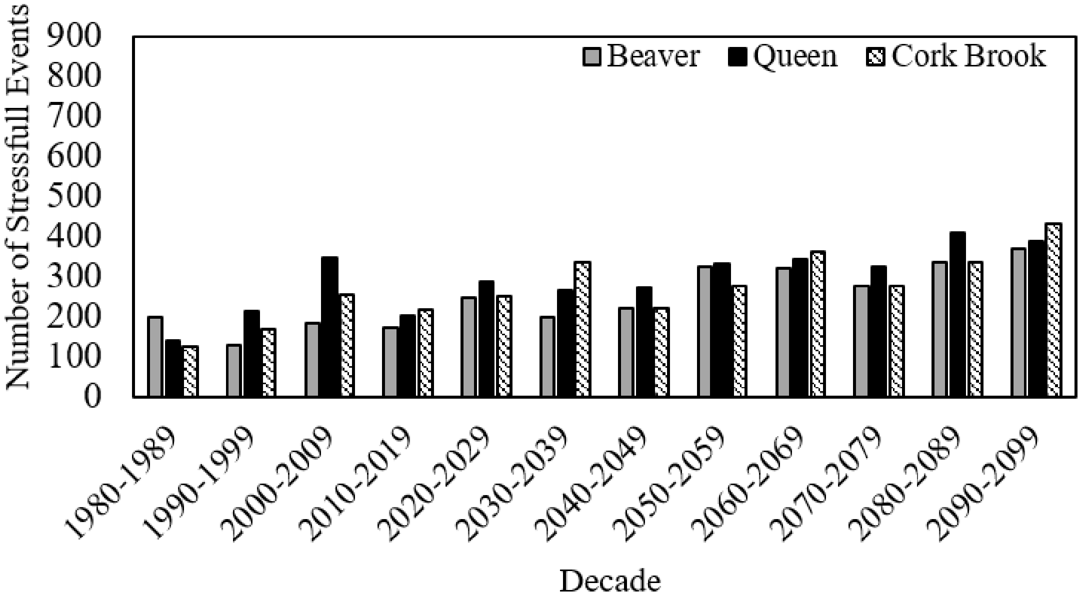


Figure 2: Number of simulated stressful events 1980-2099. Years 2010-2099 simulated high emissions climate change variables.

Table 2: Simulated stream conditions 2010-2099 in the Beaver River under low emission climate change scenario. Shows the number of days with any type of stress, stream temperature stress, flow stress and stressful events by decade.

Date	**Any Type of Stress**	**Stream Temp. >21˚C**	**Q25 or Q75 Flow**	**Stressful Event**
1980-1989	2180	358	1822	200
1990-1999	2123	301	1822	130
2000-2009	2120	300	1820	185
2010-2019	2253	434	1819	172
2020-2029	2255	434	1821	249
2030-2039	2180	358	1822	200
2040-2049	2337	530	1807	221
2050-2059	2352	532	1820	325
2060-2069	2403	582	1821	320
2070-2079	2423	606	1817	276
2080-2089	2423	600	1823	337
2090-2099	2476	653	1823	370

Table 3: Simulated stream conditions 2010-2099 in the Queen River under low emission climate change scenario. Shows the number of days with any type of stress, stream temperature stress, flow stress and stressful events by decade.

Date	Any Type of Stress	Stream Temp. >21˚C	Q25 or Q75 Flow	Stressful Event
2010-2019	2254	434	1820	203
2020-2029	2236	412	1824	287
2030-2039	2292	471	1821	267
2040-2049	2349	530	1819	273
2050-2059	2315	486	1829	334
2060-2069	2382	582	1800	343
2070-2079	2438	606	1832	326
2080-2089	2425	600	1825	412
2090-2099	2475	653	1822	389

Table 4: Simulated stream conditions 2010-2099 in Cork Brook under low emission climate change scenario. Shows the number of days with any type of stress, stream temperature stress, flow stress and stressful events by decade.

Date	Any Type of Stress	Stream Temp. >21˚C	Q25 or Q75 Flow	Stressful Event
2010-2019	2394	553	1841	216
2020-2029	2402	585	1817	252
2030-2039	2428	605	1823	335
2040-2049	2393	577	1816	223
2050-2059	2432	618	1814	278
2060-2069	2469	644	1825	363
2070-2079	2522	703	1819	276
2080-2089	2552	725	1827	338
2090-2099	2571	756	1815	433

Table 5: Simulated stream conditions 2010-2099 in the Beaver River under high emission climate change scenario. Shows the number of days with any type of stress, stream temperature stress, flow stress and stressful events by decade.

Date	Any Type of Stress	Stream Temp. >21˚C	Q25 or Q75 Flow	Stressful Event
2010-2019	2296	485	1811	203
2020-2029	2307	486	1821	308
2030-2039	2375	557	1818	317
2040-2049	2622	809	1813	364
2050-2059	2650	833	1817	516
2060-2069	2730	910	1820	547
2070-2079	2892	1074	1818	502
2080-2089	2945	1124	1821	662
2090-2099	2954	1138	1816	692

Table 6: Simulated stream conditions 2010-2099 in the Queen River under high emission climate change scenario. Shows the number of days with any type of stress, stream temperature stress, flow stress and stressful events by decade.

Date	Any Type of Stress	Stream Temp. >21˚C	Q25 or Q75 Flow	Stressful Event
2010-2019	2314	485	1829	238
2020-2029	2315	486	1829	334
2030-2039	2378	557	1821	330
2040-2049	2624	809	1815	445
2050-2059	2655	833	1822	555
2060-2069	2740	910	1830	543
2070-2079	2899	1074	1825	597
2080-2089	2953	1124	1829	694
2090-2099	2961	1138	1823	682

Table 7: Simulated stream conditions 2010-2099 in Cork Brook under high emission climate change scenario. Shows the number of days with any type of stress, stream temperature stress, flow stress and stressful events by decade.

Date	Any Type of Stress	Stream Temp. >21˚C	Q25 or Q75 Flow	Stressful Event
2010-2019	2314	485	1829	238
2020-2029	2315	486	1829	334
2030-2039	2378	557	1821	330
2040-2049	2624	809	1815	445
2050-2059	2655	833	1822	555
2060-2069	2740	910	1830	543
2070-2079	2899	1074	1825	597
2080-2089	2953	1124	1829	694
2090-2099	2961	1138	1823	682

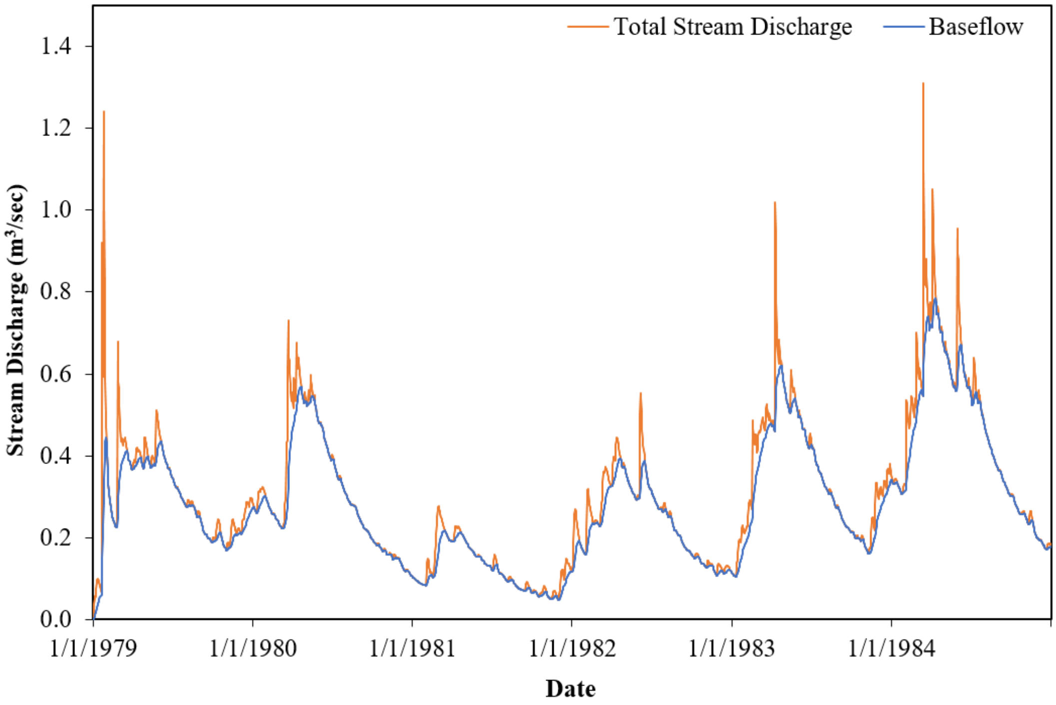


Figure 3: Example of Beaver River SWAT simulated baseflow separated from SWAT simulated total stream discharge for the years 1979-1985. Produced using Arnold, J.G., et al., Automated Base Flow Separation and Recession Analysis Techniques. Ground Water, 1995. 33(6): p. 1010-1018.

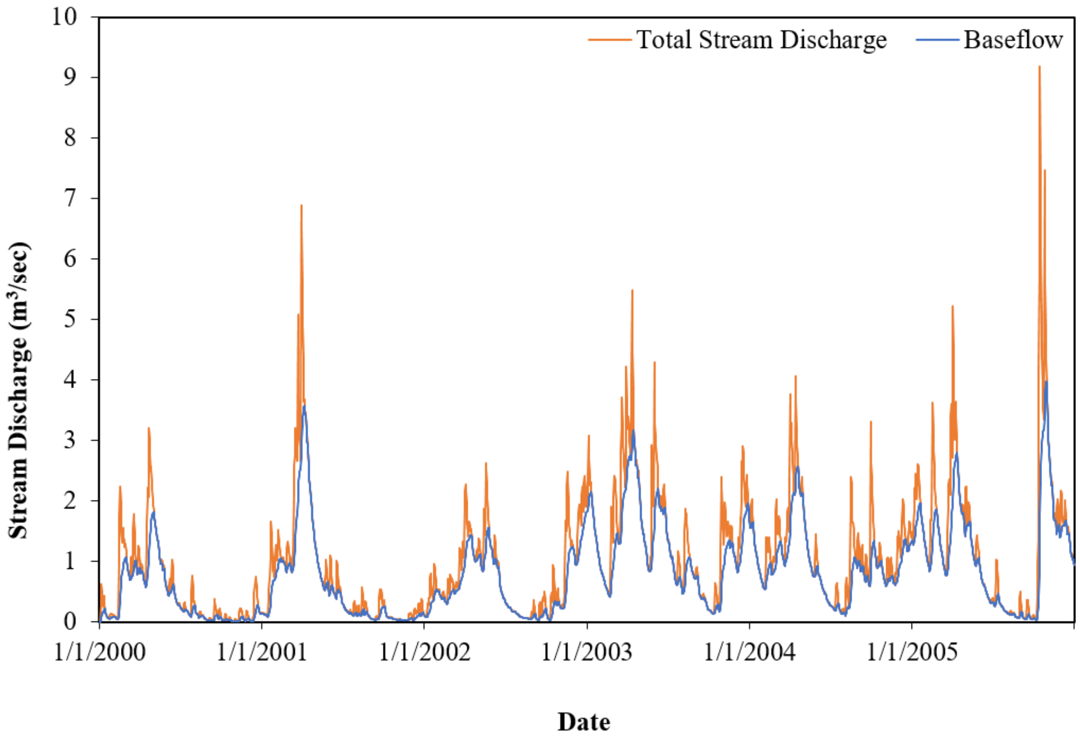


Figure 4: Example of Queen River SWAT simulated baseflow separated from SWAT simulated total stream discharge for the years 2000-2005. Produced using Arnold, J.G., et al., Automated Base Flow Separation and Recession Analysis Techniques. Ground Water, 1995. 33(6): p. 1010-1018.